BTEX Exposure Assessment and Inhalation Health Risks to Traffic Policemen in the Klang Valley Region, Malaysia

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ABSTRACT

Benzene, toluene, ethylbenzene, m,p-xylene, and o-xylene (collectively referred to as BTEX), which are prevalent in the ambient air of urban environments, potentially cause chronic health effects, particularly among outdoor workers. Aim of this study was to evaluate BTEX concentrations in the Klang Valley of Malaysia and assess the health risks to urban traffic police officers, whose duties include controlling the traffic flow and enforcing traffic laws. Air samples were collected with low-flow personal samplers during the officers’ work shifts outdoors, and the BTEX content was then analyzed via gas chromatography-mass spectrometry (GC-MS) coupled with thermal desorption (TD). A probabilistic method based on Monte Carlo simulation was applied to determine the cancer risk (CR) and hazard quotient (HQ), and a sensitivity analysis was performed to identify the greatest contributors to the estimated risks. The total BTEX concentration in the samples averaged 211.83 µg m⁻³, with the largest component being toluene (averaging 89.08 µg m⁻³ in concentration), followed by m,p-xylene (37.25 µg m⁻³), o-xylene (35.80 µg m⁻³), benzene (25.82 µg m⁻³), and ethylbenzene (23.89 µg m⁻³). The average CR value for benzene (5.31 × 10⁻⁴) as well as the 95th percentiles of the CR values for benzene and ethylbenzene (1.70 × 10⁻⁵ and 2.12 × 10⁻⁶, respectively) exceeded the acceptable level of exposure (1.0 × 10⁻⁶). The HQ values for all of the BTEX species were less than one. The sensitivity analysis revealed that the most influential parameter in increasing the estimated CR and HQ was the exposure duration, followed by the BTEX concentration. The estimated CR indicates that the prolonged exposure to benzene and ethylbenzene experienced by traffic police officers exacerbates the risk of adverse health effects. These results, which provide baseline data for determining the occupational risk to individuals who are exposed to BTEX while working on or near a road, emphasize the need for additional regulations, including the use of appropriate respiratory protective equipment.

Keywords: BTEX; Urban traffic police officers; Health risk assessment; Sensitivity analysis; Klang Valley.

INTRODUCTION

Volatile organic compounds (VOCs) are a prevalent group of air pollutants in urban and roadside areas. Benzene, toluene, ethylbenzene, and xylene, collectively known as BTEX, are mono-aromatic compounds in the VOC group. BTEX is continuously emitted from different natural and anthropogenic sources such as biogenic processes, paint application, evaporation from gasoline, industrial activities, solvent evaporation, biomass burning, and fuel combustion in motor vehicles (Lai et al., 2005; Williams and Koppmann, 2007; Kansal, 2009; Yuan et al., 2010; Yurdakul et al., 2013; Afshari et al., 2018). Vehicles are the most notable sources of BTEX emissions in urban areas in parallel with fast urban expansion leading to increased transport demand and fuel consumption. Previous studies have shown that mobile vehicle exhaust was a major influence on the levels of ambient BTEX in most urban and roadside areas (Ho et al., 2002; Wang et al., 2002; Jorquera and Rappenglück, 2004; Kerchich and Kerbachi, 2012; Afshari et al., 2018). Past literature has reported most light-duty vehicles (LDVs) used gasoline fuels (Liu et al., 2008; Tung et al., 2011; Cao et al., 2016). BTEX compounds were dominant in emissions from vehicles with gasoline fuel (Araizaga et al., 2013) while TEX were generated most from diesel-fuelled vehicles.

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Elsewhere, Yao et al. (2015) reported benzene, toluene and o-xylene (BTX) were emitted from diesel-fuelled vehicles.

Indicators for BTEx emission sources are often determined using BTEx species ratios, such as toluene to benzene (T/B), m,p-xylene to ethylbenzene (m,p-X/E), xylene to benzene (X/B), and ethylbenzene to benzene (E/B) (Elbir et al., 2007; Hoque et al., 2008; Buczynska et al., 2009; Masih et al., 2016; Dehghani et al., 2018). T/B ratios within the range 1.5–4.3 exhibited mobile emissions as the original source in the studied region (Miri et al., 2016; Raysoni et al., 2017; Abtahi et al., 2018). Apart from that, T/B values are closely linked to heavy traffic (Latif et al., 2019). The ratios of X/B, m,p-X/E, and E/B are indicative of photochemical reactivity or the so-called “freshness of air”—an indicator of the age of air mass (Hsieh and Tsai, 2003; Zhang et al., 2008; Abtahi et al., 2018). The ratio of X/B and E/B above one (> 1) and other reports the m,p-X/E value more than 3.28 indicate that monitored air masses were photochemically young (Miller et al., 2011; Kerchich and Kerbach, 2012; Bauri et al., 2016; Hajizadeh et al., 2018).

Concerns regarding human health in relation to BTEx exposure have grasped much attention due to their carcinogenic and mutagenic nature (ATSDR, 2007a, b, 2010; Esmaelnejad et al., 2015; ATSDR, 2017; Junaidi et al., 2019). BTEx compounds are likely responsible for chronic and acute health effects such as blood-related diseases (myeloid leukemia and aplastic anemia), potentially irreversible damage to the kidneys, cardiovascular disorder, nerve system disruption, headaches, and irritation to eye and skin (IARC, 1987; ATSDR, 2007a, b, 2010; Tunsaringkarn et al., 2012; Mohammadyan et al., 2016; ATSDR, 2017; Golakhshidi et al., 2019). The concern of these harmful air contaminants is not limited only to public health but similar interest to the not limited only to public health but similar interest to the...
The studied areas within the Klang Valley region.

**BTEX Personal Air Sampling**

The study was carried out from September 2017 to early January 2018. The BTEX samples were taken during the traffic policeman’s working hours involving controlling traffic flow and enforcement tasks only. To ensure no other factors, e.g., smoking, affected the readings, this outdoor personal air sampling study was designed to minimize any confounders arising from smoking and/or passive smoking which may appear during different tasks during working time, especially during indoor activities.

The personal sampling was performed using an active sampling method with low-flow personal air samplers (PAS-500; Spectrex, USA) attached to a stainless-steel tube (89 mm [length] × 6.4 mm [internal diameter]) packed with Tenax® GR (Supelco, USA) sorbent. Samples were collected when the policemen were engaged in outdoor duties (expressed as an 8-h time-weighted average [TWA]) during working hours from 7:00–9:00 a.m., 10:00 a.m.–2:00 p.m. and 5:00–7:00 p.m., except in Kuala Lumpur city center (6:00 a.m.–2:00 p.m.). The meteorological parameters such as temperature, relative humidity, and wind speed were recorded from the nearest air quality monitoring stations with an average of 28.73°C, 76.95%, and 1.062 m s⁻¹, respectively. These air quality monitoring stations are located within a range of radius of approximately 4.5–25.9 km from the sampling areas. The pump was calibrated using an air flow calibrator (Primary Calibrator 4146; TSI Inc., USA) and set to a flow rate of 20 mL min⁻¹ before and after personal sampling. The Tenax® GR tube was conditioned at 310°C for 40 min prior to sampling. The sorbent is a composite material consisting of 70% Tenax® TA and 30% graphitized carbon. This sorbent tube is recommended for both passive and active sampling for measurements including benzene, toluene, ethylbenzene and xylene (Cao and Hewitt, 1993; Gelencsér et al., 1994; Tolnai et al., 2000; Kumar and Viden, 2007). Moreover, a hydrophobic sorbent such as Tenax® was used to minimize the humidity effect during the sampling (Gallego et al., 2010). Each subject was required to attach this equipment in the breathing zone while they performed their work tasks. The samples were capped and kept in the refrigerator at 4°C until analysis.
Sample Preparation and Analysis

All sample tubes were analyzed for BTEX based on the established United States Environmental Protection Agency (U.S. EPA) TO-17 (1999) method for VOC measurement by active sampling onto sorbent tubes with some modifications (Hamid et al., 2019). Briefly, samples in the sorbent tube were directly analyzed via thermal desorption (TD; Unity-2 and Ultra-TD sampler; Markes International, UK) followed by a 6890N gas chromatograph (GC) equipped with a mass spectrometry (MS) selective detector (Agilent Technologies, USA). A DB-624 (J&W Scientific, USA) capillary column (60 m [length] × 0.32 mm [i.d.] × 1.80 µm [film thickness]) was used for the BTEX separation. Details of the set-up parameters for the TD-GC-MS method are explained by Hamid et al. (2019) (Table S2 in Supplementary 2).

Quality Control and Assurance

Prior to the analysis, BTEX measurements were calibrated using 10-ppm BTEX standards (MESKA, USA) diluted onto the sorbent tube using purified nitrogen (0.9997%). Five-point calibrations were prepared between masses of 30–450 ng with the aid of a Calibration Solution Loading Rig (CSLR; Markes International). Calibration curve linearity for benzene, toluene, ethylbenzene, m,p-xylene and o-xylene were 0.9961, 0.9977, 0.9995, 0.9998 and 0.9995, respectively. The limit of detection (LOD) for the BTEX compounds analyzed were 0.22, 0.15, 0.09, 0.09, and 0.09 µg m⁻³ for benzene, toluene, ethylbenzene, m,p-xylene, and o-xylene, respectively. A blank value (artefacts) for each tube was recorded after the recondition step and was found to be < 2 ng except for benzene (10 ng). The artefact values were used to correct the results by subtracting them from the final mass. Quality assurance of the sampling process was undertaken by routinely checking the field blank tube (closed cap) which was deployed together with the samples. The results for field blanks suggested that all compounds were not affected by the background concentrations. Quality control (QC) was performed by the analysis of Certified Reference Standard (CRS) tubes (Markes International, UK) consist of 100 ng BTX. The recovery QC results were 92% for benzene, 103% for toluene and 110% for o-xylene.

Inhalation Health Risk Assessment

The inhalation health risk assessment for cancer (CR) and non-cancer (known as the hazard quotient [HQ]) risks were determined using the U.S. EPA approach (1989). The information for health risk assessment (HRA) was obtained by questionnaire distribution during the sampling day. The HRA were able to calculate the nature and probability of the adverse health effects among the study population who were exposed to ambient BTEX pollutants. In this study, Monte Carlo simulations using Crystal Ball (version 11.1.2.4; Oracle Corp., USA) with 10,000 iterations have been applied to determine the inhalation risk to BTEX exposure. Meanwhile, the sensitivity analysis was conducted to determine which input parameters have the greatest influence on the estimated risk. The results of sensitivity analysis were first estimated prior to further cancer risk (CR) (Eq. (1)) and non-cancer risk or hazard quotient (HQ) (Eq. (2)) calculations.

\[
\text{Cancer risk (CR)} = \text{CDI} \times \text{CSFi} \tag{1}
\]

\[
\text{Hazard quotient (HQ)} = \frac{\text{EC}}{\text{RfC}} \times 1000 \tag{2}
\]

where:

- CA (µg m⁻³): Pollutant concentration in air (via personal sampling)
- IR (m³ h⁻¹): Inhalation rate (0.875 m³ h⁻¹ for adults) (U.S. EPA, 2011)
- ET (h d⁻¹): Exposure time (working hours, 8 h d⁻¹)
- EF (d y⁻¹): Exposure frequency (264 d y⁻¹)
- ED (y): Exposure duration (6.77 ± 6.09 y; max: 24 y)
- BW (kg): Body weight (mean ± SD: 74.18 ± 10.84 kg)
- AT (d): Averaging time for cancer estimation: 70 y × 365 d y⁻¹ = 25,550 d
- AT (h): Averaging time for non-cancer estimation: ED y × EF d y⁻¹ × ET h d⁻¹ = 50,688 h
- CSFi: Cancer slope factor (mg kg⁻¹ d⁻¹): Benzene: 2.73 × 10⁻² (RAIS; U.S. EPA, 2007)
- Ethylbenzene: 3.85 × 10⁻³ (RAIS; U.S. EPA, 2007)
- RfC: Inhalation reference concentration (mg m⁻³): Benzene: 3 × 10⁻³ (RAIS; U.S. EPA, 2007)
- Toluene: 5 (RAIS; U.S. EPA, 2007)
- Ethylbenzene: 1 (RAIS; U.S. EPA, 2007)
- Xylene: 1 × 10⁻¹ (RAIS; U.S. EPA, 2007)

A value of greater than 1 × 10⁻⁶ for CR estimation is considered unacceptable while a HQ of equal or less than 1 is considered safe.

Monte Carlo Simulation and Sensitivity Analysis

A single-point input parameter used in risk assessment models could lead to uncertainty. Therefore, a probabilistic risk using the Monte Carlo simulation technique was applied in most risk assessment studies to reduce uncertainties (Zhang et al., 2017; Baghani et al., 2018; Miri et al., 2018; Gholizadeh et al., 2019; Mohammadi et al., 2020). This probabilistic approach uses a range of parameter value instead of a single point value, and the risk estimation is repeated many times.

In this study, Monte Carlo simulations using Crystal Ball (version 11.1.2.4; Oracle Corp., USA) with 10,000 iterations have been applied to determine the inhalation risk to BTEX exposure. Meanwhile, the sensitivity analysis was conducted to determine which input parameters have the greatest influence on the estimated risk. The results of sensitivity analysis were

\[
\text{Exposure concentration (EC)} = \frac{(\text{CA} \times \text{ET} \times \text{EF} \times \text{ED})}{(\text{BW} \times \text{AT})} \tag{4}
\]
reported as rank correlation coefficients and the input parameter that has a higher coefficient is the most contributor in risk uncertainty. The parameters used in health risk assessment of Monte Carlo simulation and sensitivity analysis were BTEX concentrations and ED with log-normal distribution (Jia et al., 2008; Zhou et al., 2011; Dai et al., 2017) and BW was in a normal distribution. Meanwhile, other necessary parameters such as IR, ET, EF, AT, CSFi, and RIC were in a fixed value (Golkhorshidi et al., 2019; Omidi et al., 2019).

**RESULTS AND DISCUSSION**

**Personal Exposure Levels to BTEX**

The daily exposure of outdoor traffic police officers to BTEX is shown in Table 1. The average total BTEX measured was 211.83 µg m⁻³. Toluene was found the most predominant among the BTEX species (the average concentration of toluene was 89.08 µg m⁻³ with a range of 15.13–444.47 µg m⁻³). The means and standard deviations (SDs) of the concentrations of m,p-xylene, o-xylene, total xylene, benzene, and ethylbenzene were 37.25 ± 24.37, 35.80 ± 21.65, 73.04 ± 44.50, 25.82 ± 18.84, and 23.89 ± 13.25 µg m⁻³ respectively. The relative abundances for the studied areas in the Klang Valley region among these urban workers were as follows: toluene > xylene > m,p-xylene > o-xylene > benzene > ethylbenzene. These rank similarly to reported ranks in others occupational populations in urban Thailand, the Philippines, China, and India (Majumdar et al., 2008; Balanay and Lungu, 2009; Tunsaringkarn et al., 2014; Chen et al., 2016). Similarly, studies utilizing ambient monitoring found the most abundant BTEX compound to be toluene observed in urban and roadside areas of Delhi, India (Hoque et al., 2008); Ashiya, Japan (Okada et al., 2012); Beijing, China (Li et al., 2014); Ho Chi Minh, Vietnam (Giang and Oanh, 2014); Gorakhpur and Northern India (Masih et al., 2016, 2017); and Kuala Lumpur, Malaysia (Hamid et al., 2019).

The high toluene levels found may be explained by fact that the content of toluene in unleaded gasoline is up to 15% by volume in Malaysia. Xylene showed the next highest exposure levels, followed by benzene, and the lowest was ethylbenzene. Safety data sheets published by petroleum-based companies showed most unleaded gasoline of RON95 and RON97 of the Euro 2 standard in Malaysia contains concentrations of benzene and ethylbenzene of up to 5% by volume, while xylene can reach 15% by volume. Tsai and Chiang (2012), Ho et al. (2013), and Wang et al. (2017) found toluene to be the most abundant species in both light-duty gasoline- and diesel-fuelled vehicle emissions. These values illustrated the amounts of aromatic compounds released into the ambient air of urban traffic areas. The less reactive and stable benzene (a lifetime of 9.4 days) compared to ethylbenzene (1.6 days) also might explain the observed rank of these compounds in the atmosphere. Considering the maximum concentrations added to gasoline, these exhibited high levels comparable to the other countries such as Vietnam (toluene and benzene in RON95 were 1.85 wt.% and 4.2 wt.%, respectively) (Fan and Minh, 2013). Malaysia is still unsuccessful in reaching the EPA-recommended limit of 0.6% by volume. Still, the oil specification of Euro 2M RON95 remains frequently consumed among LDV users in Malaysia. Hosaini et al. (2017) accounted a total of 94% BTEX emissions in the urban microenvironment from the vehicle emissions and gasoline evaporation. As of 31 December 2017, the number of motor vehicles showed a 5.4% increase in Malaysia (RTVM, 2017). The two-stroke engine motorcycle type contributes approximately half of the vehicle emissions in Malaysia, similar to those reported in Delhi (Hoque et al., 2008), and aromatic BTEX compounds are common VOCs released from motorcycle exhaust (Tsai et al., 2018).

A large number of traffic census stations within the studied areas were reported as in the F category (extreme, unacceptable congestion, stop-and-go traffic and forced flow) of the level of service (LOS) (RTVM, 2017). Moreover, these traffic census stations have also documented the category of cars was the highest on the road with the average ranged from 56.9 to 67.8%, followed by motorcycles (12.8–22.6%), van and utilities (5.4–11.8%), medium lorries (4.6–6.7%), heavy lorries (2.1–4.1%), and buses (0.2–0.6%). As reported in RTVM (2017), the average number of vehicles during peak traffic hour (per hour) was in the range between 2330–12,039 vehicles. This problematic street condition resulted in the subject inhaling more BTEX pollutants as most of them stood in the main traffic lane during the morning, noon, and evening rush hours with long lines of vehicles and congested traffic volume leading to traffic jams and increasing emissions from cars (Buczynska et al., 2009). Moreover, land cover in most of the cities of Klang Valley region is made up of tall buildings, trapping BTEX pollutants, and allowing them to accumulate along the roadsides. In agreement with this, levels of BTEX were found to reduce by around 15%

| Pollutant       | Mean   | SD     | Median | Min   | Max   |
|-----------------|--------|--------|--------|-------|-------|
| Benzene         | 25.82  | 18.84  | 19.93  | 3.36  | 129.26|
| Toluene         | 89.08  | 60.88  | 76.81  | 15.13 | 444.47|
| Ethylbenzene    | 23.89  | 13.25  | 21.94  | 5.86  | 64.39 |
| m,p-Xylene      | 37.25  | 24.37  | 31.93  | 0.97  | 133.66|
| o-Xylene        | 35.80  | 21.65  | 29.96  | 7.02  | 111.48|
| Xylene          | 73.04  | 44.50  | 64.05  | 14.82 | 245.14|
| Total BTEX      | 211.83 | 126.02 | 182.13 | 39.21 | 642.91|
for every 5 m downwind from the traffic lane (Giang and Oanh, 2014). Additional factors such as incomplete burning processes in old car engines without catalytic converters and less maintenance are also contributors for the increments in levels of BTEX as no end-of-life vehicle policy is implemented in Malaysia. Consequently, the urban traffic police officers had a higher risk of exposure to these toxic aromatic air pollutants as they directly inhaled the BTEX compounds emitted from vehicles.

A Mann-Whitney U test showed no differences in the personal concentrations of BTEX between smokers and non-smokers. The smoker vs. non-smoker traffic policemen were exposed to benzene, toluene, ethylbenzene, m,p-xylene, o-xylene, and BTEX at levels (mean ± SD) of 26.46 ± 20.58, 89.61 ± 53.41, 23.87 ± 12.95, 35.60 ± 22.66, 35.68 ± 21.95, and 211.21 ± 121.13 µg m⁻³ vs. 24.95 ± 16.32, 88.35 ± 70.41, 23.91 ± 13.80, 39.51 ± 26.60, 35.96 ± 21.46, and 212.67 ± 133.70 µg m⁻³, with p > 0.05, respectively. Smoking activity may affect the measurements; hence this study was designed to only measure the subject’s outdoor activities. The traffic policemen were forbidden to smoke while performing their duties on the roads. These results indicated that both smoking and non-smoking traffic policemen were exposed to similar levels of BTEX during their outdoor duties.

The average individual BTEX compound exposure was lower than the present regulatory standards for BTEX occupational limits of 1.60, 75.37, 86.85, and 434.19 mg m⁻³ of 8-h TWA from American Conference of Governmental Industrial Hygienists (ACGIH, 2011). However, the average level of benzene was much higher than the annual permissible limit of 5 µg m⁻³ established by the European Union (EU; European Commission, 2015). Vietnam is the only Asian country to set the hourly limits for benzene of 22 µg m⁻³—value reported here for average benzene slightly exceed this level. If the traffic police officers are consistently exposed to these levels of BTEX, standing at the roadside for most of their outdoor work shift for their working lifetime of years, then this poses a high risk to their health.

**Comparison with Previous Studies on BTEX Exposure among Outdoor Workers**

Comparing with outdoor urban workers worldwide, the order of toluene < xylene < benzene < ethylbenzene in this study was similarly observed in Bangkok’s street vendors, Manila’s jeepney drivers, China’s taxi drivers, gasoline filling workers (Majumdar et al., 2008; Balanay and Lungu, 2009; Cattaneo et al., 2010; Tunsaringkarn et al., 2014; Chen et al., 2016). The majority of authors reported the highest exposure of toluene affected urban workers, except for security guards in Bangkok, Thailand (Tunsaringkarn et al., 2014; Kanjanasiranont et al., 2016). In Asia, the dominance of toluene in ambient air can be related to higher amounts of this compound mixed into petrol to increase its octane number. Toluene is proven as an effective antiknock additive for fuel and without it, ignition at lower temperatures is much harder. Ethylbenzene was detected at the lowest concentrations among urban workers’ samples and this can be related to a content of a maximum of 5% by volume in most fuels. The fuel composition utilized also influences the levels of BTEX emitted, as well as from vehicle exhaust, car age, photochemical reactions, regional transportation of pollutants, and temperature (Lee et al., 2002; Chen et al., 2011; Ho et al., 2013).

Considering similar job tasks to this study, traffic police officers in Bangkok, Lebanon, and Peru were exposed to 1.9–16.5-fold higher and 2.4–2.7 times lower in Italian traffic police than the present study due to the carcinogenicity of benzene, respectively (Table 2) (Cattaneo et al., 2010; Campo et al., 2011; Han et al., 2013; Borgie et al., 2014; Kanjanasiranont et al., 2017). Such distinctive levels of benzene reported depending much more on the duration and time of sampling, the instrument used, areas of selection, distance from anthropogenic sources such as petrol pumps, traffic volumes, vehicle types, industrial sources and varying fuel compositions used in each country. The Italian petrol pump attendants were also markedly exposed to the highest benzene levels, and the majority of them had been exposed to benzene levels in the range 107.8–137.5 µg m⁻³ although lower concentrations were observed for Vietnamese petrol filling workers (Majumdar et al., 2008; Tunsaringkarn et al., 2012; Lan et al., 2013). Overall, traffic police officers and petrol pump attendants are exposed to high levels of total BTEX, more than 1000 µg m⁻³ (Majumdar et al., 2008; Borgie et al., 2014; Kanjanasiranont et al., 2017). These findings illustrate that traffic police officers and petrol pump attendants are more at risk than other outdoor workers due to the fact that they work around busy roads in the rush hours (Manuela et al., 2012), or pump an average of 2000 L petroleum with 5% (v/v) benzene content during the 8-h work shift (Çelik and Akbaş, 2005).

**Inter-species Correlation**

The inter-species correlations using the personal data collected were determined to examine the source indicators. Spearman’s Rho correlation coefficients for BTEX species were evaluated as the data were not normally distributed (Table 3). Positive correlations were obtained when correlating the BTEX species with one another. A good correlation was found between all BTEX species (p < 0.01 and r > 0.80). These good correlation results indicate that these compounds originated primarily from a single source—vehicular emissions. The present findings seem to be consistent with others reported by Hoque et al. (2008), Miller et al. (2012), Rad et al. (2014), Miri et al. (2016), and Garg et al. (2018). Comparable to this study, correlation coefficients of r < 0.5 were exhibited when the BTEX species are likely to originate from multiple sources of emissions other than just vehicle exhaust (Lee et al., 2002; Parra et al., 2006).

**Source Apportionment Using BTEX Ratio Species**

BTEX species ratios were calculated to determine the sources attributing to the levels of BTEX in this study (Table 4). The toluene-to-benzene (T/B) ratio showed the value of 3.81, indicating a source of traffic-related emissions. As observed, the average composition of vehicles (Table S1) documented in the year 2017 included more than 50% cars and taxis, while motorcycles were the second-highest category.
Table 2. Comparison of personal BTEX concentrations among outdoor traffic policemen in this study and worldwide outdoor workers.

| Country                     | Outdoor workers     | Average Concentration (µg m\(^{-3}\)) | BTEX   | Reference                                      |
|-----------------------------|---------------------|----------------------------------------|--------|-----------------------------------------------|
|                            |                     | B | T   | E | m,p-X | o-X | Total X |                  |
| Klang Valley, Malaysia      | Traffic policemen   | 25.82 | 89.08 | 23.89 | 37.25 | 35.80 | 73.04 | 211.83 | This study       |
| Bangkok, Thailand           | Traffic policemen   | 426.3 | 1016.1 | 178.5 | 202.92 | 166.81 | 396.79 | 1990.6 | Kanjanasiranont et al., 2016, 2017 |
|                            | Street vendors      | 25.86 | 66.03 | 4.30 | 5.62 | 13.07 | 18.69 | 114.88 |
|                            | Motorcycle-taxi drivers | 31.74 | 56.59 | 5.80 | 5.64 | 15.24 | 20.88 | 115.01 |
|                            | Security guards     | 40.13 | 31.72 | 3.83 | 4.88 | 18.86 | 23.74 | 99.42  |
| Bangkok, Thailand           | Gasoline attendants | 107.68 | 226.68 | 7.25 | -    | -    | 11.56 | 353.17 | Tunsaringkarn et al., 2012, 2014 |
|                            | Motorcycle drivers  | 31.10 | 55.98 | 5.68 | -    | -    | 30.06 | 122.82 |
|                            | Security guardsmen  | 54.10 | 32.42 | 2.38 | -    | -    | 40.94 | 129.84 |
|                            | Street vendors      | 27.01 | 46.77 | 3.95 | -    | -    | 36.67 | 114.4  |
| Bangkok, Thailand           | Sky train security guard | 7.52  | 214.30 | -    | -    | -    | -    | -      | Chimplee and Taneepanichskul, 2015 |
| Manila, Philippines         | Jeepney drivers     | 55.6  | 196.6 | 17.9 | 72.5 | 88.5 | 161.10 | 431.2  | Balanay and Lungu, 2009 |
| Changsha City, China        | Taxi drivers        | 82.7  | 212.3 | 74.7 | -    | -    | 182.3 | 552    | Chen et al., 2016 |
| Ho Chi Minh City, Vietnam   | Motorcycle-taxi drivers | 116   | -    | -    | -    | -    | -    | -      | Lan et al., 2013 |
|                            | Petrol filling workers | 52    | -    | -    | -    | -    | -    | -      | -                 |
|                            | Street vendors      | 32    | -    | -    | -    | -    | -    | -      | -                 |
| Kolkata, India              | Pump attendants     | 137.5 | 643.6 | 118.0 | 209.7 | 68.2 | 277.9 | 1177   | Majumdar et al., 2008 |
| Milan, Italy                | Urban police        | 9.6   | -    | -    | -    | -    | -    | -      | Campo et al., 2011 |
| Milan, Italy                | Traffic police      | 10.9  | 57.1  | 8.5  | -    | 10.1 | 39.4 | 115.9  | Cattaneo et al., 2010 |
| Beirut, Lebanon             | Traffic police      | 48.8  | 1152.0 | 662.3 | 206.3 | 177.7 | 384 | 2247.1 | Borgie et al., 2014 |
| Trujillo, Peru              | Traffic police      | 187.5 | 668.1 | -    | -    | -    | -    | -      | Han et al., 2013  |
of vehicle on the roads and highways. Most of the motorcycles were designed without any exhaust gas treatment system leading to these aromatic pollutants being given out to the ambient air (Lan and Binh, 2012). Also, it was reported that the total accumulated vehicles increased 5.5% in the year 2017, of which 92% were private vehicles. LDVs such as cars and two-wheeled motor vehicles are common and dominate the traffic in Kuala Lumpur and other parts of the Klang Valley. This type of private LDV mostly run on Euro 2 gasoline. This T/B result exhibited that the toluene and benzene components in gasoline are largely emitted to the atmosphere from this type of vehicle exhaust (Hajizadeh et al., 2018). Also, the traffic volumes during peak hours similar to the times traffic police officers were out for duty indicate they were exposed to over 2000 vehicles per hour. This traffic volume data and T/B ratio result confirm that mobile emissions are a vital source of aromatic species at the roadsides of the Klang Valley region, in which similarly reported by Latif et al. (2017). This finding is in agreement with Rad et al. (2014), Miri et al. (2016), Raysoni et al. (2017), Garg et al. (2018), and Hajizadeh et al. (2018) who found T/B ratios in the range 1.5–4.3. Previously, a lower T/B ratio (2.2) was reported by Lan and Binh (2012) in Kuala Lumpur and other parts of the Klang Valley. This lower ratio values indicate an aging air mass. Comparable to this study, Lan and Binh (2012) reported a value of m,p-X/B ratio almost similar to this study (> 1) but a lower value for the o-X/B ratio (0.41). A clear distinction in T/B, E/B, T/E, and X/E ratio results from intensive traffic roadsides can be seen from studies observed in Nanjing, China (2.62, 3.02, 7.90, and 1.18) (Wang and Zhao, 2008); Hong Kong, China (3.03, 1.75, 5.27, and 1.50) (Huang et al., 2015); Xi’an, China (0.36, 12.50, 4.37, and 2.73) (Li et al., 2017); and this study in the Klang Valley, Malaysia (3.81, 1.10, 3.83, and 3.01). These differences are probably influenced by variations of fuel composition use, meteorological conditions, photochemical reactions of BTEX species, vehicle technology, and location areas (Lan and Binh, 2012).

### Health Risk Assessment of BTEX and Sensitivity Analysis

Apart from biological monitoring for benzene health outcome evaluation (Fandi et al., 2017), health risk assessment is a valid tool used to estimate cancer and non-cancer risks. The Monte Carlo simulation technique is widely used for estimating cancer and non-cancer risk of hazardous pollutant exposure in a variety of media (air, water, food, and soil) (Dai et al., 2017; Pérez-Maldonado et al., 2017; Fallahzadeh et al., 2018; Miri et al., 2018; Gholizadeh et al., 2019; Karami et al., 2019).

Figs. 2(a) and 2(b) depict the probability distribution of the predicted CR and HQ; meanwhile Fig. 2(c) shows the sensitivity analysis for the estimated risks of BTEX. The mean and 95th percentile of CR values for benzene exposure

### Table 3. Spearman’s Rho correlation for BTEX species.

|          | Benzene | Toluene | Ethylbenzene | m,p-Xylene | o-Xylene | xylene | BTEX |
|----------|---------|---------|--------------|------------|----------|--------|------|
| Benzene  | 1       | 0.841** | 0.855**      | 0.863**    | 0.880**  | 0.908**| 0.910**|
| Toluene  | 1       | 0.854** | 0.863**      | 0.890**    | 0.943**  | 0.924**|      |
| Ethylbenzene | 1| 0.875** | 0.966**      | 0.943**    | 0.924**  |        |      |
| m,p-Xylene | 1  | 0.889** | 1            | 0.962**    | 0.940**  |        |      |
| o-Xylene | 1       | 1        | 0.971**      | 0.940**    |          |        |      |
| xylene   | 1       | 1        | 0.966**      |            |          |        |      |
| BTEX     | 1       |          |              |            |          |        |      |

** Correlation is significant at the level p < 0.01.

### Table 4. Ratio of BTEX species using personal concentration.

|                              | Mean | SD  | Median | Min  | Max  |
|------------------------------|------|-----|--------|------|------|
| Individual samples of outdoor traffic policemen (n = 116) | 3.81 | 2.02 | 3.56   | 1.56 | 14.28|
| E/B                          | 1.04 | 0.31| 0.46   | 0.39 | 0.44 |
| m,p-X/B                      | 1.54 | 0.46| 1.65   | 0.99 | 2.32 |
| o-X/B                        | 1.50 | 0.39| 1.55   | 0.24 | 2.47 |
| m,p-X/E                      | 1.54 | 0.44| 1.53   | 0.10 | 2.94 |
| o-X/E                        | 1.47 | 0.19| 1.48   | 0.98 | 2.21 |
were $5.31 \times 10^{-6}$ and $1.70 \times 10^{-5}$, respectively. Meanwhile, the mean and 95th percentile of CR calculated for ethylbenzene were $6.89 \times 10^{-6}$ and $2.12 \times 10^{-6}$, respectively. The mean of CR value for benzene was greater than the acceptable U.S. EPA limit ($1.6 \times 10^{-6}$), even at a worst-case estimated risk of the 95th percentile for both benzene and ethylbenzene. Mean and 95th percentile total CR were $6.00 \times 10^{-6}$ and $1.9 \times 10^{-5}$, respectively (Fig. 2(a)). Other studies had estimated the cancer risk for benzene exposure were much higher than the present study on average, ranged from $1.50 \times 10^{-4}$ to $7.68 \times 10^{-6}$ (Baghani et al., 2018; Mohammadi et al., 2019; Omidi et al., 2019). On the contrary, Miri et al. (2016) had found the allowable level for benzene exposure ($3.94 \times 10^{-7}$).

HQ values for BTEX ranged from 0.01 to 0.24 (mean) and in the range of 0.02–0.73 at 95th percentile. At both mean and 95th percentile, the most abundant species for HQ was benzene (0.24 and 0.73), followed by total xylene (0.21 and 0.64); meanwhile toluene, and ethylbenzene reported the similar and lowest results (0.01 and 0.02). All HQ values for BTEX were considered safe, which similarly reported by Miri et al. (2016) and Mohammadi et al. (2019). However, Omidi et al. (2019) reported an unacceptable limit of BTE.
Sensitivity analysis was performed to evaluate the most influential variable for the value of CR for benzene and ethylbenzene exposures and HQ values for BTEX exposure. The results of the sensitivity analysis of CR and HQ for BTEX were shown in Fig. 2(c). As can be seen that the exposure duration parameter has a greater impact on the CR values for benzene and ethylbenzene exposures with a correlation coefficient of 0.74 and 0.80, respectively, followed by the concentrations of benzene (0.62) and ethylbenzene (0.53). An inverse relationship appeared between body weight and CR value for benzene and ethylbenzene exposures (correlation coefficient: −0.14 and −0.15), which similarly found by Miri et al. (2016). The present study also found that CR value was decreased with the increase of averaging time (correlation coefficient for CR benzene and ethylbenzene were −0.11 and −0.12, respectively). An identical scenario was shown for the estimated BTEX HQ, in which exposure duration parameter had the highest impact in the uncertainty of HQ (range of correlation coefficient: 0.75–0.82), followed by BTEX concentrations (ranged from 0.55 to 0.63). Meanwhile, averaging time (all values: 0.02) and inhalation reference concentration (−0.04 to −0.06) were the lesser contributors, and both parameters had an inverse relationship with the BTEX HQ.

The traffic police officers can spend more than 20 years working at the roadsides without job task changes. This situation leads them to be exposed to extremely high levels of carcinogenic compounds, specifically benzene. Benzene is the most stable BTEX species, and it remains in the atmosphere the longest. The lifetime of B, T, E, o-X, p-X and m-X are as follows: 9.4 days > 1.9 days > 1.6 days > 20.3 h > 19.4 h > 11.8 h (Monod et al., 2001). The longer lifetime and lesser reactivity of benzene means it can move to other regions without degradation. This shows the traffic police officers were chronically exposed to a cancer-causing agent as the depletion of benzene is negligible due to slow reactions with ozone (O₃) and nitrate (NOₓ). The main target organ of benzene is bone marrow and can cause blood-related diseases. Therefore, the preventive measures are necessary for considering the duration of exposure at the roadsides to minimize the occupational hazard to BTEX as low as reasonably practicable.

The present study was emphasized only on the inhalation risk assessment and was limited for uncertainties such as exposure via ingestion and skin, including toxicology parameters. However, the different degree of the probability distribution with different ranges of conditions for input parameters were evaluated, instead of single-point estimated value.

### Risk Reduction Using Different Type of Respirators

From the observation, a majority of traffic personnel did not wear respiratory protection, although the equipment was provided to them on a frequent basis. Moreover, they were frequently provided with a disposable half-mask, which were not appropriate for vapor pollutant filtration. To be recognized as a suitable respiratory protective equipment (RPE), the type of hazardous substances must first be identified before the correct RPE can be selected to ensure efficient protection to the users. The particulate filtration system was known for not being efficient to trap gases or vapor and vice versa for gas/vapor filter types because of the material differences made up (Health and Executive, 2013). At 95th percentile, the effectiveness of disposable dust face mask had shown a reduction in the incidence of cancer risk from $1.70 \times 10^{-7}$ to $3.40 \times 10^{-6}$ for benzene exposure; however, the value still considerably higher than an acceptable value. Even though the value of cancer risk decreases to the acceptable level ($2.12 \times 10^{-6}$ to $2.74 \times 10^{-7}$) for ethylbenzene exposure, the provided dust mask only works for particle filtration. The incidence of benzene cancer risk reduced to $8.50 \times 10^{-7}$ and $1.70 \times 10^{-7}$ from $1.70 \times 10^{-5}$ by using N95 face respirator and P100 facepiece respirator, respectively, in which P100 respirator incorporated a combination of vapor and particle filtration (Table 5).

Hence, the respirator that combines vapor and particle filtration system is proven to be efficient protective equipment for the case of benzene and ethylbenzene exposures. Nevertheless, BTEX exposure can be largely reduced by cutting down the emissions from transportation (source reduction) such as through the utilization of the fuel injection engines powered by ethanol-gasoline mixtures (Yao et al., 2017).

| Risk Reduction (at 95th percentile) | Benzene | Ethylbenzene | Conc. × 0.20 | Conc. × 0.05 | Conc. × 0.01 |
|----------------------------------|---------|-------------|--------------|-------------|-------------|
| Input value                      | 1.70 × 10^{-5} | 2.12 × 10^{-6} | 2.74 × 10^{-7} | 1.20 × 10^{-7} | 1.70 × 10^{-7} |
| Exposure reduction               | –       | –           | 95%          | 99.7%       | –           |
| Type of RPE                      | Without any respiratory protection | Disposable Dust Mask | Face Respirator N95 | Facepiece Respirator P100 with particles + vapors + gases cartridge | – |

**Table 5. Risk Reduction when using a different type of respiratory protective equipment (RPE) in outdoor traffic policemen.**
CONCLUSIONS

This study assessed the personal BTEX exposure of traffic police officers working on or near the road during rush hour and the potential CR following chronic exposure. The total BTEX in the collected samples averaged 221.83 µg m⁻³ in concentration, and the following components, in descending order of average concentration, were detected: toluene (89.08 µg m⁻³) > total xylene (73.04 µg m⁻³) > m,p-xylene (37.25 µg m⁻³) > o-xylene (35.80 µg m⁻³) > benzene (25.82 µg m⁻³) > ethylbenzene (23.89 µg m⁻³). The highest concentration of toluene was related to its presence in vehicle fuel. Although all of the BTEX pollutants that we measured were in compliance with the ACGIH occupational limits, the level of ambient benzene exceeded both the average annual limit set by the EU and the average hourly limit stated in the Vietnamese National Air Quality Standard.

Strong correlations (r > 0.8) were found between the BTEX compounds, which, based on the T/B ratio (3.81), likely originated from traffic-related sources. Notably, unacceptably high CR values were calculated for benzene and ethylbenzene, which are classified as 

\textit{carcinogenic} and 

\textit{probably carcinogenic}, respectively, reflecting the serious health risks to urban traffic police officers. According to our probabilistic risk assessment, the exposure duration was the most significant contributor to incrementing the risk values, followed by BTEX concentration.

Our results support the inclusion of BTEX species as criteria pollutants in the National Ambient Air Quality Standard. The addition of these hazardous substances in fuel must be regulated, and we also recommend that traffic police officers be required to wear appropriate personal protective equipment, such as respirators fitted with organic vapor and particle cartridges. Future environmental health criteria assessments involving biological markers for specific BTEX pollutants should investigate aromatic BTEX species, which may offer potential clues on preventing BTEX-related illnesses.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://aaqr.org/

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