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Traffic pollutant exposures experienced by pedestrians waiting to enter the U.S. at a major U.S.–Mexico border crossing

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HIGHLIGHTS

- Study measured pedestrian exposure to traffic pollutants at the San Ysidro, CA Port of Entry (POE).
- Participants wore personal air monitors for 24-h in addition to fixed site monitoring.
- Participants who crossed the border had increased exposure to 1-nitropyrene, CO, and $PM_{2.5}$.
- Fixed site measurements at the POE found elevated levels of ultrafine particles.
- Findings warrant concern for pedestrian commuters waiting in long lines at US–Mexico border POEs.

GRAPHICAL ABSTRACT

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ABSTRACT

Pedestrians waiting to cross into the US from Mexico at Ports of Entry experience long wait times near idling vehicles. The near-road environment is associated with elevated pollutant levels and adverse health outcomes. This is the first exposure assessment conducted to quantify northbound pedestrian commuter exposure to traffic-related air pollutants at the U.S.–Mexico border San Ysidro Port of Entry (SYPOE). Seventy-three persons who regularly crossed the SYPOE in the pedestrian line and 18 persons who did not cross were recruited to wear personal air monitors for 24-h to measure traffic pollutants particulate matter less than 2.5 µm ($PM_{2.5}$), 1-nitropyrene (1-NP) - a marker for diesel exhaust - and carbon monoxide (CO). Fixed site concentrations were collected at SYPOE and occurred during the time subjects were crossing northbound to approximate their exposure to 1-NP, ultrafine particles (UFP), $PM_{2.5}$, CO, and black carbon (BC) while standing in line during their border wait. Subjects who crossed the border in pedestrian lanes had a 6-fold increase in exposure to 1-NP, a 3-fold increase in exposure to CO, and a 2-fold increase in exposure to gravimetric $PM_{2.5}$, vs. non-border commuters. Univariate regression analysis for UFP (median 40,000 # cm^{-3}) found that border wait time for vehicles explained 21% of variability and relative humidity 13%, but when modeled together neither predictor remained significant. Concentrations at the SYPOE of UFP, $PM_{2.5}$, CO, and BC are similar to those in other near-roadway studies that show associations with acute and chronic adverse health effects. Although results are limited by small sample numbers, these findings warrant concern for adverse health effects

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experienced by pedestrian commuters waiting in a long northbound queue at SYPOE and demonstrates a potential health benefit of reduced wait times at the border.

1. Introduction

The U.S.–Mexico border is over 2000 miles in length and has 43 land Ports of Entry. The San Ysidro Port of Entry (SYPOE) is the westernmost port (Fig. 1A) and bounded by the community of San Ysidro, California, U.S.A. to the north and the city of Tijuana, Baja California, Mexico to the south. In 2011, the SYPOE had the highest number of northbound crossings along the US–Mexico border with 12.4 million personal vehicles and 8.5 million pedestrians (Quintana et al., 2012) and has been referred to as the busiest land border crossing in the world (GSA, 2013). Delays crossing the border northbound into the U.S. are much longer than those southbound into Mexico, and average north-bound wait times are often more than an hour for vehicles using the regular inspection lanes and for walk-in-line pedestrians, with peak times averaging 2–4 h (GAO, 2013; CBP, 2013). The pedestrian pathway (Fig. 1B and C) is located within 3 m (10 feet) of idling vehicles, and during long border wait-times pedestrians may have high exposures to traffic-related air pollutants. Acute exposure to traffic related air pollution has been shown to trigger cardiovascular events (Peters et al., 2004). Chronic exposure in close proximity to traffic exhaust is associated with a wide range adverse health effects including cardiovascular, respiratory, cancer, and reproductive effects (Brugge et al., 2007; Gauderman et al., 2007; McConnell et al., 2010; Wilhelm et al., 2011; Rosenbloom et al., 2012; Raaschou-Nielsen et al., 2011).

Of particular concern is the proximity of the bus lane to the pedestrian pathway (Fig. 1C). Diesel exhaust (DE) was recently designated a human carcinogen by IARC (IARC, 2012) and previous studies have linked DE exposure to 80% of the total carcinogenic risk from air pollution in the South Coast Air Basin in California (AQMD, 2012). Air pollutants of concern at SYPOE include both gases, such as carbon monoxide (CO), and particulates, including fine particulate matter ($PM_{2.5}$) ultrafine particles (UFP), and DE. Surveys have been conducted on pedestrians who cross the border to evaluate the frequency and purpose of their crossings (SANDAG, 2004). However, quantitative assessment of air pollutant exposures that pedestrian commuters experience during the border crossing have not been previously investigated. Walk-in-line pedestrians likely experience much greater levels of air pollution that would be predicted from regional air quality monitoring stations, which are typically located in areas relatively unaffected by local sources such as traffic. Roadside monitoring studies have found that pollutants are highly elevated near busy roads (Kinney et al., 2000; Karner et al., 2010).

The objective of this study was to characterize traffic-related air pollutant exposures experienced by pedestrians who frequently cross SYPOE and stand in long lines during the northbound commute, as compared to exposures experienced by people who live in San Ysidro or nearby but do not cross SYPOE.

2. Materials and methods

2.1. Personal sampling

Participants were recruited with the help of Casa Familiar, a community agency. "Border Commuter" eligibility criteria included: 1) ≥18 years, 2) non-smokers in a non-smoking home, 3)

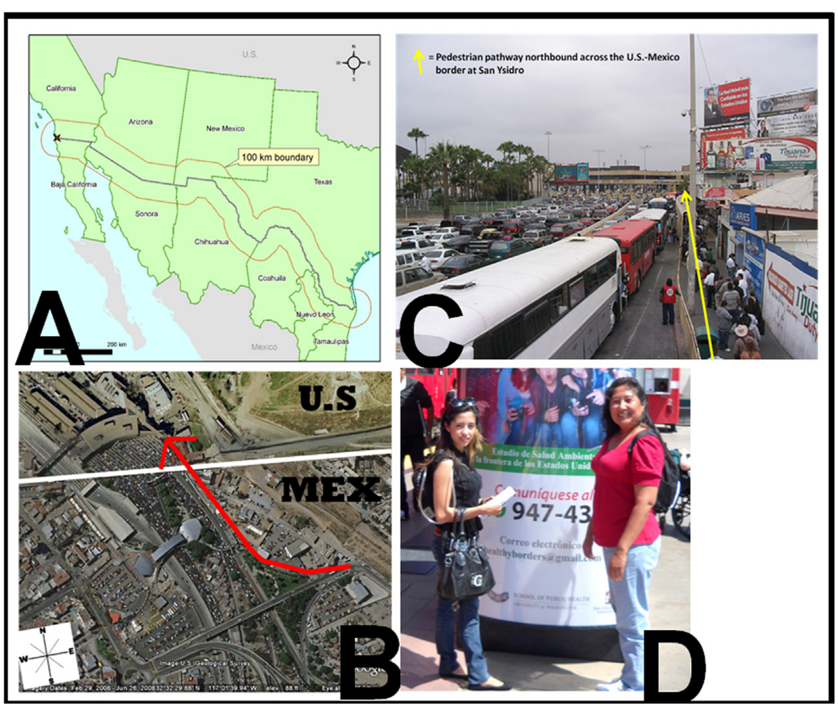

Fig. 1. (1A) U.S.–Mexico Border with San Ysidro Port of Entry marked by a red "X" Source: EPA page at http://water.epa.gov/infrastructure/wastewater/mexican/ (1B) Pedestrian pathway northbound marked by arrow (1C) Proximity of pedestrian pathway to vehicles (1D) Study participants wearing personal monitoring equipment (photo used with permission).

free of any chronic conditions, 4) not occupationally exposed to DE, and 5) cross the border as a pedestrian >4 days per month. "Non-Border Commuters" served as the comparison group. They had the same eligibility criteria except that they had to live and work or go to school in San Ysidro or nearby and had not crossed into Mexico in the previous 4 months. To minimize exposure variability between groups, the comparison group had to live in areas of similar population density as Tijuana and included zip codes 91910, 91911, 92154, 92173, and 91950. Consenting study participants were given the choice of one of two options. Option 1 included carrying a backpack for 24 h containing a CO and RH/Temp monitor, completing a 24-h time activity diary (TAD), filling out a questionnaire, and giving a spot urine sample. Option 2 included the above plus the requirement to carry a pump attached to an impactor to collect personal measurements of 1-nitropyrene (1-NP) – a marker for DE- and gravimetric-$PM_{2.5}$ (Fig. 1D). Results from the TAD and urine samples are reported elsewhere (Galaviz et al., 2013aA, B). Of the 91 study participants, 76 participants (56/73 "Border Commuters" and 15/18 "Non-Border Commuters") agreed to carry the 1-NP sampling device (Option 2). All participants were met at a location and time of their choice in South San Diego and given sampling equipment for one 24 h period that included a northbound border crossing, if applicable. All human subject data collection procedures were approved by San Diego State University (SDSU) and University of Washington (UW) IRBs. To minimize risks to participants, Customs and Border Protection (CBP) officers were given pictures of the air monitoring pumps and equipment, and were informed when participants were crossing.

2.2. Fixed site monitoring at the US–Mexico border

Measurements were collected immediately north of the primary inspection area at the SYPOE, with permission of CBP (Fig. 2A and B). This fixed sampling site was selected based primarily on security criteria while trying to maximize proximity to the pedestrian pathway to estimate exposure as accurately as possible. However, due to security reasons the fixed site sampling location was located 2.4 m further east (away from traffic) than the pedestrian pathway. Sampling pump inlets were placed 1.2 m above the ground. Fixed site equipment was started and stopped 1–2 h before and after the northbound SYPOE commute of the "Border Commuters."

2.3. Sample collection

Both personal and fixed site 1-NP was sampled with a $PM_{2.5}$ impactor (BGI HPEM, Waltham, MA and SKC PEM, Eighty Four, PA) outfitted with a 37 mm PTFE Teflon filter (#224-1709, SKC Inc., Eighty Four, PA) and drain disc (Whatman230800, Tisch Scientific, Cleves, OH), and connected to a personal air sampling pump (XR5000, SKC Inc., Eighty Four, PA) operated at 4 L per minute. Air sampling pumps were calibrated before and after use (Defender 510, SKC Inc., Eighty Four, PA). All flow rates deviated less than 10% between pre- and post- flow rate measurements. Filters were conditioned for 24 h before and after sampling in a temperature and humidity controlled room (ambient temperature, 22 ± 1 °C, relative humidity, $35 \pm 5\%$). Pre- and post-weight measurements were obtained from an ultramicrobalance (UMX-2, Mettler-Toledo, Columbus, OH). Assembly and disassembly of $PM_{2.5}$ impactors and filters occurred in a supplied air glove box (Aldrich AtmosBag Z530220, Sigma–Aldrich Co., St. Louis, MO) with a HEPA filter attached to the air inlet (Capsule 12144, Pall Corporation, Port Washington, NY). Three of the 34 sampling days were set up to collect simultaneous co-located 1-NP samples; between-filter average coefficient of variability was <6%. Filter samples were immediately placed on ice following sample collection and transported to SDSU and stored in a −20 °C freezer, prior to shipping to UW for analysis. Air filters were analyzed for 1-NP using HPLC-MS/MS from the method described by Miller-Schulze et al. (2007, 2010). The limit of detection (LOD) for gravimetric $PM_{2.5}$ was a mass LOD of 7.8 μg. The 1-NP LOD was 0.05 pg m^{-3} for personal 24-h samples and 0.24 pg m^{-3} for fixed site samples. Eighteen of the 34 (53%) gravimetric $PM_{2.5}$ samples were below the LOD while 6 of the 34 filter samples (18%) were below the 1-NP LOD. Border samples were collected for a short time (<6 h) rather than at usual 24-h sampling times, thus a high number of samples were below the LOD. Supplementary Table 1 details measurements collected per day and how many were above the LOD.

Fixed site measurements had the same start and stop time for each sampling day, except for 1-NP and gravimetric $PM_{2.5}$ which were started and stopped to encompass when each participant was in the pedestrian line at the border. The real-time instruments logged data at 5 min intervals and were used to provide estimates of concentrations during time "Border Commuters" were in line by extracting that portion of the data. If more than one "Border

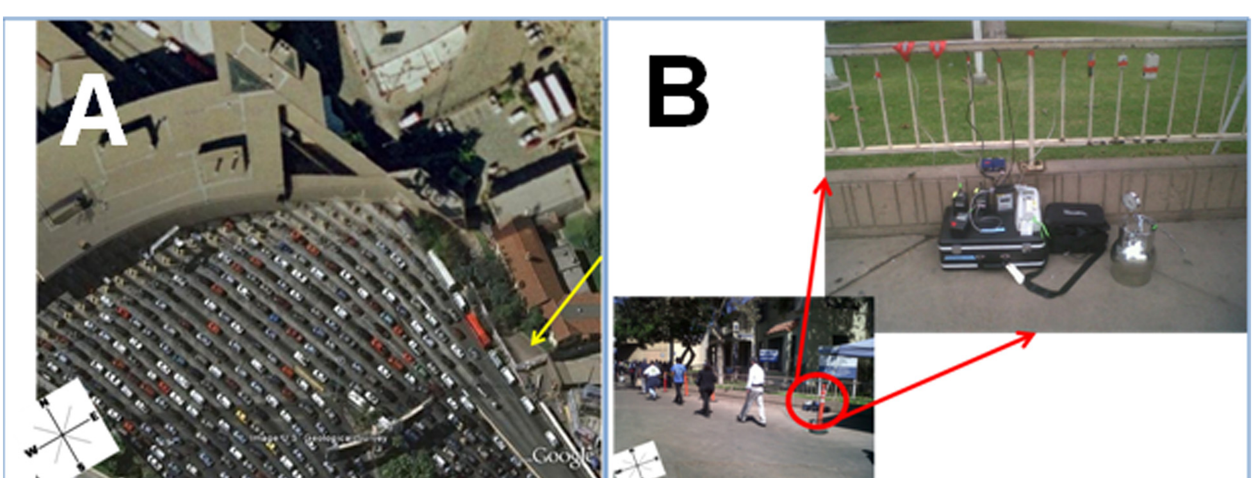

Fig. 2. (2A) San Ysidro Port of Entry (SYPOE) fixed site sampling location marked by arrow (2B) SYPOE fixed site sampling equipment.

Commuter" crossed SYPOE in one sampling day then measurements collecting average concentrations (1-NP and gravimetric $PM_{2.5}$) were set up with pre-set start and stop times for each "Border Commuter." Although there may have been more than one sample collected for 1-NP and gravimetric $PM_{2.5}$ there was no overlap of sampling time, and a concentration value was obtained by averaging the values for each sampling day.

For fixed site border measurements, real time $PM_{2.5}$ was measured using the Thermo-MIE personal DataRAM (pDR) 1200 light scattering instrument (Thermo-electron Corp., Waltham, MA) connected to a metal particle size-selective cyclone inlet (BGI model GK 2.05, Thermo Electron Corp., Waltham, MA) upstream and to a filter holder for 37 mm filters and an air sampling pump (XR5000, SKC Inc., Eighty Four, PA) operated at 4 L per minute in order to achieve a particle size cut of 2.5 µm. Before each use the pDR was zeroed. The following empirical correction factor (CF) was used when relative humidity was greater than 60%: $CF = 1 + 0.25RH^2/(1 - RH)$ (Chakrabarti et al., 2004). Ten of the 12 real time $PM_{2.5}$ samples at the border had data points above 60% RH.

UFP measurements were collected with a Condensation Particle Counter (CPC, TSI Model 3007, Inc., Shoreview, MN). Prior to field measurements, comparison with co-located CPCs revealed high correlation coefficients obtained by the least-square regression method ($R^2 = 0.96–0.99$).

BC was sampled with a black carbon aerosol monitor (microAeth AE51, AethLabs, San Francisco, CA). BC Instruments were not available until the last 5 sampling days. Three of the 5 sampling days had 2 co-located instruments which revealed high correlations between instruments ($R^2 = 0.90–0.99$).

Carbon monoxide, RH, and temperature were measured using HOBO dataloggers (HOBO Pro CO Data Logger and HOBO Pro RH/Temp Data Logger, Onset Corporation, Bourne, MA). Forty-two of the 56 personal CO measurements were invalid due to either equipment malfunction (e.g. accidentally dropped by participants or the U.S. Customs officers inspecting the equipment and taking out the battery) or persons carrying the device did not follow instructions (e.g. the device was moved to a location not accessible to air such as a purse). Pollutant measurements were corrected for temperature and pressure, although differences between pre- and post-adjusted concentrations were never more than 0.05%. Field and lab blanks accounted for 10% of collected samples.

Other variables of interest that were collected included wind speed (mph), wind direction (degrees), vehicle border wait times (minutes) and number of buses. Wind speed, wind direction, and vehicle border wait times were summarized by taking the median values for each sampling day during hours sampling was taking place. Wind speed and wind direction were collected from the website www.wunderground.com using the closest station to SYPOE, *Proteccion Civil Tijuana Station* (Latitude 32.5°N, Longitude 117.0°W, Weather Underground, Inc., Atlanta, GA). Windrose plots for meteorological data were generated using WRPLOT View Version 7 (Lakes Environmental, Waterloo, Ontario).

Border wait times for vehicles to reach the primary inspection booth are estimated by CBP and posted on their website hourly (http://apps.cbp.gov/bwt/). An estimate of border delay is determined by south-facing cameras and the use of pre-determined geographical fixes in relationship to how many vehicle lanes are open, and personal estimates by officers. CBP does not provide a historical database of vehicle border wait times to the public, therefore, a software program was developed to collect the real-time vehicle border wait data each hour as it was posted, and archive this data. In regards to collecting bus information CBP has no formal method of collecting border wait time as they do with vehicle wait time. The best estimate of bus volume was to record the total number of buses passing northbound per hour.

Table 1
Study participant characteristics.

	Border commuters			Non-Border commuters		
	n (%)	Mean	Range	*n* (%)	Mean	Range
Age	73 (80)	26	19–59	18 (20)	34	18–76
Sex						
Male	38 (52)			5 (28)		
Female	35 (48)			13 (72)		
Education						
≤High School graduate	9 (12)			2 (11)		
Some post HS education	50 (68)			8 (44)		
≥College graduate	14 (19)			8 (44)		
Main Occupation						
Employed	13 (18)			11 (61)		
Not employed outside home	14 (19)			4 (22)		
Student	46 (63)			3 (17)		

2.4. Statistical analysis

STATAIC ver11 (STATACorp LP, Texas) was used to perform all statistical analysis. An alpha level of 0.05 was used to determine statistical significance. Summary statistics for personal and fixed site measurements of 1-NP and gravimetric $PM_{2.5}$ were based on averaged daily values whereas UFP, real time $PM_{2.5}$, BC, CO, vehicle delay, temperature, and relative humidity were calculated based on the values of continuous data. Non-parametric comparison tests (Wilcoxon–Mann–Whitney *U*-test) were used to compare personal exposure to gravimetric $PM_{2.5}$, 1-NP, and CO between "Border Commuters" and "Non-Border Commuters."

Three multilinear regression models were created to determine if there were any significant meteorological, season, and traffic predictor variables for fixed site measurements of 1-NP, gravimetric $PM_{2.5}$, and UFP. There were insufficient sampling days for real time $PM_{2.5}$, BC, and CO to perform multivariate regression analysis on these variables. Continuous variables not normally distributed were log transformed. Season was dichotomized and classified into "Autumn and Winter" vs. "Spring and Summer" with "Spring and Summer" being the reference category. "Autumn and Winter" were defined as the time period between September 1st and February 28th. Based on previous data (Quintana et al., 2014), wind direction was dichotomized to look at the effect of border concentrations during periods when winds came from the coast (West and Northwest) and thus was classified into "W and NW" vs. "Other" where "W and NW" served as the reference category. The final linear regression model of interest took the form:

$$\begin{aligned}\log(Y_i) = {} & ß_0 + ß_1 \log(\text{temperature}) + ß_2 \log(\text{RH}) + ß_3(\text{season}) \\ & + ß_4 \log(\text{wind speed}) + ß_5(\text{wind direction}) \\ & + ß_6 \log(\text{bus count}) + ß_7 \log(\text{vehicle delay}) + \varepsilon_i\end{aligned}$$

where Y_i was the average, log-transformed concentration of 1-NP, gravimetric $PM_{2.5}$, or UFP at the fixed site, $\beta_1–\beta_7$ were the slope estimates for the corresponding covariates, and ε_i was the error term.

3. Results

Data collection occurred between March 30th, 2010 and December 17th, 2010. Ninety-one healthy participants (73 "Border Commuters" and 18 "Non-Border Commuters") enrolled in the study; all self-classified as Hispanic (Table 1). "Border commuters" ($n = 73$) cited the major reason for crossing was for work or school with students making up the majority of "Border Commuters" but a minority of "Non-Border Commuters"(Table 1).

"Border Commuters" crossed the border on 35 separate dates. Typically, 2 persons crossed the border on one day (range 1–6), but usually at separate times, which is why there are a greater number of measurements for the personal estimates vs. fixed site measurements. Table 2 presents the concentrations of measured pollutants and delay variables at the border fixed site in two ways: first, for the overall values for the 35 days (called 'Fixed-Site Overall'), then as concentrations and variables measured during only those times that the "Border Commuters" were standing in line waiting to cross (called 'Border Commuter Exposure').

During the sampled days, the median (interquartile range; IQR) value for temperature was 64 °F (57–69) and 72% (63–78) for relative humidity. Of the sampled pollutants, UFPs had a median concentration overall of 40,000 particles cm^{-3}, with some days averaging as high as 91,000 particles cm^{-3} (Table 2). Within a day, short-term excursions over 90,000 were common (Supplementary Table 2). For DE markers, 1-NP had a median of 1.3 pg m^{-3} (range 0.2–9.5), and BC a median of 4 μg m^{-3}, (range 3–13). CO had a median of 5 ppm (range 3–6), gravimetric $PM_{2.5}$ a median of 15 μg m^{-3} (range 8–167), and real time $PM_{2.5}$ a median of 41 μg m^{-3} (range 14–81) (Table 2). Variability between and within days is shown in Supplementary Fig. 1. BC was only collected on 5 of the 6 last sampling days as this was when instrumentation was available for use. Concentrations of other pollutants on the days BC was collected were higher than when averaged over their entire sampling days (Supplementary Table 3). During the time border commuters were in line to cross northbound, the reported mean northbound vehicle delay time (an indicator of the amount of idling traffic near pedestrian line) was 83 min with a range of 32–137 min. The "Border Commuters" spent an average of 60 min and up to 200 min waiting in the pedestrian line to cross northbound.

Meteorological data show winds coming predominantly from the west, which is typical for this area (Fig. 3). Eight of the 35 sampling days were affected by light rain, ranging from 0.02 to 0.3 inches during data collection days. A statistically significant decrease in average concentration for fixed site measurements during days with rain was only seen for 1-NP (median: 0.70 ± 0.66 vs. 2.4 ± 2.5 pg m^{-3}, $p = 0.02$).

Table 3 compares the 24-h personal traffic-related air pollution measurements between "Border Commuters" and "Non-Border Commuters." "Border Commuters" experienced significantly increased 24-h personal exposures to all pollutants. For 1-NP, a marker for DE and a potent mutagen, levels were more than 8 times higher for those crossing the border compared to "Non-Border Commuters" (mean 1.7 ± 2.6 vs. 0.22 ± 0.21 pg m^{-3}). Personal 1-NP measurements were positively associated with border measurements of 1-NP ($r = 0.34$, $p = 0.01$, $n = 56$), indicating that the border explained 12% of variance in personal 1-NP exposures. Personal $PM_{2.5}$ and CO did not show any associations with border measurements of $PM_{2.5}$ and CO, respectively.

To investigate predictor variables of fixed site SYPOE border concentrations, univariate and multivariate analysis was applied. No significant predictor variables for 1-NP were identified (Table 4). The concentration of gravimetric $PM_{2.5}$ decreased with increasing wind speed but no other significant predictor variables were noted (Table 5). Increased vehicle delay times and RH were significant predictors of UFP concentrations and explained 21% and 13% of the variance, respectively (Table 6). However, when modeled together the significance was lost for both predictor variables, with slight decreases in beta coefficients from the univariate to multivariate analysis (Table 7).

4. Discussion

This study is the first to measure exposures to pedestrians crossing at a major US–Mexico border crossing (SYPOE). Median levels of UFP recorded at the POE during time subjects were crossing in the pedestrian line were more than 4 times higher than those measured non-simultaneously in 2010 in San Ysidro at a Duty Free store near the POE (39,000 cm^{-3} vs. 8000 p/cc), and 6–10 times higher than at other nearby sites (Quintana et al., 2014). Levels of traffic-related pollutants $PM_{2.5}$, UFP, BC, and CO at the POE were similar to other near-road studies on very busy roads. In 2012, a study conducted near a major freeway with heavy-duty diesel

Table 2
Levels of traffic-related pollutants at the US–Mexico border crossing at San Ysidro, CA and estimated exposure[a] to pedestrians during their northbound wait in the pedestrian line.

	n[b]	Mean (SD)	GM	95% CI	RSD%[c]	25th, 50th, 75th, 95th percentiles	Min	Max
Fixed site overall[d]								
Average 1-NP (pg m^{-3})	34	2.0 (2.3)	1.1	[0.78, 1.7]	116	0.5, 1.3, 2.6, 9.3	0.2	9.5
Gravimetric $PM_{2.5}$ (μg m^{-3})	34	24 (28)	18	[15, 23]	118	13, 15, 22, 58	8	167
UFP (# cm^{-3} × 10^3)	31[b]	40 (17)	36	[30, 43]	43	24, 40, 52, 72	14	82
Real time $PM_{2.5}$ (μg m^{-3})	12[b]	41 (21)	35	[24, 52]	37	23, 41, 57, 81	14	81
BC (μg m^{-3})	5[b]	7 (5)	5	[2, 14]	73	3, 4, 11, 13	3	13
CO (ppm)	17[b]	5 (2)	5	[4, 6]	36	3, 5, 6, 8	2	8
Vehicle wait time (min)	27	79 (23)	75	[66, 85]	29	61, 79, 93, 107	29	132
# Buses passing gate/hour	29	53 (22)	48	[41, 57]	42	39, 51, 58, 96	20	105
'Border commuter' exposure								
1-NP (pg m^{-3})	67	2.0 (2.0)	1.3	[1.0, 1.6]	97	0.7, 1.3, 2.8, 6.4	0.2	9.3
Gravimetric $PM_{2.5}$ (μg m^{-3})	67	24 (24)	19	[16, 22]	101	13,17, 26, 48	7	147
UFP (#cm^{-3} × 10^3)	50[b]	42 (20)	37	[32, 43]	48	28, 39, 54, 85	12	91
Real time $PM_{2.5}$ (μg m^{-3})	17[b]	48 (22)	41	[30, 58]	46	30,53, 57, 94	6	94
BC (μg m^{-3})	18[b]	7 (4)	6	[4, 8]	57	3, 6, 11, 13	3	13
CO (ppm)	37[b]	5 (2)	5	[4, 5]	33	4, 6, 6, 8	2	8
Vehicle wait time (min)	58	83 (25)	79	[73, 86]	30	65, 83, 100, 128	32	137
Border commute (min)	73	66 (42)	55	[48, 63]	63	30, 60, 80, 155	20	200

1-NP = 1-nitropyrene, $PM_{2.5}$ = particulate matter with aerodynamic diameter less than 2.5um, UFP = ultrafine particulates, BC = black carbon, CO = carbon monoxide, CI = confidence interval, GM = geometric mean, Min = minimum, Max = maximum.
[a] Exposure was estimated from values obtained from fixed site equipment during time participant was in line.
[b] Real-time data were averaged according to the integrated sample time of the gravimetric PM2.5 samples and each period averaged is treated as a single sample.
[c] Relative standard deviation was calculated by taking the standard deviation and dividing by the mean.
[d] Sampling times ranged from 53 to 548 min with an average of 197 ± 99 min.

Table 3
Comparison between 24-h personal exposure to traffic-related air pollutants among border commuters and non-border commuters.

24-h[a] traffic pollution measures	n[b]	Mean (SD)	GM	95% CI	Median	IQR	Min	Max	p-Value[c]
1-NP (pg m^{-3})									
Border commuters	56	1.7 (2.3)	0.73	0.50–1.07	0.96	0.33–1.87	0.05	12.8	<0.01
Non-border commuters	15	0.22 (0.21)	0.15	0.09–0.24	0.15	0.05–0.30	0.05	0.86	
$PM_{2.5}$									
Border commuters	56	39 (30)	31	26–37	26	18–49	13	146	<0.01
Non-border commuters	15	21 (11)	19	15–24	18	13–22	13	48	
CO (ppm)									
Border commuters	14[b]	2.8 (1.8)	2.3	1.6–3.4	2.2	1.4–4.0	0.8	7.2	<0.01
Non-border commuters	15[b]	1.0 (0.79)	0.6	0.3–1.2	0.8	0.2–1.7	0.1	2.4	

1-NP = 1-nitropyrene, PM2.5 = particulate matter with aerodynamic diameter less than 2.5um, CO = carbon monoxide, GM = geometric mean, IQR = interquartile range, Min = minimum, Max = maximum.
[a] Actual minutes sampled ranged from 964 to 2140 min.
[b] Real-time data were averaged according to the integrated sample time of the gravimetric PM2.5 samples and each period averaged is treated as a single sample.
[c] Wilcoxon–Mann–Whitney U-test, significant at the 0.05 level (2-tailed).

traffic in Los Angeles, CA (samplers located 15 m from the end of the 710 freeway) found median real time $PM_{2.5}$ concentrations to be 12.1 μg m^{-3} in the winter and 14.2 μg m^{-3} in the summer, BC concentrations to be 4.0 μg m^{-3} in the winter and 2.1 μg m^{-3} in the summer, UFP concentrations to be 33,200 cm^{-3} in the winter and 32,500 cm^{-3} in the summer, and CO concentrations to be 0.39 ppm in the winter and 0.25 ppm in the summer (AQMD, 2012). In the only other study to measure UFP related to a US–Mexico POE, a fixed site sampler located near the El Paso International Bridge of the Americas crossing into El Paso, Texas recorded a similar level of UFP (mean 35,000 cm^{-3}) (Olvera et al., 2013).

In regards to 1-NP, measurements were lower than some other studies that quantified 1-NP near heavy traffic roadways. For example, Reisen and Arey (2005) reported an average concentration of 4.3 pg m^{-3} for 1-NP at a sampling site located near two freeways and a busy street in Los Angeles, CA. One potential reason our study has lower 1-NP levels may be due to the fact that there are limited sources of DE, including the restriction against commercial trucks at SYPOE. However, the fact remains that "Border Commuters" have increased exposure to 1-NP vs. "Non-Border Commuters" as evidenced by the 24-h personal samples, with border concentration explaining 12% of personal exposure to 1-NP for the "Border Commuters". Other aspects of their 24-h days may have influenced their exposure, which is a limitation of this comparison. A separate manuscript describes at-home concentrations experienced by "Border Commuters" and "Non-Border Commuters" and characterizes contribution of microenvironments, such as at-home exposure, to understand what predictor variables should be accounted for when assessing exposure in this setting (Galaviz et al., 2013b).

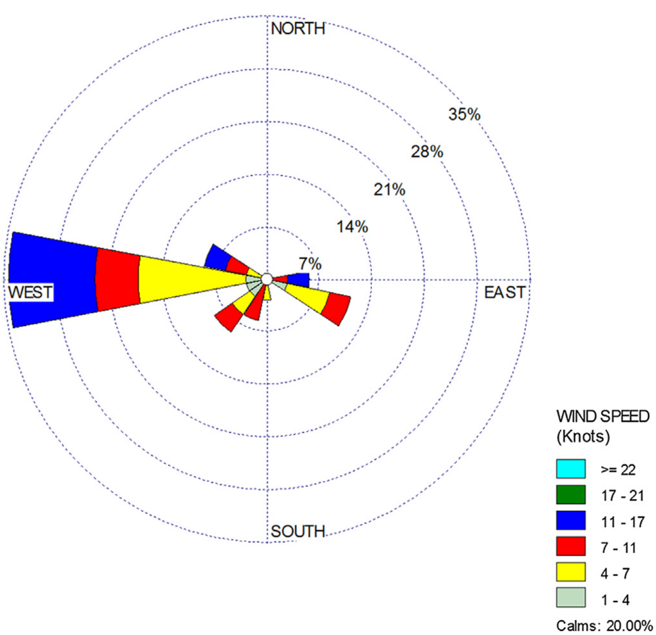

Fig. 3. Windrose for sampling days.

Table 4
Univariate regression predictors of the diesel traffic-related pollutant, 1-nitropyrene, measured at the US–Mexico Port of Entry at San Ysidro (n = 34).

Model parameter (n = 34)	β (SE)	r^2	CI	p-value
Temperature	0.20 (3.5)	<0.01	[−6.8, 7.2]	0.95
Relative humidity	0.84 (0.82)	0.03	[−0.84, 2.5]	0.32
Season	0.39 (0.41)	0.03	[−0.44, 1.2]	0.34
Wind speed	−0.28 (0.51)	0.01	[−1.3, 0.76]	0.59
Wind direction	−0.35 (0.38)	0.03	[−1.1, 0.43]	0.36
Bus count	−0.59 (1.1)	0.01	[−2.9, 1.7]	0.61
Vehicle delay	0.66 (0.66)	0.04	[−0.71, 2.0]	0.33

Table 5
Univariate regression predictors of the traffic pollutant, gravimetric $PM_{2.5}$, measured at the US–Mexico Port of Entry at San Ysidro.

Model parameter (n = 34)	β (SE)	r^2	CI	p-value
Temperature	−2.88 (1.85)	0.07	[−6.6, 0.89]	0.13
Relative humidity	0.58 (0.45)	0.05	[−0.35, 1.5]	0.21
Season	0.29 (0.22)	0.05	[−0.16, 0.75]	0.20
Wind speed	−0.76 (0.25)	0.22	[−1.3, −0.25]	0.01[a]
Wind direction	−0.14 (0.21)	0.01	[−0.57, 0.30]	0.52
Bus count	0.08 (0.67)	<0.00	[−1.3, 1.5]	0.90
Vehicle delay, minutes	0.11 (0.40)	<0.01	[−0.72, 0.94]	0.79

[a] Significant at the 0.05 level (2-tailed).

Table 6
Univariate Regression predictors of the traffic pollutant, ultrafine particulate matter, measured at the US–Mexico Port of Entry at San Ysidro.

Model parameter (n = 31)	β (SE)	r^2	CI	p-value
Temperature	0.86 (1.59)	0.01	[−2.4, 4.1]	0.60
Relative humidity	−0.72 (0.35)	0.13	[−1.4, −0.01]	0.05
Season	0.32 (0.18)	0.10	[−0.043, 0.68]	0.08
Wind speed	0.02 (0.22)	<0.00	[−0.43, 0.46]	0.94
Wind direction	0.11 (0.17)	0.01	[−0.23, 0.45]	0.52
Bus count	0.06 (0.56)	<0.00	[−1.1, 1.2]	0.92
Vehicle delay, Minutes	0.82 (0.34)	0.21	[0.12, 1.5]	0.02[a]

[a] Significant at the 0.05 level (2-tailed).

Table 7
Multivariate regression predictors of the traffic pollutant, ultrafine particulate matter, measured at the US–Mexico Port of Entry at San Ysidro.

Model parameter ($n = 31$)	β (SE)	r^2	CI	p-value
Relative humidity	−0.43 (0.37)	0.26[a]	[−1.2, 0.34]	0.26
Vehicle delay, minutes	0.67 (0.36)		[−0.083, 1.4]	0.08

[a] Adjusted $r^2 = 0.19$.

BC has been used in many studies as a marker for DE. However, recent research has shown that 1-NP is a promising marker for DE due to numerous factors, including: 1) analytical sensitivity, 2) specificity to DE, 3) absence of significant formation via secondary photochemical processes, and 4) detectability across a wide range of exposures (Arey, 1998; Murahashi et al., 1995; Hayakawa et al., 1995, 1994; Bamford et al., 2003; Bamford and Baker, 2003). Due to small sample size for BC measurements in the current study, associations between BC and 1-NP were not calculated.

Limitations of this study include small sample sizes for fixed site measurements. This reduced our ability to undertake more complex regression modeling, including examining the effect of interaction terms such as wind speed, wind direction, and season. In addition, fixed site sampling occurred only during hours in which supervision by a CBP officer could be arranged, which was limited to 6am-5pm, Monday-Friday. Vehicle data for buses was collected using a visual inspection as the primary source of estimation. Border wait time was obtained through CBP, which may have not been updated in real-time and has been criticized as inaccurate (US GAO, 2013). Also, the fixed site equipment was located in an area near CBP officers for security reasons. It would have been preferred to set up the equipment south of the primary inspection gate to get a more precise measurement of pedestrian exposure to traffic related pollutants along the queue. Our sampling location likely underestimated pedestrian exposure to traffic-related pollution while standing in line. For personal sampling, a limitation was that we did not give more monitoring equipment to the study participants, and that significant data losses occurred. C Security concerns at the SYPOE also limited the amount of equipment we were able to give participants.

It should be noted that air concentrations reported here ought not to be compared directly to national and state regulatory standards as the standards apply to large air basin monitoring. Of the air pollutants measured in this study, only $PM_{2.5}$ and CO are regulated in the USA (US Environmental Protection Agency, 2012). For $PM_{2.5}$, the U.S. has an annual average limit of 12 μg m^{-3} and a 24-h average limit of 35 μg m^{-3} (EPA, 2012). Although there is no regulatory standard for UFPs, research has suggested that UFPs may be important contributors to health risks due to their large surface area and their ability to reach the alveoli (Delfino et al., 2005) and to translocate into the systemic circulation (Nemmar et al., 2002; Geiser et al., 2005). BC is another air contaminant of health concern with no environmental regulatory standard. SYPOE is currently undergoing a reconfiguration and expansion. San Diego's Regional Planning Agency predicts a 70% increase of vehicle traffic by 2030 (SANDAG, 2004). The new SYPOE will have 62 northbound vehicle primary inspection booths with one dedicated bus lane; however, the pedestrian pathway will still be in the same geographic location and still within feet from idling vehicle and bus traffic with no physical barrier between vehicles and pedestrians. Such physical barriers have been shown to decrease pollutant exposure (Bowker et al., 2007; Hagler et al., 2011). In addition, the pedestrian pathway is located between 24-lanes of vehicle traffic to the west and a wall to the east (Fig. 1C). This wall could increase pedestrian exposure to pollutants as previous work has shown significant increases in pollutant concentrations with such barriers immediately downstream of a source and receptor (Hagler et al., 2010). This wall poses a significant concern considering the predominant wind direction comes from the west (Fig. 3). Although some buildings may be taken down as a result of the reconfiguration, some of the historical buildings will remain. Overall, despite the new SYPOE configuration, it will remain a high-density traffic corridor for both vehicles and pedestrians and thus will remain a potentially high exposure environment for pedestrian commuters.

The primary method of reducing traffic-related pollutant exposure would be the use of zero to near-zero emission vehicle technologies; however, factors such as enforcement and feasibility can affect the availability and usage of such vehicles. In addition, the variability of emission vehicle technologies between U.S. and Mexico is considerable when accounting for factors such as vehicle engine type and grade of fuel. The most practical measure to mitigate pedestrian exposures would be to reduce the number of minutes that the pedestrians have to wait in line. This would directly decrease their exposure.

In conclusion, this is the first study that has attempted to quantify traffic-related exposure to pedestrians crossing the US Mexico border at a Port of Entry. Exposure to traffic related air pollutants were substantially greater for "Border Commuters" who crossed the SYPOE as pedestrians, compared to a comparison group who did not commute across the border. Measures to reduce pedestrian exposure to traffic-related air pollutants would be prudent as pollutant levels at the SYPOE are elevated and may pose a health risk. A health study to identify possible adverse health effects and quantify risk experienced by pedestrian commuters is recommended. Having a specific marker for DE, such as 1-NP, has the benefit of improved specificity and could be incorporated into future health effects studies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2013.12.042.

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