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Tollbooth Workers and Mobile Source-Related Hazardous Air Pollutants: How Protective Is the Indoor Environment?

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Tollbooth workers are potentially exposed to high levels of mobile source-related air pollutants due to the proximity and intensity of the source. To evaluate this worker hazard, we measured the concentration of air toxins including volatile organic compounds (VOCs) and particle-bound polycyclic aromatic hydrocarbons (PAHs) inside and outside a Baltimore Harbor Tunnel tollbooth during the summer of 2001. Mean outdoor benzene and 1,3-butadiene concentrations varied by shift with the morning (10.7 and 19.8 $\mu g/m^3$) exceeding afternoon (7.2 and 14.9 $\mu g/m^3$) and the lowest levels observed during the night (3.7 and 4.9 $\mu g/m^3$, respectively) when traffic volume was the lowest. In comparison, considerable protection was provided to workers by the indoor environment where lower concentrations of 1,3-butadiene and benzene were observed for all three shifts (2.9 and 6.7, 0.9 and 3.2, and 0.9 and 2.4 $\mu g/m^3$, respectively). The greatest protection offered by the tollbooth was observed during the afternoon shift (5−8-fold reduction in indoor concentration), whereas the morning and night shifts experienced similar protection (2−4-fold reduction). Chlorinated hydrocarbons were observed at higher concentrations within the tollbooth, indicating the presence of indoor sources and the opportunity for exposure mitigation. Levels of PAHs were similarly reduced from outdoors (50 ng/m^3) to indoors (15.4 ng/m^3). The protective nature of the tollbooth highlighted in this study is likely due to the positive pressure control ventilation system that was present at this specific facility, which represents 55% of tollbooths in Maryland. This study provides an estimate of tollbooth workers potential exposures to various mobile source-related pollutants and highlights the protective nature of tollbooths equipped with positive pressure control ventilation systems.

Introduction

The potential for tollbooth worker exposure to high levels of mobile source-related air pollution is of concern due to both the proximity and the intensity of the emission source. Tollbooth workers routinely spend a large fraction of their workday within arms-length of vehicles emitting a wide range of toxic pollutants. Traffic volumes at tollbooth facilities can number in the thousands of vehicles per hour. The exposure potential is further heightened, despite advances in emission control technology due to rising vehicle miles traveled and a growing proportion of heavier, less fuel efficient sport utility vehicles (*1*). Furthermore, tollbooth-related vehicle operation including acceleration and deceleration is associated with high engine and brake wear emissions (*2*, *3*). As a result, tollbooth facilities are likely to represent a worst-case scenario for occupational exposure to mobile source-related air pollution. Yet, little has been done to evaluate worker exposure related to the indoor tollbooth environment. The extent of exposure will be largely influenced by the protection provided by the indoor tollbooth environment.

Vehicle exhaust is known to contain a wide range of toxic pollutants including particulate matter (PM) (*2*, *4*), volatile organic compounds (VOCs), particle-phase organic compounds, carbonyls (*3*, *5*), carbon monoxide (CO), nitrogen oxides (NOX) (*6*), as well as dioxins and furans (*7*). Exposure to cancer-causing pollutants that are present in vehicle exhaust is of particular interest for assessing risk. Among the vehicle exhaust carcinogens, most of the cancer risk is attributed to benzene, 1,3-butadiene, and particle-bound polycyclic aromatic hydrocarbons (PAH) due to their high concentrations in exhaust and potency (*8*, *9*). A recent study conducted at the same tollbooth facility that is the subject of this investigation reported that the curbside concentration of these carcinogens is associated with traffic volume and vehicle type (*10*). A number of studies have linked traffic levels to increased cancer risk including childhood leukemia (*11*, *12*), while others looking at short-term effects have reported statistically significant positive associations for acute irritant effects of the nose and throat along with nausea and headaches (*13*), central nervous systems complaints (*14*), and decreased pulmonary function (*15*).

Despite the potential for high-level exposures to a variety of hazardous air pollutants among tollbooth workers, little is known of toll collectors' exposures in the U.S. Recent studies conducted in Taiwan have characterized worker exposures to PM and PAH using a combination of air and biological monitoring (*16*−*19*). In comparison, the studies conducted in the United States are more historical and focus on CO, lead, NO_2, SO_2, asbestos, and particulate matter (PM) (*20*, *21*). Recent studies have reported ambient tollbooth pollution levels of carbonyls (*22*), VOCs, and PAHs (*10*); however, the relevance of such ambient measurements to worker exposure is unknown. Recognizing the exposure potential and related health risks, the current study was conducted specifically to assess the effectiveness of the indoor tollbooth environment in protecting workers from exposure to mobile source-related carcinogens.

Method

Worker exposure and the protection provided by the indoor environment were evaluated by examining traffic volume, the associated curbside pollutant concentration, and ultimately the concentration inside the tollbooth. Air pollution measurements were concurrently made inside and outside a single tollbooth at the Baltimore Harbor Tunnel (BHT) facility during seven weekdays from June 18, 2001 to June 28, 2001. The BHT Plaza is located south of Baltimore City on highway 895. At this facility, there are 14 tollbooths, 7 each on the northbound and southbound lanes. The BHT facility operates three shifts per day: morning shift from 6:00 am to 2:00 pm, afternoon shift from 2:00 pm to 10:00 pm, and night shift from 10:00 pm to 6:00 am.

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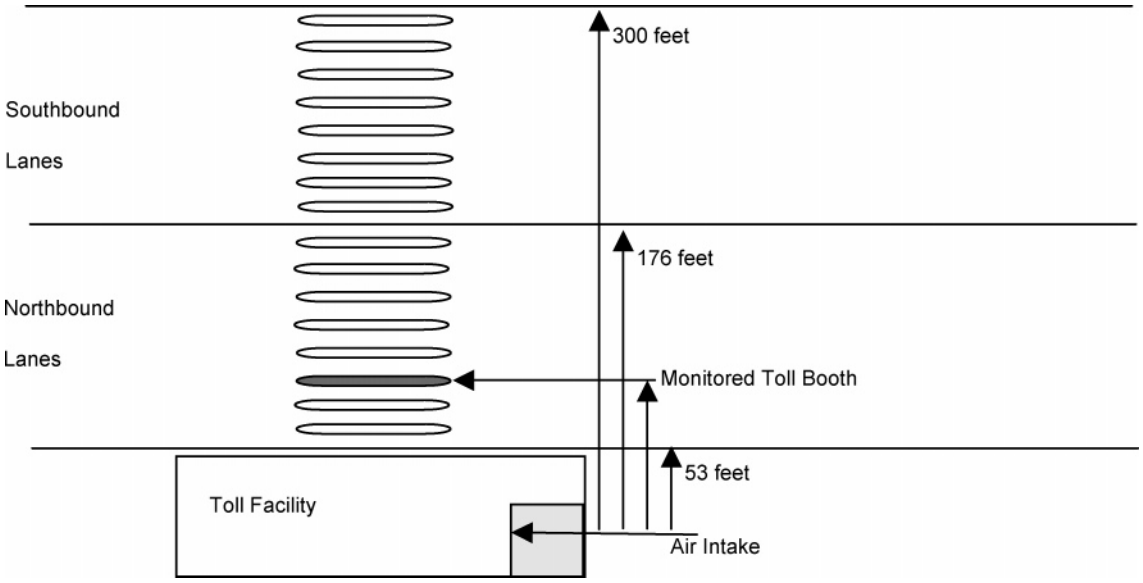

FIGURE 1. Schematic of Baltimore Harbor Toll Plaza illustrating the location of air intake for the control ventilation system that supplies the administration building and the individual tollbooths.

A single control ventilation system is used for supplying air to the 14 tollbooths as well as the administrative building that are present at the Baltimore Harbor Tunnel Plaza. The air intake for the control ventilation system is located at the back of the administrative building, which faces away from the highway. The distance from the intake of the control ventilation system to the nearest and farthest tollbooth is approximately 55 and 300 ft, respectively, as shown in Figure 1. The tollbooth where monitoring was conducted was located 180 ft from the air intake. Three air ducts enter each booth from an access tunnel below the plaza. One small vertical supply grille with adjustable vanes (2' by 2.95") is in the front "service" door, and a large duct is in the middle of the tollbooth. The larger middle ductwork has two discharge louvers (18" by 14"), one near the top of the booth and one near the bottom of the booth. Two smaller linear diffuser ducts (3' by 3") in the ceiling introduce air into the booth from the front and the back. Together, these ducts are capable of delivering 500 cubic ft of conditioned air, designed to keep the tollbooth under positive pressure (*23*). A heating unit and a small individual air conditioning unit are in the ceiling of each tollbooth. The heating and individual AC units recirculate the inside air, conditioning the air for comfort. Airflow to the booth is controlled via a temperature sensor inside the booth. Prior to delivery, the intake air is filtered through a set of prefilters (Heavy Duty Precisionaire) and then a box filter (Multiflow, Type S, Koch Filter Corp). The box filter is rated to provide 85% efficiency in removing 1 μm particles. The prefilters are replaced every 3 months, and the box filters are replaced once a year.

Hourly traffic count data for both northbound and southbound traffic during the study period were obtained from the Maryland Tollbooth Authority (MDTA). The MDTA maintains hourly records of all vehicles passing through each tollbooth. The hourly traffic data were summed into 3-h intervals corresponding to the VOC integrated sampling period.

VOC samples were collected inside and outside the tollbooth using a PerkinElmer STS-25 Sequential Sampler (PerkinElmer, Shelton, CT). The sampler was set to collect samples every 3 h sequentially for 24 h. Samples were collected onto stainless steel PerkinElmer Air Toxic Tubes (3.5 in. long, 0.25 in. outer diameter) packed with a mixed sorbent comprised of carbopack B and corboxen 1000 (Supelco cat # 25051, Bellefonte, PA). A SKC 210 pocket pump (SKC Inc., Eighty Four, PA) set at a nominal flow rate of 25 mL/min was used to draw air through the sampling tubes. Pumps were calibrated upon initiation of sampling using a DryCal DC-2 primary standard (BIOS International Corp., Butler, NJ). Sample flows were checked after sampling to account for any drift during sampling.

Every morning, VOC samples from the previous 24 h were retrieved from the field and analyzed the same day using a method previously described (*10*, *24*). In short, the samples were thermally desorbed using a PerkinElmer ATD-400 (PerkinElmer, Shelton, CT), separated and analyzed with a Shimadzu GC-17A/QP-5000 GC/MS (Shimadzu Biotech, Columbia, MD) in selective ion monitoring (SIM) mode. Chromatographic separation was achieved using a Restek Rtx-624 column, 60 m $\times$ 0.25 mm ID with 1.4 μm thickness (Restek Corp., catalog no. 10969). A working stock solution consisting of 500 μg/mL 1,3-butadiene, and 200 μg/mL VOCs was prepared using a 2 mg/mL 1,3-butadiene stock solution (Accustandard, catalog no. S-406A-10x) and 2 mg/mL custom VOC mix (Accustandard, catalog no. S-2081-R10-10x). Six point calibration standards were prepared in methanol using the working stock. One microliter of standard was injected onto clean sampling tubes using a modified GC injector port (50 °C, helium flow of 80 mL/min for 10 min). The final amount on sampling tubes ranged from 0 to 50 ng for 1,3-butadiene and 0 to 20 ng for the rest of the VOCs. To account for any sample contamination during the sampling phase, field ($n = 7$) and laboratory ($n = 10$) blanks were deployed and analyzed. Reported concentrations have been blank adjusted.

Particle-bound PAH was measured using an Ecochem PAS 2000 PAH Ambient Analyzer (Ecochem Technologies, West Hills, CA). This is a direct-reading instrument that measures PAH on particles by photoionization. Particles entering the instrument are irradiated with a UV light at 222 nm (6.7 eV). Particles containing PAH with photoelectric threshold less than 6.7 eV will lose an outer shell electron and become positively charged. The charged particles are collected onto a filter, resulting in an electrical current proportional to the ions collected. Therefore, all particles with a photoelectric threshold less than 6.7 eV will be ionized and measured as PAH (*25*). Air is sampled at a flow rate of 2 L/min, and the inlet is not configured to provide a specific size classification. However, electrons emitted from larger particles are more likely to be recaptured; therefore, ionization and instrument

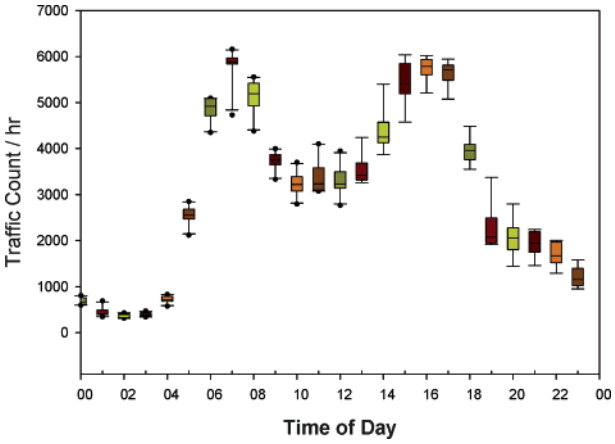

FIGURE 2. Hourly traffic volume (weekday) at the Baltimore Harbor Tollbooth facility by time of day. The horizontal line in the box represents the median; the box represents the 25th and the 75th percentile, the whiskers represent the 10th and the 90th percentile, and the dots represent the 5th and the 95th percentile.

response is most effective for particles containing PAH in the size range of <1−2 μm in diameter (*26*). The Echochem PAS 2000 was placed side-by-side with the STS-25 sequential samplers, indoors and outdoors, and monitoring was conducted continuously for 2 days during the study period. Measurements were logged in 1-min intervals. These data were combined to give 3-h average concentrations corresponding to the traffic count intervals.

All statistical analyses were performed using Intercooled Stata, version 7.0 for Windows (Stata Corp., TX). The normality of VOC and PAH concentration distributions was assessed using the Shapiro−Wilk test. Differences in pollutant levels indoors and outdoors were tested using the nonparametric Mann−Whitney test.

Results

The combined northbound and southbound traffic profile at the BHT ranged from 400 to 5900 vehicles per hour (72 000 per day) with a distinctive bimodal distribution corresponding to the morning and afternoon rush hours (Figure 2). These high traffic levels and their large variability highlight the significant exposure potential due to source activity.

The concentration profile of 1,3-butadiene and benzene outside the tollbooth tracks with the bimodal traffic pattern observed in Figure 2, with peaks occurring in the morning and afternoon associated with rush-hour traffic. In contrast to the outdoor concentrations, indoor levels are much lower and lack a distinct bimodal pattern (Figure 3A and B).

The concentrations of VOCs at the tollbooth varied by location (indoor vs outdoor) and type (Table 1). Inside the tollbooth, chloroform (0.1 μg/m^3), followed by styrene (0.4 μg/m^3), was present at the lowest concentration, while MTBE (17.2 μg/m^3) and dichlorobenzene (95.7 μg/m^3) were found to be at the highest concentration. Likewise, for measurements made outside of the tollbooth, chloroform (<LOD, <0.04 μg/m^3) and trichloroethylene (0.1 μg/m^3) were the two VOCs with the lowest concentrations, while MTBE was measured at the highest concentration (i.e., 35 μg/m^3).

A statistically significant ($p < 0.05$) positive association was observed between indoor and outdoor concentrations of both 1,3-butadiene and benzene based on simple linear regression (Figure 4). These results suggest that the linear regression model explained as much as 33% and 27% of the total variation in indoor concentrations of 1,3-butadiene and benzene, respectively. Moreover, similar observed slopes (0.20) for these two VOCs provide an indication of the protection offered by the tollbooth indoor environment.

The protection provided by the indoor environment was further evaluated using indoor/outdoor concentration ratios. Based on the distribution of indoor/outdoor concentration ratios, the pollutants clearly fall into two categories, that is, those with an indoor source (median ratio > 1) and those without an indoor source (median ratio < 1), respectively (Figure 5). The latter group is comprised of chlorinated hydrocarbons, whereas the former group is largely comprised of aliphatic and aromatic mobile source-related hydrocarbons of outdoor origin.

The 8-h time-weighted average (TWA) concentration of selected VOCs for the three different shifts were derived from the 3-h incremental measurements (Table 2). For benzene and 1,3-butadiene, the morning shift (6:00 am−2:00 pm) was characterized by the highest concentration, whereas the night shift (10:00 pm−6:00 am) was characterized by the lowest concentrations both inside and outside the tollbooth. For the indoor environment, the concentration during the morning shift was significantly higher than the afternoon and night shifts ($p < 0.05$), but there was no difference between the afternoon and night shift concentrations ($p > 0.05$). For the outdoor concentrations, the differences between all shifts were statistically significant ($p < 0.05$). Furthermore, the indoor concentrations at any given shift were significantly lower than the concurrent outdoor concentrations ($p < 0.05$).

Discussion

As evidenced by this study, as well as other peer-reviewed reports (*16*, *27*), tollbooth workers are potentially exposed to elevated levels of toxic mobile source emissions. Worker exposures are influenced both by source terms (e.g., traffic volume, operating conditions, and proximity to passing vehicles) as well as by mitigation through the control ventilation system and/or respiratory protection. This study is unique in characterizing indoor and outdoor mobile source-related pollutant levels and assessing the effectiveness of the tollbooth control ventilation system in protecting workers.

The Maryland Transportation Authority reports that there are seven toll facilities with 78 toll booths and 292 toll booth workers in the State of Maryland. Of the 78 tollbooths, 55% are equipped with control ventilation systems comparable to the BHT. The remaining facilities are ventilated using single unit fans and/or air conditioners. National data are not available by which to assess the representativeness of these Maryland data. Results of the current study are likely to be relevant to the 55% of tollbooth facilities equipped with comparable control ventilation systems.

The concentration profile of 1,3-butadiene and benzene measured outside the tollbooth clearly shows a traffic-related increase during the morning and afternoon rush hours. This increase, however, is not manifested indoors, demonstrating the protection offered by the tollbooth. We observed that the concentration of 1,3-butadiene and benzene varied by shift both indoors and outdoors. Inside the tollbooth, the morning shift concentrations were significantly higher than the afternoon and the night shifts ($p < 0.05$); however, there was no difference between the afternoon and night shift ($p > 0.05$). For the outdoor measurements, both 1,3-butadiene and benzene concentrations for morning and afternoon shifts were higher than the night shift concentration ($p < 0.05$). These results are in agreement with a recent tollbooth study by Tsai et al. (*27*) conducted in Taiwan who measured indoor concentrations of BTEX and MTBE. The authors reported indoor benzene levels of 19.9, 21.75, and 11.75 μg/m^3 (geometric mean) for afternoon (8:00 am−4:00 pm), night (4:00 pm−12:00 am), and late night shifts (12:00 am−8:00 am), respectively. However, the magnitude of these concentrations is far greater than what we observed at the BHT

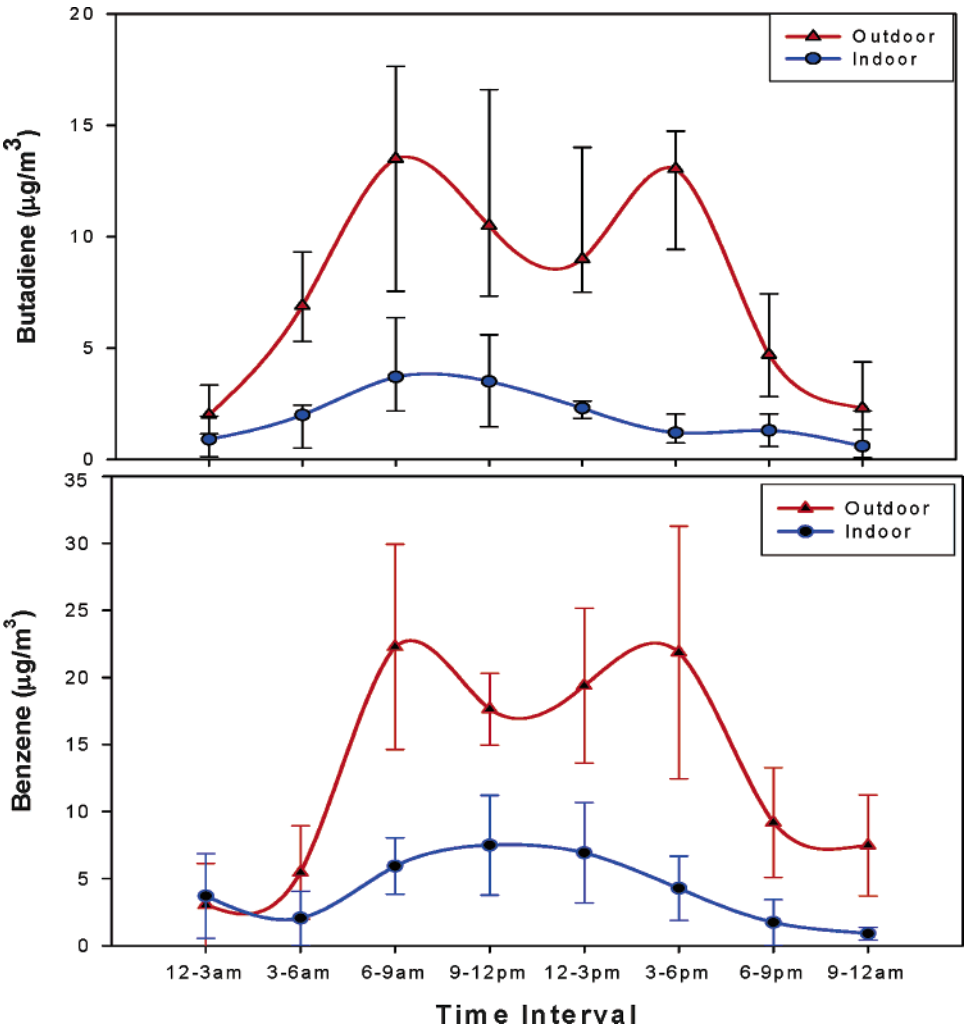

FIGURE 3. Indoor and outdoor concentration of butadiene and benzene at the BHT tollbooth facility by time of day. The actual points on the figure represent the median concentration, and the whiskers represent the 5th and 95th percentile.

TABLE 1. Distribution of VOCs (μg/m^3) and PAH (ng/m^3) Concentrations Measured Indoors and Outdoors

	indoor						outdoor					
analyte	min	25th percentile	median	mean	75th percentile	max	min	25th percentile	median	mean	75th percentile	max
1,3-butadiene	0.23	0.23	1.31	1.60	2.12	8.09	0.23	3.13	6.46	7.24	11.41	20.5
benzene	0.29	1.21	3.55	4.12	6.33	14.9	0.73	5.53	12.9	13.3	20.2	35.0
PAH	1.87	6.30	15.4	34.7	37.6	285	2.92	18.2	50.0	135	148	1130
MTBE	0.50	13.0	17.2	18.8	25.5	43.8	0.17	22.3	35.0	39.6	51.2	121
toluene	0.23	3.81	9.00	9.75	13.9	40.4	0.23	8.49	17.6	17.9	26.0	45.2
carbon tetrachloride	0.13	1.44	1.90	1.98	2.36	3.90	0.13	1.96	3.44	3.06	4.17	6.03
m,p-xylene	0.08	3.15	5.13	6.64	7.79	31.8	0.08	5.50	9.13	10.6	15.4	27.6
o-xylene	0.05	1.22	1.83	2.04	2.51	7.64	0.37	1.97	3.25	3.65	5.45	8.53
trimethylbenzene	0.08	2.01	2.67	2.83	3.69	6.62	0.08	2.58	4.47	5.35	7.90	13.8
ethylbenzene	0.06	1.30	2.01	2.81	2.94	11.8	0.06	1.69	3.18	3.67	4.76	21.7
styrene	0.05	0.26	0.40	0.45	0.53	1.19	0.05	0.20	0.53	0.61	1.00	1.68
chloroform	0.04	0.04	0.10	0.63	0.75	5.39	0.04	0.04	0.04	0.05	0.04	0.49
methylene chloride	0.07	5.80	8.41	18.1	11.1	364	0.07	0.85	1.33	2.17	2.16	25.3
tetrachloroethylene	0.10	1.33	2.10	1.95	2.71	4.23	0.10	0.10	0.25	0.39	0.59	2.11
dichlorobenzene	0.19	82.5	95.7	97.4	113	153	0.19	2.75	4.36	4.50	5.42	13.6
trichloroethylene	0.06	1.92	3.11	3.19	4.49	6.89	0.06	0.06	0.06	0.08	0.06	0.56

likely due to the absence of any control ventilation at the Taiwanese facility. Another potential explanation for the differences is that the Taiwanese study was conducted during the winter months in contrast to our summer-time study.

The observed 8-h TWA concentrations of 1,3-butadiene and benzene (indoors or outdoors) were far below occupation guidelines of ACGIH's (American Convention of Governmental Industrial Hygiene Association) threshold limit value of 4.4 and 1.6 mg/m^3 or that of OSHA's (Occupational Safety and Health Administration) permissible exposure level, 2.2 and 3.2 mg/m^3.

A recent study conducted at the same tollbooth facility (*10*) has identified the traffic (volume and class) and meteorological determinants for select gas and particle-phase

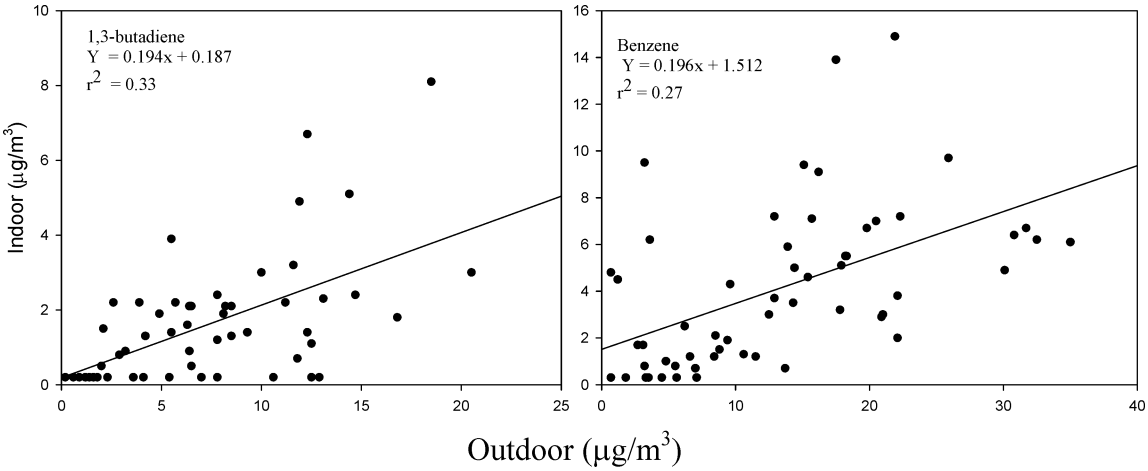

FIGURE 4. Scatter plot and linear regression showing the association between outdoor and indoor concentrations of 1,3-butadiene and benzene.

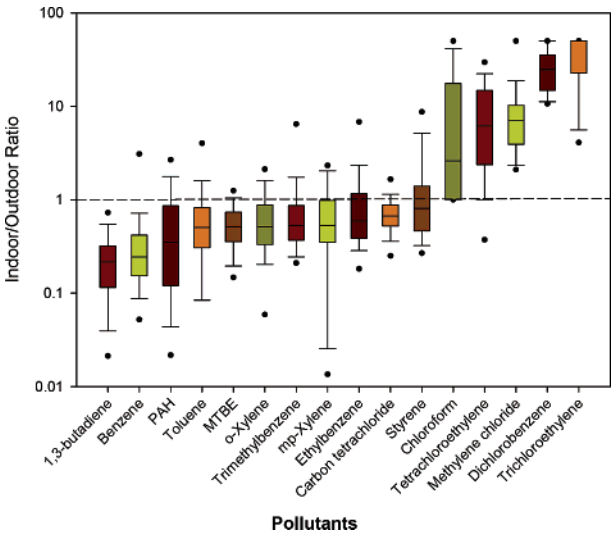

FIGURE 5. Indoor/outdoor VOC and PAH ratios measured at the Baltimore Harbor Tunnel tollbooth. The horizontal line in each box represents the median, the box ends indicate the 25th and the 75th percentile, the whiskers represent the 10th and the 90th percentile, and the dots represent the 5th and the 95th percentile. The dotted line across the graph corresponds to a ratio of 1, that is, the same indoor/outdoor concentration.

TABLE 2. Time-Weighted Average Concentrations of Benzene and 1,3-Butadiene Inside and Outside the Tollbooth by Workshift

location	workshift	butadiene (µg/m³)	standard deviation	benzene (µg/m³)	SD
inside tollbooth	morning shift	2.91[a–c]	0.90	6.70[a–c]	1.31
	afternoon	0.91[c]	0.40	3.21[c]	1.20
	night	0.92[c]	0.51	2.42[c]	1.42
outside tollbooth	morning shift	10.7[a,b]	3.20	19.8[a,b]	2.81
	afternoon	7.23[b]	1.72	14.9[b]	4.70
	night	3.71	0.91	4.90	2.21

[a] Significant difference in concentration ($p < 0.05$): as compared to afternoon shift. [b] Significant difference in concentration ($p < 0.05$): as compared to night. [c] Significant difference in concentration ($p < 0.05$): indoor as compared to outdoor.

curbside pollutant concentrations. Due to a combination of traffic and meteorological conditions, outdoor concentrations tended to be highest during the morning shift. Protection as indicated by the indoor/outdoor ratios varied with shift. The greatest protection was observed during the afternoon shift when the indoor concentrations were 5−8-fold lower than the corresponding outdoor concentrations. For the morning and night shifts, reductions were comparable and ranged from 2- to 4-fold.

Because the tollbooth ventilation system lacks controls for gaseous pollutants, the protection observed among the VOCs with indoor/outdoor ratios <1 (Figure 5) is likely due to dilution occurring over the 180 ft separation between the ventilation intake and the tollbooth. This dilution will be modified by meteorology and/or orientation of source activity (i.e., morning rush hour dominated by southbound traffic; afternoon rush hour dominated by northbound traffic) providing a possible explanation for the observed differences in indoor/outdoor ratios by shift.

Some of the VOCs measured are not emitted from mobile sources and therefore serve as a negative control for the impact of mobile source emissions on the indoor tollbooth environment. All of the mobile source pollutants (e.g., 1,3-butadiene, benzene, MTBE, ethylbenzene, PAHs) were characterized by indoor/outdoor ratios that were on average less than 1. In contrast, the chlorinated hydrocarbons including chloroform, tetrachloroethylene, methylene chloride, dichlorobenzene, and trichloroethylene were all characterized by ratios greater than 1, suggesting an indoor source contribution. Wallace et al. (*28*) made a similar observation for the residential indoor environment. The indoor contribution is likely associated with the use of consumer products. Methylene chloride is a degreaser used in consumer products. Dichlorobenzene is used in air fresheners and mothballs. Trichloroethylene and tetrachloroethylene are commonly used in dry-cleaning; therefore, higher indoor concentration may have resulted from off-gassing from workers dry-cleaned uniforms. This observation is substantiated by reports from the tollbooth administrator that workers receive an allowance for uniform dry cleaning and they are expected to wear clean and pressed uniforms. The indoor/outdoor ratio for chloroform and trichloroethylene may be biased because in contrast to the indoor measurements, a large fraction of the outdoor measurements were below detection. Although concentrations of these chlorinated hydrocarbons were consistently higher indoors than outdoors (Figure 5), the indoor concentrations varied considerably, suggesting an indoor source that varied across workers (e.g., dry-cleaned clothes) and/or shifts (e.g., due to maintenance or cleaning solvents).

The observation of indoor/outdoor ratios >1 for the chlorinated hydrocarbons is indicative of indoor sources and is consistent with reports for the residential environment (*29*−*31*). Sax et al. (*29*) reported indoor/outdoor ratios >1

TABLE 3. Median Indoor/Outdoor Ratios Observed at the BHT Tollbooth Facility As Compared to Published Reports for Urban Residential Locations

VOC	tollbooth	NY homes (Sax et al.)	LA homes (Sax et al.)	Baltimore (Payne-Sturges et al.)
1,3-butadiene	0.2			
benzene	0.3	1.4	1.1	1.4
PAH	0.3			
MTBE	0.5	1.1	1.0	1.0
toluene	0.5	2.0	1.3	3.1
carbon tetrachloride	0.6	0.9	1.0	0.9
m,*p*-xylene	0.6	1.3	1.1	1.9
o-xylene	0.6	1.3	1.0	
1,2,4-trimethylbenzene	0.6			
ethylbenzene	0.6	1.3	1.1	2.0
styrene	0.8	2.3	1.5	1.7
chloroform	2.7	10.2	4.3	10.5
methylene chloride	6.3	2.1	1.6	2.7
tetrachloroethylene	8.3	1.3	1.1	1.8
1,4-dichlorobenzene	21.9	4.2	2.7	
trichloroethylene	50.9	1.5	1.1	1.1

for chloroform and dichlorobenzene for homes in New York City and Los Angeles (Table 3). Ratios were mixed for styrene, methylene chloride, toluene, and benzene, that is, greater than 1 among New York homes but less than 1 among homes in Los Angeles. The mean ratios for the remaining VOCs (i.e., ethylbenzene *o*-xylene, *m*,*p*-xylene, MTBE, tetrachloroethylene, trichloroethylene, and carbon tetrachloride) were all close to 1 for both New York and Los Angeles homes. Similarly, ratios of 1.3 and 4.6 were reported for benzene and toluene across homes in EPA Region 5 (*30*). Of particular relevance, for a South Baltimore community within 5 km of the tollbooth facility, Payne-Sturges et al. (*31*) reported mean VOC ratios close to 1 for MTBE, carbon tetrachloride, and trichloroethylene, and mean ratios >1 for tetrachloroethylene, methylene chloride, chloroform, ethylbenzene, xylene, toluene, and benzene. In contrast to Sax et al. and Payne-Sturges et al., numerous VOCs measured at the tollbooth (1,3-butadiene, benzene, MTBE, toluene, carbon tetrachloride, xylene, trimethylbenzene, and ethylbenzene) had indoor/outdoor ratios less than 1. The likely difference in the observed indoor/outdoor ratios between this study and the residence-based reports is attributable to different factors that are specific to each environment. At the tollbooth, high outdoor concentrations result from the high activity and proximity of the source (vehicles), while effective control ventilation helps to maintain relatively low indoor concentrations, resulting in indoor/outdoor ratios less than 1. In contrast, residential indoor/outdoor ratios tend to be greater than or equal to 1 due to lower activity and proximity of the source outdoors combined with the presence of other VOC sources inside (e.g., gasoline storage, deodorants, air fresheners, household cleaners, various solvents, dry-cleaned cloths, and paints).

The outdoor VOC concentrations observed at the tollbooth tended to be higher than what has been observed for the urban residential environment. Outdoor concentrations of mobile source-related VOCs (MTBE, benzene, and ethylbenzene) at the tollbooth were 1.3 (ethylbenzene) to 8 (MTBE)-fold higher than outdoor concentrations at urban locations (Table 4) (*29*, *31*). In the urban environment, 1,3-butadiene was reported to be below the limit of detection (0.06 $\mu g/m^3$), whereas we observed a mean concentration of 6.5 $\mu g/m^3$ outside the tollbooth. The chlorinated hydrocarbons including tetrachloroethylene, chloroform, and trichloroethylene were the exceptions where concentrations were observed to be 1.1−5-fold lower outside the tollbooth as compared to the reported outdoor urban residential environment.

The indoor VOC comparisons between tollbooth and urban homes were very different. Here, mobile source-related VOC levels were comparable or less than that observed in the indoor urban environment. In contrast, although concentrations of the chlorinated hydrocarbons including carbon tetrachloride, methylene chloride, trichloroethylene, and dichlorobenzene were within the range of what has been observed among urban homes, mean levels tended to range from 2 (carbon tetrachloride)- to 24 (1,4-dichlorobenzene)-fold higher inside the tollbooth. For the mobile source-related VOCs, the fact that the outdoor concentrations tended to be much higher while indoor levels tended to be comparable to the urban residential environment highlights the protection offered by the tollbooth with the control ventilation system.

Similar to the mobile source-related VOCs measured outdoors, the concentration of particle-bound PAH inside the tollbooth (15.4 ng/m^3) was comparable to indoor nonsmoking semi-urban homes, reported by Dubowsky et al. (*32*), who observed geometric mean PAH concentrations of 8, 19, and 31 ng/m^3 for suburban, semi-urban, and urban locations, respectively. In contrast, median outdoor PAH

TABLE 4. Median VOC ($\mu g/m^3$) and PAH (ng/m^3) Concentrations Measured at BHT Tollbooth Relative to Homes Located in Urban Centers

	indoor concentration				outdoor concentration			
	New York homes[a]	Los Angeles homes[a]	Baltimore homes[b]	inside tollbooth	New York homes[a]	Los Angeles homes[a]	Baltimore homes[b]	outside tollbooth
chloroform	2.15	0.40	2.30	0.10	0.20	0.10	0.22	0.04
1,4-dichlorobenzene	7.50	3.95		95.7	1.85	1.55		4.36
styrene	0.75	0.90	0.43	0.40	0.30	0.60	0.25	0.53
1,3-butadiene	0.70	0.50		1.31	ND	ND		6.46
methylene chloride	1.80	1.50	0.95	8.41	0.75	0.80	0.35	1.33
toluene	11.0	15.0	12.1	9.00	5.85	11.9	3.88	17.6
trichloroethylene	0.25	0.15	0.18	3.11	0.30	0.10	0.17	0.06
benzene	2.55	3.30	2.45	3.55	1.60	3.25	1.79	12.9
ethylbenzene	1.60	2.30	1.95	2.01	1.15	2.40	1.00	3.18
o-xylene	1.70	3.00		1.83	1.30	3.35		3.25
m,*p*-xylene	5.00	8.45	7.60	5.13	3.65	8.95	3.97	9.13
MTBE	12.5	12.5	4.25	17.2	10.5	14.5	4.30	35.0
tetrachloroethylene	2.75	1.60	0.50	2.10	1.40	1.40	0.28	0.25
carbon tetrachloride	0.55	0.55	0.85	1.90	0.55	0.55	0.90	3.44
trimethylbenzene				2.70				4.47
PAH				15.4				50.0

[a] Sax et al. [b] Payne-Sturges et al.

concentrations (50 ng/m^3) at the tollbooth far exceeded the indoor urban location (outdoor levels were not reported in this study).

Despite the high outdoor levels, the fact that workers are experiencing indoor exposures similar to the urban indoor residential environment indicates the effectiveness of the ventilation control at the tollbooth facility. Yet, some mobile source-related VOCs (1,3-butadiene and MTBE) were still higher inside the tollbooth as compared to the indoor environment at city homes. The higher concentration of chlorinated VOCs (methylene chloride, TCE, and dichlorobenzene) inside the tollbooth as compared to the city homes is likely to be related to cleaning solvents and/or off-gassing from dry-cleaned uniforms. Indoor source contributions for these chlorinated VOCs present an opportunity for intervention to reduce exposure and risk.

The data presented in this study indicate that high concentrations of mobile source-related VOCs are present outside of tollbooth facilities due to the intensity and proximity of mobile sources. At the site investigated, we observed that the control ventilation system resulted in indoor exposures comparable to what is experienced in the urban indoor residential environment. The low indoor/outdoor ratios ranging from 0.7 (styrene) to 0.2 (1,3-butadiene) indicate the protection provided by the control ventilation equipped tollbooth to the harmful pollutants that are associated with mobile sources. However, it is likely that the indoor measurements represent the best case scenario for worker exposure because their job task involves leaning outside the booth for toll collection. Given this exposure scenario, methods including personal and/or biological monitoring will be needed to accurately evaluate worker exposure. The observed higher concentration of chlorinated hydrocarbons within the tollbooth indicates an indoor source contribution suitable for remediation.

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