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Health risk assessment of BTEX exposure at roadside and on-road traveling route in Bangkok Metropolitan Region

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Abstract

Exposure to high levels of benzene, toluene, ethylbenzene, and xylenes (BTEX) poses health risks in high-traffic urban areas. BTEX exposure at two microenvironments, the roadside and along the traveling routes, within urban and suburban areas of the Bangkok Metropolitan Region was examined to assess cancer and noncancer risks. The lifetime cancer risk (LCR) for benzene and noncancer hazard index (HI) for all BTEX compounds were evaluated for adult male and female groups (drivers, passengers, and street vendors) in two scenarios: average case and worst case. With the assumption of negligible exposure outside the two considered microenvironments, the pickup drivers had the highest LCR and HI. Higher exposure risks were found in urban areas than in the suburbs and among men than females. Higher toluene levels were found at all monitoring sites in two microenvironments, but benzene was the most important in causing noncancer risk. The HI for all target groups ranged from 8.5E-03 to 4.0E-01, indicating a low noncancer risk from BTEX exposure (HI < 1). The LCR caused by benzene exposure ranged from 1.7E-06 to 7.2E-05, which is higher than the United States EPA most health-protective limit (1E-06). Further research should include other microenvironments by assessing the 24-hour exposure of all considered groups.

Keywords: Exposure, BTEX, cancer risk, hazard quotient, traffic, Bangkok

INTRODUCTION

Globally, air pollution causes approximately 7 million deaths yearly[1]. Many toxic air pollutants are present in indoor and outdoor air, such as particulate matter (PM), including the most concerned fine particles (particles with a diameter ≤ 2.5 μm or $PM_{2.5}$), gaseous pollutants, and semi-volatile organic compounds (S-VOCs). Volatile organic compounds (VOCs) consist of toxic air pollutants and are present at considerably high levels in indoor and outdoor air[2-4]. VOCs also serve as precursors to form secondary toxic air pollutants, including secondary PM, mostly of $PM_{2.5}$ size, and ground-level ozone. Benzene, toluene, ethylbenzene, and xylenes, collectively known as the BTEX group, are VOCs with carcinogenic and non-carcinogenic effects. Long-term exposure to BTEX can negatively impact the development of immune function, reproduction and respiratory system, as well as worsen hematological and cardiovascular diseases[4-8]. The International Agency for Research on Cancer has classified benzene as a group 1 carcinogen, which causes acute myeloid leukemia in adults[5].

Benzene is primarily released from anthropogenic sources, including combustion and non-combustion processes. The latter include the evaporative emissions from the gasoline distribution system as benzene is found naturally in petroleum products such as crude oil and gasoline[5]. Previous studies have reported high benzene exposures, resulting in a higher lifetime cancer risk (LCR) than the recommended range by United States EPA[9,10]. These include, for example, workers at petroleum refueling stations in South Africa[11], workers in a printing and copying center in Ardabil, Iran[12], workers at petroleum product distributors in Northern Iran[13], and residents of an urban hot spot in Shiraz, Iran[14] and Tehran, Iran[15].

As leaded gasoline had been phased out, to boost the octane number, benzene (in a benzene-toluene-xylene mixture) is added to unleaded gasoline[5]. As a result, BTEX emissions in major cities were primarily caused by mobile sources[4,16], and high BTEX concentrations have been reported at roadside and city center locations[16-19]. Residents living in areas with high traffic volumes are exposed more to BTEX[20]. A few previous studies in Thailand assessed the levels of BTEX and associated health risks for occupational exposure. Accordingly, workers at five gasoline stations in Khon Kaen province had an unacceptable risk to BTEX with HI > 1[21]. Workers at gasoline stations in Chonburi had lower HI ranging from 5.3E-05 to 6.3E-04[22], while in Bangkok, HI was 1.8E-04[23].

The monitoring results in Thailand between 2013 and 2019 revealed that benzene levels likely decreased. This decrease reflected the success of countermeasures to control VOC emissions from the transportation sector, such as the development of clean vehicle technology and fuel quality improvement[24]. In Thailand, for example, the limit of benzene content in gasoline is 1% by volume[25]. Nevertheless, the benzene levels in the ambient air still exceeded the annual national ambient air quality standard (NAQQS) of 1.7 μg/m^3 in several areas, especially near busy roads and industrial estates. The annual average benzene concentrations in three Bangkok high-traffic areas ranged from 2.3 to 3.6 μg/m^3[24]. A study in Bangkok found high BTEX levels in closed vehicles, implying that health risks should be considered when traveling in urban areas[26]. However, there was not any comprehensive assessment study reporting the risk of BTEX exposure for street vendors and on-road commuters in Thailand. This study aims to partly fill in the data gap by assessing cancer and noncancer risk of BTEX exposure in these target populations using the BTEX measurement data reported in our previous study[26].

MATERIAL AND METHOD

Study area

The study was conducted in the Bangkok Metropolitan Region (BMR) of Thailand[27]. BMR consists of Bangkok and five surrounding provinces: Nakhon Pathom, Nonthaburi, Pathum Thani, Samut Prakan, and Samut Sakhon [Figure 1]. BMR has a registered population of 10,864,169 people (as of November 2022), accounting for 16% of the population (66,099,975) of Thailand[28]. Air pollution is a significant issue in Bangkok and the surrounding areas[29]. Data from 10-year air monitoring (2012-2021) revealed that $PM_{2.5}$ and benzene levels exceeded the NAAQS, particularly at the roadside in Bangkok. Ozone levels in some areas of the surrounding provinces also exceeded the NAAQS. Transportation and biomass open burning (rice straw field burning) are the major sources of air pollutants in BMR[30]. Due to intensive emissions and meteorological conditions, BMR's dry season (mid-October to mid-May) is characterized by significantly higher air pollution levels, especially PM_{10} and $PM_{2.5}$, than in the wet season[31]. Our previous research monitored air pollutant levels ($PM_{2.5}$, BTEX, NO_2, SO_2) at the roadside and along traveling routes in the urban and suburban areas of BMR. High levels of BTEX were found, especially in congested urban areas, which suggests a high risk of exposure. Hence, a more in-depth study on the risk of BTEX exposure for people in BMR is needed[26].

Monitoring design

Sampling and analysis

The roadside and on-route BTEX monitoring was conducted in both the urban area in Bangkok and the suburban area of Pathum Thani. The BTEX sampling was done using Method 1501 of the National Institute for Occupational Safety and Health (NIOSH)[32]. Tubes containing the adsorbent of SKC-coconut shell charcoal (diameter: 6 mm; length: 70 mm; 100 mg/50 mg) were used for sampling. The air was pumped through each tube with a calibrated constant flow rate of 0.18 L/min. The BTEX samples were extracted using a carbon disulfide (CS_2) solvent and analyzed by Gas Chromatography-flame ionization detector (GC-FID) following the procedure detailed in our previous publication[26].

Table 1 summarizes the monitoring plan, whereas a more detailed monitoring design has been described in our previous publication[26]. Briefly, the roadside monitoring was conducted at the Dindaeng Road, a busy road with a high traffic density, to represent the Bangkok city center, and a segment of the Phaholyothin Road running through the peri-urban area in Pathum Thani province to represent the suburban area. Note that the Phaholyothin Road is National Highway No. 1, the primary road connecting Bangkok to the northern and northeastern regions of Thailand. At the selected roads, BTEX sampling was conducted simultaneously on both sides to account for the pollutant dispersion within the road so that the average value would be representative for both leeward and windward sides of each road. The on-route measurements were also conducted in both urban and suburban areas. The urban route was selected to be representative of the Bangkok city center, covering 41.5 km, which was divided into three sub-routes [Figure 1]. The suburban route was selected along the Phaholyothin Road, passing Pathum Thani with a total length of 55 km. On-road monitoring was done when traveling in a van, a pickup truck, and a motorcycle, respectively. The monitoring was done during both dry and wet seasons in the more polluted urban area, while for the suburban area, the monitoring was done only during the dry season.

The roadside BTEX samples were collected with the air intake height at approximately 3 m above the ground and more than 3 m from the travel lanes to avoid the mixing zone effects[33]. Each roadside sample was collected with the sampling pump operated for 1 hour, hence producing the hourly average BTEX results.

Table 1. Summary of sampling design and BTEX monitoring periods in different microenvironments

Area	Season	Roadside	On-route		
			Period	Route length	Vehicles (speed, km/h)
Urban	Wet	28 Jun-4 Jul 2010	7-11 Jul 2010	41.5 km	Van (30 ± 14)
	Dry	4-11 Dec 2010	12-15 Dec 2010	41.5 km	Van (30 ± 6.9) Pickup (26 ± 10)
Suburban	Dry	18-21 Dec 2010	24 Dec 2010-1 Jan 2011	55 km	Pickup (53 ± 5.5) Motorcycle (51 ± 5.5)

The on-route BTEX samples were taken both inside and outside of every selected vehicle[26]. The inside van measurement of BTEX was done with the sampling equipment attached to a seat behind the driver, while the air conditioner (A/C) was off and the adjacent window was halfway open. These samples were used for the exposure assessment for the driver and for van passengers. For the pickup vehicle, the inside measurements were done in the closed cabin with the A/C on while the ventilation air intake was set at different ratios, and the BTEX analysis results were used for the exposure assessment of drivers. The outside pickup measurements were done in the open back wagon, which is more relevant for passenger exposure. The measurements for the motorcycle were made with the equipment placed in a backpack placed at the breathing level.

The suburban on-route monitoring was done with one BTEX sample taken over the entire route, which was about 1 h. The urban on-route was divided into three sub-routes representing different areas that the road was crossing, and a sample was taken while traveling on each sub-route [Figure 1]. Note that a round trip on the urban route took about 1.5 to 3 hours. The sampling time on each sub-route depended on the vehicle travelling speed which in turn depended on the congestion conditions on the sub-route. To represent the exposure levels on the entire urban route, a distance-weighted average was calculated from the measurements over three sub-routes[26]. On each monitoring day, three round trips were made, on either urban or suburban route, to capture the morning rush hours (started at 6:00-6:30 am), less congestion during noon (started at around 11:30 am) and evening rush hours (started at 16:00). The average of BTEX levels measured on these three round trips per route was used to represent the exposure levels on a monitoring day.

During the monitoring period, 380 hourly BTEX roadside samples were collected from the Din Daeng and 110 samples from the Phaholyothin Road. On-route urban (wet and dry season) and suburban monitoring (only dry season) yielded 186 and 30 round-trip samples, respectively. The BTEX results (with $PM_{2.5}$, NOx, SOx) were analyzed to assess the seasonal variation, the diurnal variations and the association with the hourly traffic flow, and the differences in pollution levels between two monitoring areas and between inside and outside vehicles[26]. The previous study suggested a high exposure to traffic-induced pollutants and recommended a comprehensive risk assessment.

QA/QC

QA/QC for BTEX sampling and analysis have been detailed in our previous publication[26]. Briefly, the sampling pump was calibrated with a soap film flowmeter for the designated flow rate (0.18 L/min). Benzene contamination in the carbon disulfide (CS_2) solvent was removed before it was used for sample extraction using concentrated sulfuric acid and nitric acid. The quality control (QC) samples included both field blanks and laboratory blanks, which were prepared and analyzed as detailed in our previous study[26], and the results indicated non-detected levels of toluene, ethylbenzene and xylenes. However, a low level of benzene was detected in several blank samples, suggesting some amount of the benzene contaminant (in the

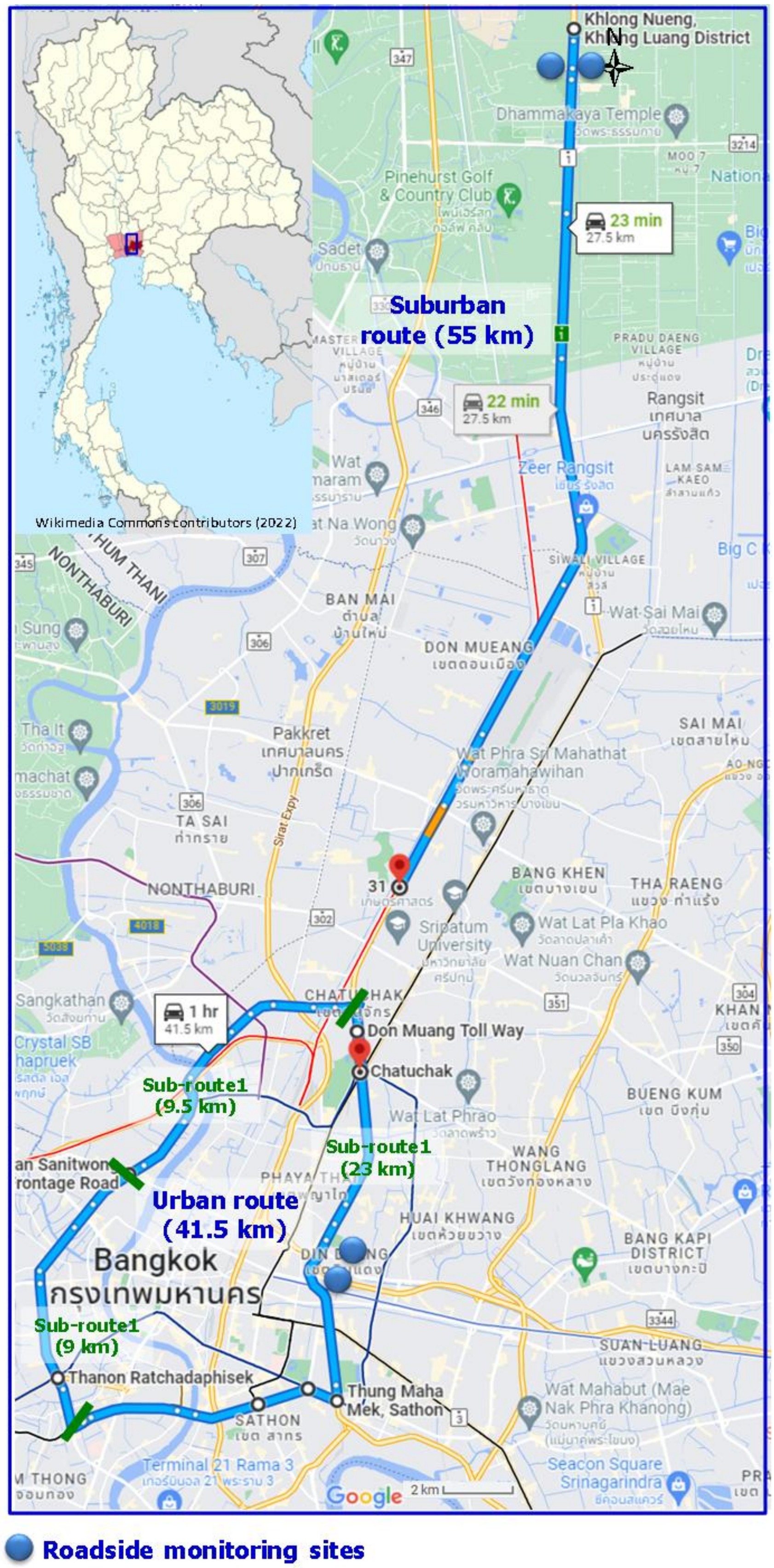

Figure 1. Map of sampling routes and roadside in the Bangkok Metropolitan Region.

solvent) still remained even after the clean-up process. The analytical results of the samples were accordingly corrected for the average level of benzene in the blank samples. To check for the potential breakthrough of BTEX during the sampling, 69 sampled tubes collected during rush hours, when the BTEX levels were likely the highest, were analyzed for the front and backup parts of the adsorbent. The results of the separate analyses for the front and backup adsorbent parts of each selected sampled tube confirmed that no breakthrough had occurred in the samples, based on the criteria provided by NIOSH[32] as detailed in our previous study[26]. The mixed standard of BTEX (Fluka manufacturer) was used to prepare calibration curves with 5 data points, and the determination coefficients (R^2) of the linear regression relationship was above 0.99 for every species. The minimum detectable quantity of the method was 0.2-0.3 ng, and the precision, i.e., the ratio between the standard deviation and the average value based on repeated injections of each sample, was 8%-13% for these compounds.

Health risk assessment

Three target groups were included for health risk assessment: drivers, passengers, and street vendors. The first group included van, pickup, and motorcycle drivers, with two microenvironments considered, i.e., driving (working) time on the routes and resting (waiting for the next service) at the roadside. The second group included passengers who traveled inside the van, sat in the open cargo bed of the pickup truck, or rode on the motorcycle. Two microenvironments were also considered for their exposure time, i.e., waiting time at the roadside at the pickup points or stations and traveling time in the vehicles. Finally, for the street vendors, the estimated time working at the roadside was used, i.e., only one microenvironment was considered. Supplementary Table 1 explains the inhalation exposure pathways of the studied groups. Note that with a focus on the traffic-induced BTEX, this study only considered these two related microenvironments for drivers and passengers, and one for street vendors. Thus, the exposure outside these microenvironments, e.g., at home, at work for passengers, may be significant but was excluded from the exposure assessment.

The BTEX exposure was calculated using the representative pollutant levels measured at the roadside and on-road traveling routes in urban and suburban areas. Equation 1 was used to calculate the daily doses (*DD*, mg/kg-day) of inhalation exposure for a target group[34].

$$DD = \frac{\Sigma(C_j)\times(IR)\times(EL_j)}{BW} \quad (1)$$

Where, C_j is the pollutant concentration (mg/m^3) in the microenvironment j, *IR* is the inhalation rate (m^3/h), EL_j is the exposure length (h/day) in the microenvironment j, and *BW* is the body weight (kg) of the target population group.

We included two scenarios for the health risk assessment, i.e., the average case and the worst case for both cancer and noncancer risks. Based on the BTEX measurement data from our previous study[26], we used the median or 50th percentile (P50) values of the BTEX concentrations for the average case, while the 95th percentile values (P95) were used for the worst case. Furthermore, the worst case was also considered with higher risk levels than the average case for other parameters. For example, the average case used an average inhalation rate of 20 m^3/day (0.83 m^3/hour), while the P95 case used an upper bound value of 30 m^3/day (1.25 m^3/hour)[35]. The exposure length was estimated based on Thai labor law[36] for drivers and street vendors. It was 8 hours (P50) and a maximum of 10 hours (P95). Thai labor law requires at least one hour of rest for the driver during the workday. The travel time on the road was applied to the passengers, which was 64-203 minutes for a one-way trip and 13 minutes for waiting for vehicles at the roadside[37]. Thai male and female body weights were 68.9 and 57.4 kg, respectively[38]. Using Equation 2, the lifetime average daily dose (*LADD*, mg/kg-day) was calculated[34].

$$LADD = \frac{(DD)\times(AF)\times(ED)\times(YF)}{TL} \quad (2)$$

Where *AF* indicates the absorption factor (100%)[34], *ED* represents the exposure duration (days), *YF* is the yearly factor, and *TL* defines the typical lifetime (days). The lifetime exposure duration of passengers and vendors was determined based on the Thai worker age with the working age from 15 to 59 years old; hence, the total working time is 45 years[39]. For drivers, the working age range is from 18 to 59 years old; hence, the total working time is 38 years[36]. According to the labor protection law, typically, there are 5 workdays per week, with an additional 6 days per week. Therefore, these workdays were applied for P50 (5 days) and P95 cases (6 days), respectively. Further, we assumed a working period of 50 weeks per year. The exposure levels of the van drivers and passengers were assessed separately for dry and wet seasons; therefore, the duration of the season was considered for adjusting the *LADD* of these groups, i.e., the wet season (5 months, i.e., $YF = 5/12$) and dry season (7 months, i.e., $YF = 7/12$). Whereas $YF = 1$ was used to calculate *LADD* for the other groups, which was determined using the annual average of BTEX levels. Thai males and females have 71.8 and 79.3 years of life expectancy, respectively[40]. The variables used to estimate exposure are summarized in Table 2.

Further, LADD results were used to assess the risk. The carcinogenic effect, i.e., leukemia, was assessed for the benzene exposure, while the noncancer risks, e.g., haematotoxicity and genotoxicity, were assessed for the exposure to all BTEX compounds. Using Equation 3, the integrated lifetime cancer risk *LCR* was calculated by multiplying the *LADD* by the slope factor (SF). The SF of benzene was calculated using the unit risk value of 7.8×10^{-6} per μg/m^3[41], as well as the inhalation rate and body weight[34,42]. For example, in the case of P50, the SF is 0.0269 $(mg/kg/day)^{-1}$ at a standard inhalation rate of 20 m^3/day and a male body weight of 68.9 kg. For general guidance, the United States EPA Clean Air Act requires that the *LCR* associated with pollutants in ambient air should not exceed certain levels, i.e., 1×10^{-6} as the most health-protective, 1×10^{-5} as the mid-point, and 1×10^{-4} as the least health-protective[9,10].

$$LCR = LADD \times SF \quad (3)$$

The noncancer risk for each BTEX compound was expressed as a hazard quotient (HQ) and calculated using Equation 4 for each considered population group. The hazard index (HI) was computed by summing up the HQ of all BTEX pollutants. The chronic inhalation reference concentrations (RfC) were obtained from the Integrated Risk Information System (IRIS) online database to assess the noncancer risk[43]. For benzene, toluene, ethylbenzene, and xylenes, the RfC values are 0.03 mg/m^3, 5 mg/m^3, 1 mg/m^3, and 0.1 mg/m^3, respectively. Based on the RfC, inhalation rate and body weight, the inhalation reference dose (RfD, mg/kg-day) was calculated[16,34,44-46]. For example, the RfD for benzene at a standard inhalation rate of 20 m^3/day and a male body weight of 68.9 kg is 0.0087 mg/kg-day. The noncancer HQ assumes a level of exposure below which sensitive populations are unlikely to experience adverse health effects. If the exposure level exceeds this threshold (i.e., LADD/RfD > 1), potential noncancer effects may be of concern.

$$HQ = \frac{LADD}{RfD} \quad (4)$$

RESULTS AND DISCUSSION

BTEX exposure levels in the study areas

A summary of the BTEX levels is given in Table 3[26]. As detailed in our previous publication[26], the roadside BTEX levels in the urban area were significantly higher than those measured in the suburban area. Higher levels were, in fact, recorded in the wet season, which was largely due to more traffic congestion during rainy weather on this road. The levels measured at the urban roadside have been found to strongly associate with hourly traffic flows, suggesting that traffic was the main source of the pollutants. On the suburban road, the BTEX also showed the association with hourly flows of the bus and the motorcycle. The on-route BTEX levels were significantly higher on the more congested urban route than on the suburban route suggesting more exposure. Higher general background pollution in the study area during the dry season explained the higher levels observed inside vehicles, i.e., the van, than in the wet season.

Toluene was the most prevalent BTEX pollutant at the roadside and the on-road routes [Table 3]. The average hourly concentration of toluene in the urban area during the wet season (30 μg/m^3) was higher than that in the dry season in both urban (17 μg/m^3) and suburban areas (14 μg/m^3). Compared to the free-flow highway in the suburbs, the congested urban road caused higher BTEX levels at the roadside. In addition, heavy traffic jams during the wet season contributed to the higher BTEX level compared to the dry season mentioned above[26].

In the urban area, the toluene concentrations in the van were higher during the dry season (84 μg/m^3) than in the wet season (47 μg/m^3). During the dry season in the urban area, the toluene concentration inside the pickup cabin (71 μg/m^3) was higher than in the open space of the pickup wagon (33 μg/m^3). A similar trend was also observed in the suburban area [Table 3]. A comparison between the vehicle types shows that during the dry season in the urban area, toluene levels inside the van (84 μg/m^3) were higher than inside the pickup (71 μg/m^3) and in the pickup wagon (33 μg/m^3). Furthermore, toluene levels on the suburban traveling route by motorcycle (39 μg/m^3) were higher than that inside the pickup cabin (33 μg/m^3) and pickup wagon (9.1 μg/m^3). A similar pattern to that observed for toluene was seen for benzene, ethylbenzene, and xylenes. Traffic congestions that slowed down the vehicle speeds, and ineffective A/C filtration for the closed vehicle's cabin explained the higher BTEX levels measured in the microenvironments[26]. The calculated P50 and P95 of the BTEX concentrations obtained from the measurements at each site/route are used for exposure assessment [Table 4].

Cancer risk

Benzene is classified as a human carcinogen (IARC group 1) based on sufficient evidence that it causes leukemia. The lifetime cancer risk of inhalation of benzene exposure is summarized in Table 5. The calculation results show that the average cancer risk (LCR_{50}) of male passengers ranged from 1.8E-06 to 1.0E-05, with in-van passengers having the highest risk. In the worst-case scenario (LCR_{95}) for in-van passengers, the cancer risk was 4.8E-05, which is interpreted that, on average, there are five cancer cases in 100,000 people exposed to this pollution level. For the drivers, the LCR_{50} ranged from 1.0E-05 to 1.9E-05, with pickup drivers in urban areas posing the most significant risk, with LCR_{95} of 7.2E-05. The maximum risk for street vendors was observed in the urban area, with a value of 2.4E-05.

Males were found to have a higher cancer risk than females across all population groups. Men have a shorter lifespan (71.8 years) than women (79.3 years), hence resulting in lower typical lifetime days (TL),

Table 2. Summary of the values used to calculate exposure and risk

Variable	Population groups	P50	P95	Unit
Inhalation rate	All	20	30	m3/day
Waiting time	Passengers, waiting at roadside	13	13	minutes
One-way travel time	Passengers, on-route, urban, wet season	100	140	minutes
	Passengers, on-route, urban, dry season	98	203	minutes
	Passengers, on-route, suburban, dry season	64	72	minutes
Working time	Drivers, driving on-route	7	9	hours/day
	Drivers, resting time at roadside	1	1	hours/day
	Street side trader, working at roadside	8	10	hours/day
Exposure Frequency	All	250	300	days/year
Exposure Duration	Passengers, street side vendors	45	45	years
	Drivers	38	38	years
Yearly factors	Van drivers and van passengers in dry season	7/12	7/12	unitless
	Van drivers and van passengers in wet season	5/12	5/12	unitless
Workdays in a week	All	5	6	days
Working week in a year	All	50	50	weeks
Body weight, man	All	68.9	68.9	kg
Body weight, woman	All	57.4	57.4	kg
Lifetime, man	All	71.8	71.8	years
Lifetime, woman	All	79.3	79.3	years

P50 and P95 denote the variables used in the average and worst-case scenarios, respectively.

Table 3. Summary of the BTEX levels, average and 1 standard deviation (μg/m^3), exposed by different population groups

Site/route	Season	Benzene	Toluene	Ethylbenzene	Xylenes
Roadside measurements (average for both sides of each road during the monitoring period)					
Urban (Din Daeng)	Wet	9.7 ± 4.5	30 ± 13	4.4 ± 2.3	11 ± 4.7
Urban (Din Daeng)	Dry	6.9 ± 2.9	17 ± 8.8	2.3 ± 1.2	5.9 ± 3.1
Suburban (Phaholyothin)	Dry	5.3 ± 3.1	14 ± 14	2.3 ± 1.7	3.7 ± 2.7
On-route measurements (average for whole route during monitoring period)					
Urban in van (driver)	Wet	14 ± 4.4	47 ± 16	6.9 ± 2.6	25 ± 11
Urban in van (driver)	Dry	26 ± 11	84 ± 41	9.4 ± 4.8	31 ± 16
Urban in pickup cabin (driver)	Dry	24 ± 9.0	71 ± 28	6.9 ± 2.5	22 ± 8.8
Urban pickup wagon (passengers)	Dry	13 ± 3.0	33 ± 11	3.4 ± 1.4	12 ± 4.6
Suburban in pickup cabin	Dry	14 ± 5.5	33 ± 13	3.5 ± 1.0	8.9 ± 2.9
Suburban pickup wagon	Dry	4.9 ± 1.6	9.1± 3.1	ND-1.7	2.8 ± 0.9
Suburban motorcycle	Dry	15 ± 4.0	39 ± 12	4.5 ± 1.4	14 ± 5.0

Source: Adapted from Kim Oanh *et al.* for the exposure assessment[26].

and with the assumption of the same working age span for both men and women, a higher lifetime average daily dose (LADD) for man was obtained. The range of LCR_{50} for all considered population groups was from 1.7E-06 to 1.9E-05, while that for LCR_{95} was from 3.3E-06 to 7.2E-05. Compared to the EPA Clean Air Act risk range (1.0E-06 - 1.0E-04), most of the exposed population groups had LCR_{50} above the lower value of the recommended range, i.e., 1.0E-06 but below the upper value of the range (1.0E-04). Note that the lower value of the EPA recommended range is the more health-protective level, whereas the upper value is the less health-protective level. The LCR_{50} of most of the exposed population groups was less than the midpoint of the EPA risk range (1.0E-05). The maximum cancer risk in the worst case LCR_{95} (7.2E-05)

Table 4. Air pollutant concentrations at the roadside and on-road measurements (μg/m^3) used for the average (P50) and worse case (P95) scenarios for risk assessment

Area	Season	Mode	Benzene		Toluene		Ethylbenzene		Xylene	
			P50	P95	P50	P95	P50	P95	P50	P95
Urban	Wet	roadside	9.4	16.7	29.7	51.3	3.9	8.5	10.3	18.0
		van-inside	15.2	26.6	47.0	96.8	7.4	15.9	24.6	61.2
	Dry	roadside	7.1	12.2	15.1	32.7	1.9	4.2	5.5	11.7
		van-inside	24.9	57.3	82.3	178.1	8.8	20.9	28.7	74.6
		Pickup-inside	22.0	55.5	66.3	151.7	6.7	15.3	19.6	52.1
		Pickup-outside	13.7	28.2	35.4	78.9	4.0	8.3	11.5	31.7
Suburban	Dry	roadside	4.7	12.7	9.5	44.6	1.7	5.2	2.7	9.9
		Pickup-inside	12.0	24.4	29.5	55.5	3.1	5.2	8.6	13.0
		Pickup-outside	5.2	6.9	8.9	13.8	1.7	1.7	3.1	3.8
		Motorcycle	15.7	20.0	41.0	49.3	4.9	5.7	14.5	18.8

obtained for the most exposed group of pickup drivers was also below the upper value of the EPA recommended range. Compared to the target population groups, the average cancer risk was found to be higher in the driver group (1.5E-05) than in the vendor (6.8E-06) and passenger (5.6E-06) groups.

It is important to note that this study considered the cancer risk posed by benzene exposure while spending time in only certain microenvironments, i.e., on the roadside and on travel routes in the study areas. There is also a risk of exposure to benzene while people spend time in other microenvironments in their daily life, i.e., at home and in the workplace, and hence the results of LCR may be underestimated. Further, it is worth mentioning that for the passenger group, this study only considered the exposure duration (ED) coinciding with their working age span, i.e., with the work-related trips; hence, the risk of exposure associated with traveling outside the working age was not included. Thus, future studies should investigate the exposure for 24 hours per day and for the lifetime of all target population groups to improve the results.

Figure 2A (right panel) compares the cancer risk due to occupational benzene exposure of three different target groups obtained by this study (driver, passenger and street vendor) and more than 30 exposed populations in different microenvironments reported in 26 other studies worldwide. More details of the studies used for the comparison are presented in Supplementary Table 2. All the studies reported risks above the lower value of the EPA recommended range (1.0E-06), except for one study in Iran, which reported a LCR of 3.9E-07 for the adult inhabitants in Tehran, Iran[47]. Compared to the upper value of the EPA recommended range (1.0E-04), about 2/3 of the reported groups had the LCR below that and the rest 1/3 (11 groups) are above that. The highest LCR value of 1.6E-02 was reported for tanker loading workers in Iran[13].

The LCR values obtained for the three groups in this study, namely from the highest of 1.5E-05 for the drivers to 6.8E-06 for street vendors and the least of 5.6E-06 for passengers, thus were in the middle of the reported range. Our LCR values perhaps are more representative of the normal urban microenvironments in BMR, whereas the occupational exposure to benzene reported for the workers (tanker loading and tank-gauging) *etc.*,[13] were much higher.

Noncancer risk

The hazard quotient and hazard index of inhalation exposure to BTEX are summarized in Table 5. Among the BTEX compounds, benzene posed the greatest risk to the exposed people at the roadside and along the

Table 5. Summary of the carcinogenic risks and hazard quotients associated with BTEX inhalation exposure

	Population groups	Working area	LCR50	LCR95	Benzene		Toluene		Ethylbenzene		Xylene		HIBTEX	
					HQ50	HQ95	HQ50	HQ95	HQ50	HQ95	HQ50	HQ95	HQ50	HQ95
Male	Van driver	Urban	1.8E-05	5.9E-05	7.8E-02	2.5E-01	1.5E-03	4.9E-03	9.1E-04	3.2E-03	3.0E-02	1.2E-01	1.1E-01	3.7E-01
	Pickup driver	Urban	1.9E-05	7.2E-05	8.1E-02	3.1E-01	1.4E-03	5.1E-03	7.4E-04	2.6E-03	2.2E-02	8.7E-02	1.0E-01	4.0E-01
		Suburban	1.0E-05	3.3E-05	4.5E-02	1.4E-01	6.5E-04	2.0E-03	3.5E-04	9.4E-04	9.5E-03	2.3E-02	5.5E-02	1.7E-01
	Motorcycle driver	Suburban	1.4E-05	2.7E-05	5.8E-02	1.2E-01	9.0E-04	1.8E-03	5.4E-04	1.0E-03	1.6E-02	3.2E-02	7.5E-02	1.5E-01
	In-van passengers	Urban	1.0E-05	4.8E-05	4.3E-02	2.0E-01	8.3E-04	3.9E-03	5.0E-04	2.5E-03	1.6E-02	9.0E-02	6.1E-02	3.0E-01
	Pick up passengers	Urban	6.7E-06	3.3E-05	2.9E-02	1.4E-01	4.4E-04	2.4E-03	2.5E-04	1.2E-03	7.1E-03	4.7E-02	3.6E-02	1.9E-01
		Suburban	1.8E-06	3.7E-06	7.8E-03	1.6E-02	8.3E-05	2.3E-04	7.8E-05	1.4E-04	1.4E-03	2.9E-03	9.4E-03	1.9E-02
	Motorcycle passengers	Suburban	5.0E-06	9.0E-06	2.1E-02	3.8E-02	3.3E-04	5.9E-04	2.0E-04	3.4E-04	5.7E-03	1.1E-02	2.7E-02	5.0E-02
	Street side trader	Urban	9.0E-06	2.4E-05	3.8E-02	1.0E-01	6.1E-04	1.7E-03	3.9E-04	1.3E-03	1.1E-02	3.1E-02	5.0E-02	1.3E-01
		Suburban	5.2E-06	2.1E-05	2.2E-02	9.1E-02	2.7E-04	1.9E-03	2.4E-04	1.1E-03	3.9E-03	2.1E-02	2.7E-02	1.1E-01
Female	Van driver	Urban	1.6E-05	5.3E-05	7.0E-02	2.3E-01	1.4E-03	4.4E-03	8.2E-04	2.9E-03	2.7E-02	1.0E-01	9.9E-02	3.4E-01
	Pickup driver	Urban	1.7E-05	6.5E-05	7.3E-02	2.8E-01	1.3E-03	4.6E-03	6.7E-04	2.3E-03	2.0E-02	7.9E-02	9.5E-02	3.7E-01
		Suburban	9.5E-06	3.0E-05	4.0E-02	1.3E-01	5.9E-04	1.8E-03	3.2E-04	8.5E-04	8.6E-03	2.1E-02	5.0E-02	1.5E-01
	Motorcycle driver	Suburban	1.2E-05	2.5E-05	5.2E-02	1.1E-01	8.1E-04	1.6E-03	4.9E-04	9.3E-04	1.4E-02	2.9E-02	6.8E-02	1.4E-01
	In-van passengers	Urban	9.1E-06	4.3E-05	3.9E-02	1.8E-01	7.5E-04	3.5E-03	4.6E-04	2.3E-03	1.5E-02	8.2E-02	5.5E-02	2.7E-01
	Pick up passengers	Urban	6.0E-06	3.0E-05	2.6E-02	1.3E-01	4.0E-04	2.1E-03	2.2E-04	1.1E-03	6.5E-03	4.3E-02	3.3E-02	1.7E-01
		Suburban	1.7E-06	3.3E-06	7.1E-03	1.4E-02	7.5E-05	2.0E-04	7.1E-05	1.2E-04	1.3E-03	2.6E-03	8.5E-03	1.7E-02
	Motorcycle passengers	Suburban	4.5E-06	8.1E-06	1.9E-02	3.5E-02	3.0E-04	5.3E-04	1.8E-04	3.1E-04	5.2E-03	9.6E-03	2.5E-02	4.5E-02
	Roadside vendors	Urban	8.1E-06	2.1E-05	4.2E-02	1.1E-01	6.6E-04	1.9E-03	4.2E-04	1.4E-03	1.2E-02	3.3E-02	5.4E-02	1.5E-01
		Suburban	4.7E-06	1.9E-05	2.4E-02	9.9E-02	3.0E-04	2.1E-03	2.6E-04	1.2E-03	4.2E-03	2.3E-02	2.9E-02	1.2E-01

LCR: Lifetime cancer risk; HQ: Hazard Quotient; HI: Hazard Index; LCR, HQ and HI values are unitless; HI_{BTEX}: Hazard index of benzene, toluene, ethylbenzene and xylene; HQ_{50}: Hazard quotient for the average case; HQ_{95}: Hazard quotient for the worst case.

travel route. The benzene hazard quotient for males was from 7.8E-03 to 8.1E-02 for the average case (HQ_{50}) and 1.6E-02 to 3.1E-01 for the worst case (HQ_{95}). The hazard index values, i.e., the sum of HQ of all BTEX species, for males ranged from 9.4E-03 to 1.1E-01 for the average case (HI_{50}) and from 1.9E-02 to 4.0E-01 for the worst case (HI_{95}). The van passengers had the highest risk (6.1E-02, average) among the passenger group, while the van drivers in the urban areas had the highest risk (1.1E-01) among the driver group. People in cities were more at risk than those in suburban areas due to the exposure to higher pollution levels. However, all the HI values were below 1.0; hence, none of the target populations were at risk of BTEX exposure above the recommended threshold (HI = 1.0).

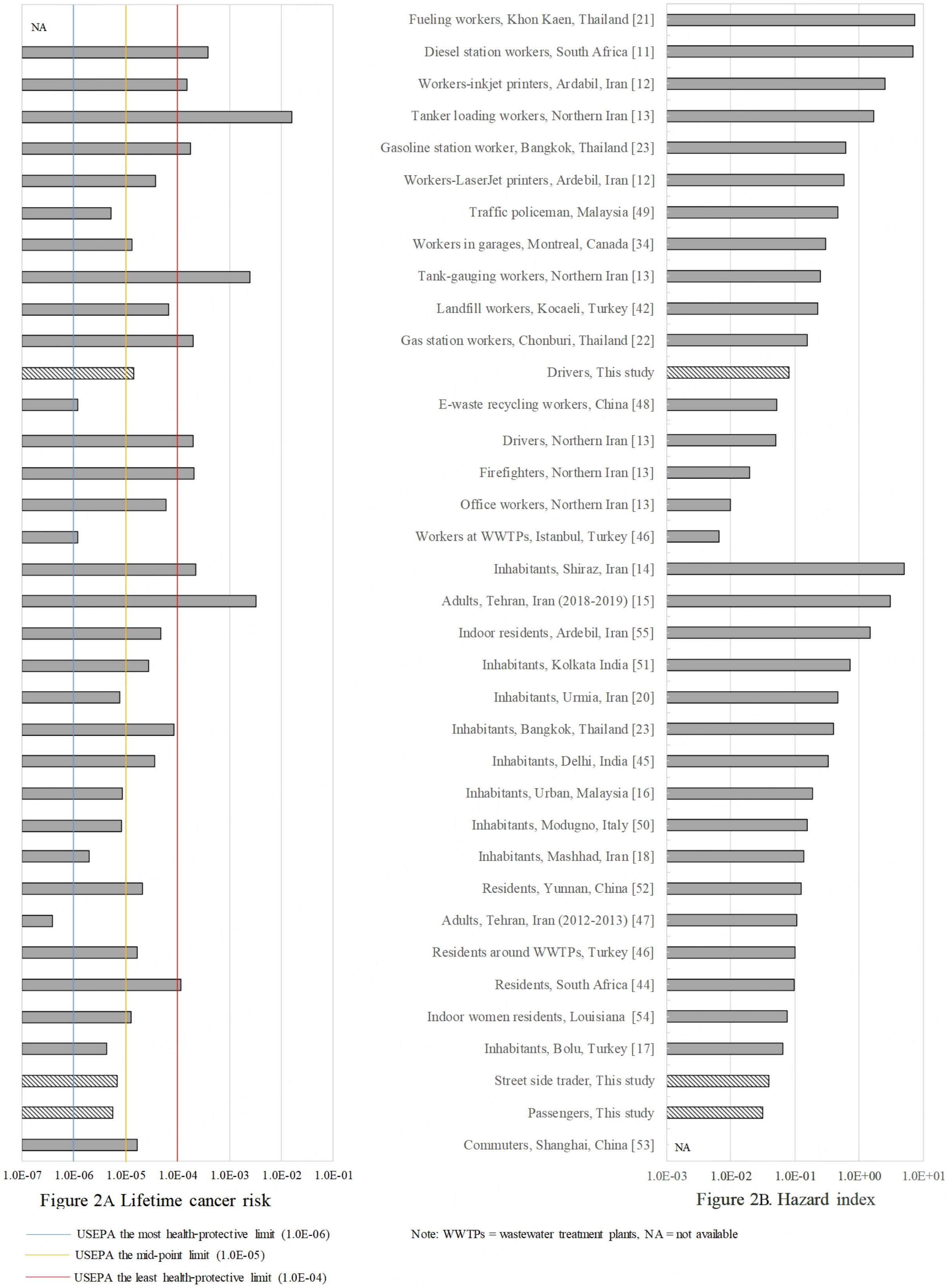

Figure 2. Comparison of cancer and noncancer risks of BTEX inhalation exposure.

Figure 2B compares the HI values obtained in this study with other studies (more details are in Supplementary Table 2). Most of the studies reported HI < 1.0, except for four exposed groups in the studies for occupational exposure in Iran[12-13], South Africa[11] and the workers at refueling stations in Khon Kaen, Thailand[21]. As seen above, the HI values found for the three target groups in our study were the highest for drivers (8.2E-02), followed by street vendors (4.2E-02), and the lowest for passengers (3.2E-02), which are all in the middle of the range of the presented results. The minimum HI presented in Figure 2B of 6.7E-03 was found for the adult workers (8 h/day) at a wastewater treatment plant in Turkey[46], while the maximum HI of 7.3 was reported for the workers at refueling gasoline stations in Khon Kaen, Thailand[21].

Uncertainty of the risk assessment results

Several assumptions used in the risk calculation process contribute to the uncertainty of exposure and risk results. First, the area monitoring of BTEX obtained at two certain roadsides was used to represent the urban and suburban exposure, respectively. Similarly, the on-route monitoring was only done for two selected routes and only for selected vehicles and consequently may not capture the overall pictures of the driver and passenger exposure levels. The monitoring, therefore, should also be done for taxi and bus passengers. More fixed roadsides and traveling routes should also be included in the monitoring program, which should cover both dry and wet seasons in the study area.

Uncertainty in parameter estimates can also result from the use of surrogate data. In the study, we used an indirect approach to estimate several parameters. A standard inhalation rate was assumed for the exposure assessment. The literature review provided body weight, roadside waiting time, and working hours; although relevant for Thai people, they were not directly obtained from the study population. These parameters may differ between individuals and activities and change over time hence should be obtained by conducting specific surveys for the study groups.

The most important factor causing the uncertainty of the results is related to the limited number of microenvironments considered in this study. Drivers, for example, may be exposed to BTEX at home and elsewhere outside their workplace. Passengers are also exposed to BTEX at home, at their workplace, *etc.*; hence, these microenvironments should be considered to provide a full picture of the risk due to BTEX exposure that people encounter during their lifetime. Our results, therefore, are relevant for the roadside and on-route exposure that are more related to traffic emissions. Finally, in the risk assessment, health outcomes were only considered from the exposure to BTEX but not to other pollutants, such as $PM_{2.5}$, heavy metals *etc.*, that co-exist in the air. For benzene cancer risk, co-exposure to styrene has been linked to an increased risk of leukemia[5].

CONCLUSIONS

Considering only two microenvironments closely related to traffic pollution in daily life, the lifetime cancer risk, both average and the worst-case scenarios, of the target population groups of drivers, passengers, and street vendors in BMR found in the study ranged from 2 to 19 per million. For all target groups, the cancer risk exceeded the more health-protective risk limit but was lower than the less-protective limit of the EPA recommended range. Males were found to have a higher cancer risk than females in their typical lifetime, and urban inhabitants had a higher cancer risk than suburban inhabitants because of the higher BTEX pollution in the urban areas. The drivers were more at risk of developing cancer than the street vendors and passengers.

Toluene was found in the highest concentrations at the roadside and on the traveling route, but benzene poses the greatest noncancer risk. Pickup drivers in the urban study area had the highest noncancer risk, with a maximum HI of 0.4, which is less than the recommended threshold of 1.0. Thus, all three target groups in this study had noncancer risk of HI < 1.0 resulting from the exposure to BTEX during the time spent at the roadside and along the travel route during their lifetime.

The results of this study only reflected the exposure in the considered two microenvironments of roadside and traveling route and hence do not cover the total risks associated with the BTEX, which also occur in other microenvironments of their daily life. Future studies should include exposure in other microenvironments to obtain complete daily exposure and improve the results. Uncertainty in the results of the risk assessment can be reduced by including more monitoring data and by including local surveys to collect the relevant parameters from the study population for risk calculation.

DECLARATIONS

Authors' contributions

Conceptualization and methodology, data collection and analysis, original draft preparation and revision, reviewing and editing the paper content: Kongpran J

Conceptualization and methodology, reviewing, editing and finalizing the paper content: Kim Oanh NT

Data collection and analysis, reviewing the paper: Hang NT

Availability of data and materials

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

All authors have given consent to publish this paper in the Journal of Environmental Exposure Assessment.

REFERENCES

1. World Health Organization. Compendium of WHO and other UN guidance on health and environment, 2022 update. Available from: https://apps.who.int/iris/handle/10665/352844[Last accessed on 23 Oct 2022].
2. Alford KL, Kumar N. Pulmonary health effects of indoor volatile organic compounds-a meta-analysis. *Int J Environ Res Public Health* 2021;18:1578. DOI PubMed PMC
3. Maung TZ, Bishop JE, Holt E, Turner AM, Pfrang C. Indoor air pollution and the health of vulnerable groups: a systematic review focused on particulate matter (pm), volatile organic compounds (VOCs) and their effects on children and people with pre-existing lung disease. *Int J Environ Res Public Health* 2022;19:8752. DOI PubMed PMC
4. Montero-Montoya R, López-Vargas R, Arellano-Aguilar O. Volatile organic compounds in air: sources, distribution, exposure and associated illnesses in children. *Ann Glob Health* 2018;84:225-38. DOI PubMed PMC
5. International Agency for Research on Cancer. Benzene Volume 120. Available from: https://publications.iarc.fr/576 [Last accessed on 23 Feb 2023].
6. U.S. Environmental Protection Agency. Toxicological Review of Toluene. Available from: https://www.epa.gov/sites/default/files/

2014-03/documents/toluene_toxicology_review_0118tr_3v.pdf [Last accessed on 23 Feb 2023].
7. United States Environmental Protection Agency. Chemical assessment summary- ethylbenzene; CASRN 100-41-4. Available from: https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0051_summary.pdf [Last accessed on 23 Feb 2023].
8. United States Environmental Protection Agency. Chemical assessment summary-xylenes; CASRN 1330-20-7. Available from: https://iris.epa.gov/static/pdfs/0270_summary.pdf [Last accessed on 23 Feb 2023].
9. World Health Organization. Air quality guidelines for Europe (Second edition). Available from: https://apps.who.int/iris/handle/10665/107335 [Last accessed on 23 Feb 2023].
10. Loren Raun. Benzene Risk: Determining carcinogenic health risk concentration levels for benzene in ambient air at EPA, TCEQ and the City of Houston. Available from: http://www.greenhoustontx.gov/reports/benzenerisk.pdf [Last accessed on 23 Feb 2023].
11. Moolla R, Curtis CJ, Knight J. Occupational exposure of diesel station workers to BTEX compounds at a bus depot. *Int J Environ Res Public Health* 2015;12:4101-15. DOI PubMed PMC
12. Rostami R, Fazlzadeh M, Babaei-Pouya A, et al. Exposure to BTEX concentration and the related health risk assessment in printing and copying centers. *Environ Sci Pollut Res Int* 2021;28:31195-206. DOI PubMed
13. Heibati B, Pollitt KJG, Karimi A, et al. BTEX exposure assessment and quantitative risk assessment among petroleum product distributors. *Ecotoxicol Environ Saf* 2017;144:445-9. DOI PubMed
14. Dehghani M, Fazlzadeh M, Sorooshian A, et al. Characteristics and health effects of BTEX in a hot spot for urban pollution. *Ecotoxicol Environ Saf* 2018;155:133-43. DOI PubMed
15. Kermani M, Asadgol Z, Gholami M, et al. Occurrence, spatial distribution, seasonal variations, potential sources, and inhalation-based health risk assessment of organic/inorganic pollutants in ambient air of Tehran. *Environ Geochem Health* 2021;43:1983-2006. DOI PubMed
16. Latif MT, Abd Hamid HH, Ahamad F, et al. BTEX compositions and its potential health impacts in Malaysia. *Chemosphere* 2019;237:124451. DOI PubMed
17. Dörter M, Mağat-Türk E, Döğeroğlu T, et al. An assessment of spatial distribution and atmospheric concentrations of ozone, nitrogen dioxide, sulfur dioxide, benzene, toluene, ethylbenzene, and xylenes: ozone formation potential and health risk estimation in Bolu city of Turkey. *Environ Sci Pollut Res Int* 2022;29:53569-83. DOI PubMed
18. Alahabadi A, Fazeli I, Rakhshani MH, Najafi ML, Alidadi H, Miri M. Spatial distribution and health risk of exposure to BTEX in urban area: a comparison study of different land-use types and traffic volumes. *Environ Geochem Health* 2021;43:2871-85. DOI PubMed
19. Phuc NH, Kim Oanh NT. Determining factors for levels of volatile organic compounds measured in different microenvironments of a heavy traffic urban area. *Sci Total Environ* 2018;627:290-303. DOI PubMed
20. Mohammadi A, Ghassoun Y, Löwner MO, et al. Spatial analysis and risk assessment of urban BTEX compounds in Urmia, Iran. *Chemosphere* 2020;246:125769. DOI PubMed
21. Chaiklieng S. Risk assessment of workers' exposure to BTEX and hazardous area classification at gasoline stations. *PLoS One* 2021;16:e0249913. DOI PubMed PMC
22. Yimrungruang D, Cheevaporn V, Boonphakdeeb T, Watchalayann P, Helander HF. Characterization and health risk assessment of volatile organic compounds in gas service station workers. *Environmentasia* 2008;2:21-9. DOI
23. Tunsaringkarn T, Siriwong W, Rungsiyothin A, Nopparatbundit S. Occupational exposure of gasoline station workers to BTEX compounds in Bangkok, Thailand. *Int J Occup Environ Med* 2012;3:117-25. PubMed
24. Pollution Control Department. Summary of the situation of volatile organic compounds (VOCs) in 2019 (in Thai). Available from: https://www.pcd.go.th/maptapoot/page/9 [Last accessed on 23 Feb 2023].
25. Songpun N, Chaiklieng S, Preuktharatikul V. Comparison of benzene exposure among occupations at gasoline service stations in Khon Kaen province (in Thai). *PHJBUU* 2020;15:26-35. DOI
26. Kim Oanh N, Kongpran J, Hang N, et al. Characterization of gaseous pollutants and PM2.5 at fixed roadsides and along vehicle traveling routes in Bangkok Metropolitan Region. *Atmospheric Environment* 2013;77:674-85. DOI PubMed
27. Wikimedia Commons contributors. File:Thailand Bangkok and vicinity.svg. Available from: https://commons.wikimedia.org/w/index.php?title=File:Thailand_Bangkok_and_vicinity.svg&oldid=679850278.
28. Department of Provincial Administration. Official statistics registration systems (in Thai). Available from: https://stat.bora.dopa.go.th/stat/statnew/statMONTH/statmonth/#/view [Last accessed on 23 Dec 2022].
29. Pollution Control Department. The state of air and noise pollution in Thailand 2021 (in Thai). Available from: https://www.pcd.go.th/wp-content/uploads/2022/11/pcdnew-2022-11-01_07-34-54_842781.pdf [Last accessed on 23 Dec 2022].
30. Narita D, Oanh NTK, Sato K, Huo M, Permadi DA, Chi NNH, Ratanajaratroj T, Pawarmart I. Pollution characteristics and policy actions on fine particulate matter in a growing asian economy: the case of Bangkok Metropolitan Region. *Atmosphere* 2019;10:227. DOI
31. Chirasophon S, Pochanart P. The Long-term Characteristics of PM10 and PM2.5 in Bangkok, Thailand. *Asian J Atmos Environ* 2020;14:73-83. DOI
32. The National Institute for Occupational Safety and Health. Hydrocarbons aromatic 1501. Available from: https://www.cdc.gov/niosh/docs/2003-154/pdfs/1501.pdf [Last accessed on 23 Feb 2023].
33. Oanh N, Martel M, Pongkiatkul P, Berkowicz R. Determination of fleet hourly emission and on-road vehicle emission factor using integrated monitoring and modeling approach. *Atmos Res* 2008;89:223-32. DOI

34. Badjagbo K, Loranger S, Moore S, Tardif R, Sauvé S. BTEX Exposures among Automobile Mechanics and Painters and Their Associated Health Risks. *Hum Ecol Risk Assess* ;16:301-16. DOI
35. U.S. Environmental Protection Agency. Risk assessment guidance for superfund volume i human health evaluation manual (part A). Available from: https://epa-prgs.ornl.gov/radionuclides/HHEMA.pdf [Last accessed on 23 Feb 2023].
36. Road Safety Research Center. Working hours analysis on Labor's work in the New Year's tragedy (in Thai). Available from: https://www.roadsafetythai.org/content/doc_20181211170426.pdf [Last accessed on 23 Feb 2023].
37. Kannikar Saengsurisri. Consumers' Attitudes and Behavior toward the Transit Van Service of Bangkok Mass Transit of Authority (BMTA). A Case Study of Victory Monument Area: Srinakharinwirot University; 2003 (in Thai). Available from: http://thesis.swu.ac.th/swuthesis/Mark/Kannikar_S.pdf [Last accessed on 23 Feb 2023].
38. National Science and Technology Development Agency. Size Thailand (in Thai). Available from: http://waa.inter.nstda.or.th/stks/pub/2012/20120417-SizeThailand.pdf [Last accessed on 23 Feb 2023].
39. National Statistical Office. Report on population characteristics, the 2015-2016 survey of population change (in Thai). Available from: http://www.nso.go.th/sites/2014/DocLib13/Forms/AllItems.aspx [Last accessed on 23 Feb 2023].
40. Thailand Development Research Institute. TDRI report (in Thai). Available from: https://tdri.or.th/wp-content/uploads/2019/08/wb152.pdf [Last accessed on 23 Feb 2023].
41. U.S. Environmental Protection Agency. Chemical assessment summary-benzene; CASRN 71-43-2. Available from: https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0276_summary.pdf [Last accessed on 23 Feb 2023].
42. Durmusoglu E, Taspinar F, Karademir A. Health risk assessment of BTEX emissions in the landfill environment. *J Hazard Mater* 2010;176:870-7. DOI PubMed
43. U.S. Environmental Protection Agency. IRIS Assessments. Available from: https://iris.epa.gov/AtoZ/?list_type=alpha [Last accessed on 23 Feb 2023].
44. Masekameni MD, Moolla R, Gulumian M, Brouwer D. Risk Assessment of Benzene, Toluene, Ethyl Benzene, and Xylene Concentrations from the Combustion of Coal in a Controlled Laboratory Environment. *Int J Environ Res Public Health* 2018;16:95. DOI PubMed PMC
45. Mehta D, Hazarika N, Srivastava A. Diurnal variation of BTEX at road traffic intersection points in Delhi, India: source, ozone formation potential, and health risk assessment. *Environ Sci Pollut Res Int* 2020;27:11093-104. DOI PubMed
46. Ulutaş K, Kaskun S, Demir S, Dinçer F, Pekey H. Assessment of H_2S and BTEX concentrations in ambient air using passive sampling method and the health risks. *Environ Monit Assess* 2021;193:399. DOI PubMed
47. Miri M, Rostami Aghdam Shendi M, Ghaffari HR, et al. Investigation of outdoor BTEX: concentration, variations, sources, spatial distribution, and risk assessment. *Chemosphere* 2016;163:601-9. DOI PubMed
48. Liu R, Ma S, Chen D, et al. Human exposure to BTEX emitted from a typical e-waste recycling industrial park: External and internal exposure levels, sources, and probabilistic risk implications. *J Hazard Mater* 2022;437:129343. DOI PubMed
49. Fandi NFM, Jalaludin J, Latif MT, Hamid HHA, Awang MF. BTEX exposure assessment and inhalation health risks to traffic policemen in the Klang Valley Region, Malaysia. *Aerosol Air Qual Res* 2020;20:1922-37. DOI
50. Amodio M, de Gennaro G, Marzocca A, Trizio L, Tutino M. Assessment of impacts produced by anthropogenic sources in a little city near an important industrial area (Modugno, Southern Italy). *Sci World J* 2013;2013:150397. DOI PubMed PMC
51. Dutta C, Som D, Chatterjee A, Mukherjee AK, Jana TK, Sen S. Mixing ratios of carbonyls and BTEX in ambient air of Kolkata, India and their associated health risk. *Environ Monit Assess* 2009;148:97-107. DOI PubMed
52. Qin N, Zhu Y, Zhong Y, et al. External exposure to BTEX, internal biomarker response, and health risk assessment of nonoccupational populations near a coking plant in southwest China. *Int J Environ Res Public Health* 2022;19:847. DOI PubMed PMC
53. Gong Y, Wei Y, Cheng J, Jiang T, Chen L, Xu B. Health risk assessment and personal exposure to Volatile Organic Compounds (VOCs) in metro carriages - a case study in Shanghai, China. *Sci Total Environ* 2017;574:1432-8. DOI PubMed
54. Wickliffe JK, Stock TH, Howard JL, et al. Increased long-term health risks attributable to select volatile organic compounds in residential indoor air in southeast Louisiana. *Sci Rep* 2020;10:21649. DOI PubMed PMC
55. Mokammel A, Rostami R, Niazi S, Asgari A, Fazlzadeh M. BTEX levels in rural households: Heating system, building characteristic impacts and lifetime excess cancer risk assessment. *Environ Pollut* 2022;298:118845. DOI PubMed