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The concentration of BTEX in selected urban areas of Malaysia during the COVID-19 pandemic lockdown

Nor Syamimi Sufiera Limi Hawari a, Mohd Talib Latif a,b,*, Haris Hafizal Abd Hamid a, Teoh Hwai Leng a, Murnira Othman c, Anis Asma Ahmad Mohtar a, Azliyana Azhari d,c, Doreena Dominick f,g

a Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
b Department of Environmental Health, Faculty of Public Health, Universitas Airlangga, 60115 Surabaya, Indonesia
c Institute for Environment and Development (LESTARI), Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
d Monash Climate Change Communication Research Node, School of Arts and Social Sciences, Monash University Malaysia, 47500 Bandar Sunway, Selangor Darul Ehsan, Malaysia
e Center for Research in Development, Social and Environment, Faculty of Social Science and Humanities, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia
f Centre for Atmospheric Chemistry, University of Wollongong, Wollongong, NSW 2522, Australia
g School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

ABSTRACT

Volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene and xylene (BTEX) are air pollutants that harm human health. This study aims to identify BTEX concentrations before the lockdown known as the Movement Control Order was imposed (BMCO), during the implementation of the Movement Control Order (MCO), and then during the Conditional Movement Control Order (CMCO). These orders were introduced during the COVID-19 pandemic in Malaysia. The study utilised data measured by the continuous monitoring of BTEX using online gas chromatography instruments located at three urban area stations. The results showed that the BTEX concentrations reduced by between 38% and 46% during the MCO compared to the BMCO period. The reduction of human mobility during the MCO and CMCO influenced the lower BTEX concentrations recorded at a station within the Kuala Lumpur area. The results of the BTEX diagnostic ratios and principal component analysis showed that the major source of BTEX, especially during the BMCO and CMCO periods, was motor vehicle emissions. Further investigation, using correlation analysis and polar plots, showed that the BTEX concentrations were also influenced by meteorological variables such as wind speed, air temperature and relative humidity.

1. Introduction

Volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene and xylene (BTEX) are important in atmospheric...
chemistry because they are major contributors to the formation of surface ozone and other photochemical oxidants (Kalabokas et al., 2001; Kim et al., 2020). BTEX are mainly emitted by anthropogenic sources such as motor vehicles and industrial emissions. Moreover, BTEX are classified as hazardous air pollutants (HAPs), which present health risks to humans (Presto et al., 2016; Mazaheri Tehrani et al., 2020). Of the BTEX compounds, benzene is the most hazardous to humans, having carcinogenic effects. Benzene concentrations recorded in Kuala Lumpur, Malaysia, have been reported as higher than the value recommended by the European Union (EU) (5 μg m⁻³) for the one year average. A high concentration of benzene in Kuala Lumpur has the potential to contribute to a higher cancer risk of one person per one million population (> 1 × 10⁻⁶) (Latif et al., 2019; Niu et al., 2022).

BTEX concentrations were found to be lower in several areas as a result of the lockdown imposed during the COVID-19 pandemic (Resmi et al., 2020; Pakkattil et al., 2021; Wang et al., 2021). Wang et al. (2021) reported that average VOC concentrations, including BTEX, were reduced by half during the lockdown period compared to the pre-lockdown period in Nanjing, China. Another recent study by Pakkattil et al. (2021), undertaken in six major Indian metro cities, showed that BTEX concentrations were significantly reduced during the lockdown. The study suggests that the reduction in the use of motor vehicles in cities during lockdown resulted in lower BTEX concentrations in ambient air. A study by Kerimray et al. (2020) in Almaty, Kazakhstan, however, showed different results. Benzene and toluene concentrations were found to have been elevated during the lockdown due to coal-related combustion activities, such as those from power plants, households, waste burning, bath-houses and bus-fleet stations. Ratios between the concentrations for each BTEX compound have been used to discern the potential sources of BTEX. For example, during the lockdown imposed due to the COVID-19 pandemic, the toluene/benzene ratio was found to be below the value of one, thus indicating a lower influence by motor vehicles during the lockdown (Kerimray et al., 2020).

In order to control the spread of the COVID-19 outbreak, the Malaysian government announced the implementation of a lockdown, or Movement Control Order (MCO), which was imposed from 18th March 2020 to 3rd May 2020. The impact of movement restrictions during the MCO resulted in a reduced number of vehicles on the road and minimised industrial activity. As a result, the concentrations of criteria pollutants (PM₁₀, PM₂.₅, CO, O₃ and NO₂) in Malaysia were reported to have decreased during the MCO period (Abdullah et al., 2020; Ash’aari et al., 2020; Mohd Nadzir et al., 2020; Latif et al., 2021). Similarly, during the lockdown period or MCO implementation, a reduction in major air pollutants was reported in many other locations, such as in China (Wang and Su, 2020; Zhu et al., 2020), Italy (Collivignarelli et al., 2020), Singapore (Li and Tartarini, 2020) and Southeast Asia (Kanniah et al., 2020). According
to Faridi et al. (2021), this decrease is predominantly due to a significant drop in vehicular traffic and drastically reduced population mobility.

This study aims to determine the BTEX concentrations in Malaysia before the movement control order (BMCO), during lockdown or the movement control order (MCO), and then during the conditional movement control order (CMCO). This study also aims to investigate the contribution of motor vehicle emissions as well as industrial activities on BTEX concentrations when economic and outdoor activities in Malaysia were restricted.

2. Methodology

2.1. Study area

The three stations in this study are located in the urban areas of Shah Alam, Cheras and Seremban as shown in Fig. 1. The stations are administered by a company that monitors air quality on behalf of the Malaysian Department of the Environment (DOE), Pakar Scieno TW Sdn Bhd (PSTW). These stations are located in the central-west area of Peninsular Malaysia. The three locations of Shah Alam, Cheras and Seremban were chosen to represent urban areas in the central region of the Malaysian Peninsula. This region is the central economic hub in Malaysia. All of these stations are in urban areas situated in the largest conurbation area, Kuala Lumpur's Extended Mega Urban Region (Halim et al., 2020).

Shah Alam and Cheras are situated in the state of Selangor and the Federal Territory of Kuala Lumpur, respectively, which are considered to be the most developed states in Malaysia. Kuala Lumpur is the capital city of Malaysia, and the population of Kuala Lumpur is 1.77 million (DOSM, 2021a). The Cheras station is situated near the expressway and residential area in the Kuala Lumpur urban environment. The Shah Alam station is situated in residential and industrial areas with a population of 543,000, as reported in the Population and Housing Census of Malaysia (2010). Meanwhile, the Seremban station is located within the capital state of Negeri Sembilan, south of Kuala Lumpur. This station is situated near residential and industrial areas with a population of 514,000, as reported in the Population and Housing Census of Malaysia (2010).

2.2. Air quality and meteorological data acquisition

The BTEX data were obtained from the DOE for five months (January to May 2020). The BTEX data were among 30 VOC ozone precursors monitored by the DOE using an online gas chromatography analyser (Model GC BTX 5000, AMA Instruments, Germany). The online gas chromatography analyser was equipped with a flame ionisation detector (FID) and AMAsep-1 column (30 m, 0.32 mm ID, 1.5 μm film). The monitoring was set to measure VOCs with a sampling interval of 1 h. Routine quality control (QC) was performed using 10 ppb VOC standard gas to validate the instrument’s performance every two weeks. The certified gas standard contains 30 ozone precursor compounds at 1 ppm in nitrogen and is auto-diluted with purified nitrogen to 10 ppb with an auto-calibration of monitoring devices (Model DIM 200, AMA Instruments, Germany). The QC drift was found to be <20% for all compounds during the study period. Limits of detection for individual BTEX were as reported by a previous study by Latif et al. (2019).

The hourly air quality data, such as particulate matter with aerodynamic diameters of <10 μm (PM10), particulate matter with aerodynamic diameters of <2.5 μm (PM2.5), carbon monoxide (CO), ozone (O3), nitrogen dioxides (NO2) and meteorological variables data were also obtained from the DOE. A tapered element oscillating microbalance (Model TEOM 1405-DJ, Thermo Fisher Scientific, USA) monitor was used to measure the hourly PM10 and PM2.5 concentrations, while a CO analyser (Model 48i, Thermo Fisher Scientific, USA) was used to record the hourly CO concentrations. Hourly O3 was recorded using a UV photometric O3 analyser (Model 49i, Thermo Fisher Scientific, USA). A chemiluminescence NOx analyser (Model 42i, Thermo Fisher Scientific, USA) was used to measure the hourly NO2 concentrations. An all-in-one weather sensor (Model AIO 2, Met One Instruments, USA) was used to record the meteorological variables. This weather sensor consists of a precision thermistor to determine air temperature, a capacitive polymer sensor to determine humidity and a sonic anemometer to determine wind direction and wind speed. Photovoltaic pyranometer equipment (Model P/N 102725, Climatronix Corporation, USA) was used to monitor solar radiation (PSTW, 2018).

2.3. Sampling campaign and BTEX measurements during the BMCO, MCO and CMCO periods

The lockdown or MCO in Malaysia was put into effect from 18th March 2020, followed by the conditional movement control order or CMCO from 4th May 2020. During the MCO period, strict control orders were implemented with only essential services allowed to function and travel restricted to a 10 km radius. During the CMCO, most rules were relaxed with more economic sectors allowed to be open. A detailed description of activities permitted during the MCO and CMCO is presented in Table S1. These two control orders were imposed to prevent the spread of COVID-19. During the MCO, all social and economic activities were restricted, with the exception of those relating to vital activities such as accessing healthcare and food supplies. Due to this government-imposed restriction, most people were encouraged to stay at home, which significantly reduced the quantity of traffic on the roads. It was reported by the Department of Statistics Malaysia (DOSM, 2021b) that all sectors recorded negative Gross Domestic Products (GDP) growth with −5.6% for 2020 annual national GDP following 4.4% in 2019. The services sector is one of the main contributors to Malaysia’s economy and recorded −5.5% growth. In addition to that, the other four main economic activities also recorded negative economic growth; agriculture (−2.2%), mining and quarrying (−10.6%), manufacturing (−2.6%) and construction (−19.4%).

The percentage reduction between the BTEX concentrations recorded during the BMCO period and the BTEX concentrations recorded during the MCO in 2020 was calculated based on the difference between the concentration of air pollutants recorded during
the MCO and those recorded during the BMCO period. Similarly, the percentage reduction between BTEX recorded during the MCO and the BTEX concentrations recorded during the CMCO in 2020 was also calculated based on the difference between the concentration of air pollutants recorded during the CMCO and those recorded during the MCO.

2.4. Data analysis

Data analysis in this study was carried out using XLSTAT and R statistical analysis version 3.6.3 software (R Development Core Team, 2011). Statistical analyses carried out included one-way ANOVA and the t-test to determine the normality and significant difference of BTEX concentrations between periods (namely BMCO, MCO and CMCO) and between sampling stations. Normal distribution was found for all data (p < 0.05), and the t-test determined that the data was significantly different (p < 0.05) for all locations. Correlation and polar plot analyses were applied to investigate the relationship between meteorological variables and BTEX concentrations. The correlation analysis was determined using the Statistical Package for the Social Sciences (SPSS) software version 21 (IBM, USA).

Principal component analysis (PCA) and the ratios between individual BTEX compounds were used for the determination and classification of BTEX sources. The PCA was applied to the hourly BTEX dataset and hourly air quality data (PM\textsubscript{10}, PM\textsubscript{2.5}, CO, O\textsubscript{3} and NO\textsubscript{2}) for each station to identify and group the air pollutant contributions during the BMCO, MCO and CMCO periods. The hourly criteria air pollutants such as PM\textsubscript{10}, PM\textsubscript{2.5}, CO, O\textsubscript{3} and NO\textsubscript{2} measured at the same stations were also considered as additional parameters, along with BTEX in the PCA analysis. The Statistical Package for the Social Sciences (SPSS) software version 21 (IBM, USA) was used for PCA. PCA analysis converts a large set of data into a more interpretable dataset with factors or components with variables that have linear combinations among them (Ravindra et al., 2008; Mor et al., 2021). The new components or factors are reported as percentage variance where the first component reports the highest variation in the data set possible, followed by the second, third and so on (Holland, 2008; Vidhya, 2016). The varimax rotation method was used for the PCA analysis with a factor that only included eigenvalues greater than one. The higher the factor loading values of that variable, the more the variable contributes to the variation accounted for by that component/factor (Jolliffe, 1986). Therefore, only factor loadings with values >0.7 were used to interpret the PCA results. Method Detection Limit (MDL) values were applied for missing data input. The MDL values were provided by PSTW (2018).

3. Results and discussion

3.1. BTEX concentrations during the BMCO, MCO and CMCO periods

The results of BTEX concentration during the BMCO, MCO and CMCO periods are presented in Table 1. Overall, the BTEX concentrations during the BMCO period at all stations were higher when compared to the MCO and CMCO periods. Shah Alam station recorded the highest total BTEX concentrations during the BMCO (7.47 ± 6.88 ppb), MCO (4.61 ± 3.74 ppb) and CMCO (7.67 ± 5.37 ppb) periods, while Seremban station recorded the lowest total BTEX concentrations during the same time periods: BMCO (2.85 ± 2.91 ppb), MCO (1.73 ± 1.19 ppb) and CMCO (3.37 ± 3.95 ppb). The highest reduction of BTEX during the MCO compared to the BMCO period was recorded at Cheras (–46%), followed by Seremban (–39%) and Shah Alam (–38%) (Table 2). The BTEX concentrations in Shah Alam and Seremban increased significantly after the CMCO began, with the increments reaching +66% and +95%, respectively. The BMCO at Cheras station was recorded at a lower concentration during the CMCO with a reduction of +6% compared to the MCO. The results show that the BTEX concentrations in Kuala Lumpur, where Cheras station is located, were significantly influenced by the MCO due to a reduction of motor vehicles on the roads and continued to decrease when the CMCO started due to the limited movement of motor vehicles in and around Kuala Lumpur.

In general, each BTEX compound recorded at the three selected monitoring stations showed a reduction during the MCO and then

| Parameter | Shah Alam | Cheras | Seremban |
|-----------|-----------|--------|----------|
| BTEX      | 7.47 ± 6.88 | 4.61 ± 3.74 | 7.67 ± 5.37 |
| Benzene   | 1.11 ± 1.44 | 0.64 ± 0.30 | 0.93 ± 0.50 |
| Toluene   | 3.78 ± 3.85 | 2.59 ± 2.94 | 4.32 ± 4.07 |
| Ethylbenzene | 0.71 ± 0.50 | 0.35 ± 0.50 | 0.65 ± 1.26 |
| m,p-Xylene | 1.41 ± 1.43 | 0.73 ± 1.30 | 0.54 ± 0.92 |
| o-Xylene  | 0.52 ± 0.63 | 0.29 ± 0.20 | 0.48 ± 0.33 |

Note: BMCO = Before Movement Control Order (1\textsuperscript{st} January to 17\textsuperscript{th} March 2020), MCO = Movement Control Order (18\textsuperscript{th} March to 3\textsuperscript{rd} May 2020), CMCO = Conditional Movement Control Order (4\textsuperscript{th} May to 31\textsuperscript{st} May 2020).
returned to previous concentrations during the CMCO (Table 1 and Table 2). The Shah Alam station observed a reduction in BTEX compounds of between −31% and −51%, with the highest reduction recorded for ethylbenzene. The reductions recorded at the Cheras station were between −32% and −54%, where once again ethylbenzene recorded the highest reduction. The reductions recorded at the Seremban station were between −23% and −58% but, here, m,p-xylene recorded the highest reduction. Based on the results, the reduction of BTEX concentrations can clearly be seen during the MCO period compared to the BMCO period due to the reduction in the number of vehicles on the road as shown by the reduction of mobility (Fig. 2) and minimal industrial activities in Malaysia as indicated by the reduction of GDP from the year 2019 to 2020 (Fig. S1). Based on the study by Latif et al. (2021), it can be asserted that human mobility during the MCO was significantly reduced in urban areas, most notably in Kuala Lumpur and the Klang Valley where Shah Alam and Cheras are located.

The concentrations for each BTEX compound recorded during the CMCO and MCO at all three stations varied significantly from each other. For Shah Alam and Seremban stations, all compounds showed higher concentrations during the CMCO compared to the MCO, with the range of change being between +45% (benzene) and +86% (ethylbenzene); and between +67% (benzene) and +137% (ethylbenzene), respectively. For Cheras station, the BTEX concentrations such as toluene (−30%) and ethylbenzene (−18%) continued to decrease during the CMCO compared to the MCO, while other compounds, such as m,p-xylene (+34%) and o-xylene (+100%), increased significantly. The increase in BTEX concentrations during the CMCO compared to the MCO, especially at Shah Alam and Seremban stations, shows that the BTEX concentrations are influenced by population mobility especially, from motor vehicles when people started to go to work again.

The daily mean BTEX concentrations, as presented in Fig. 3, showed a reduction during the MCO, which was imposed between 18th March and 3rd May 2020. Immediately after the CMCO was implemented, the concentrations of each BTEX compound increased significantly, notably at Shah Alam and Seremban stations. The increase in BTEX concentrations at these two stations is expected due to the increase in the motor vehicles as shown by the increase in mobility (Fig. 2). Based on our previous work (Latif et al., 2021), the BTEX concentrations were recorded at higher concentrations in areas with a high number of motor vehicles on the roads. The BTEX concentrations at Shah Alam station increased significantly during the CMCO as the number of motor vehicles on the nearby roads increased once again due to people returning to work around this residential area and the industrial area nearby. The relatively lower

Table 2
The differences in BTEX concentrations between MCO and BMCO (D1) and between CMCO and MCO (D2) with their percentage changes (%1 and %2). %D1: percentage changes between MCO and BMCO. %D2: percentage changes between CMCO and MCO.

| Parameter   | Shah Alam  | Cheras  | Seremban |
|-------------|------------|---------|----------|
| Unit (ppb)  | D1 %1 D2 %2 | D1 %1 D2 %2 | D1 %1 D2 %2 |
| BTEX        | −2.86 −38 +3.06 +66 | −2.72 −46 −0.190 −6 | −1.12 −39 +1.64 +95 |
| Benzene     | −0.470 −42 +0.290 +45 | −0.410 −39 +0.0300 +5 | −0.190 −30 +0.300 +67 |
| Toluene     | −1.19 −31 +1.73 +67 | −1.61 −50 −0.480 −30 | −0.510 −40 +0.690 +92 |
| Ethylbenzene| −0.360 −51 +0.300 +86 | −0.390 −54 −0.0600 −18 | −0.0800 −23 +0.370 +137 |
| m,p-Xylene  | −0.680 −48 +0.570 +78 | −0.230 −32 +0.170 +34 | −0.230 −58 +0.120 +41 |
| o-Xylene    | −0.230 −44 +0.190 +66 | −0.190 −42 +0.260 +100 | −0.110 −44 +0.170 +121 |

Fig. 2. Mobility trend during the BMCO, MCO and CMCO periods in Kuala Lumpur (Google LLC, 2020).
BTEX concentrations continued at Cheras station during the CMCO compared to the other two stations. This may have been due to the continued lower numbers of motor vehicles at this station and the surrounding area during the CMCO.

Further investigation using diurnal concentrations during the BMCO, MCO and CMCO periods (Fig. 3) shows that the highest BTEX

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**Fig. 3.** Time series of the daily mean of BTEX concentrations. Vertical dashed lines represent the three studied stages, before the Movement Control Order, BMCO (1st January to 17th March 2020), during the Movement Control Order, MCO (18th March to 3rd May 2020), and during the Conditional Movement Control Order, CMCO (4th May to 31st May 2020), at (a) Shah Alam, (b) Cheras and (c) Seremban stations.
Fig. 4. Diurnal patterns of BTEX and air temperature at (a) Shah Alam, (b) Cheras and (c) Seremban stations before the Movement Control Order, BMCO (1st January to 17th March 2020), during the Movement Control Order, MCO (18th March to 3rd May 2020) and during the Conditional Movement Control Order, CMCO (4th May to 31st May 2020).
concentrations were recorded during the rush hour (7.00 am - 10.00 am). The BTEX concentrations during the BMCO period were noted as being the highest when compared to those during the MCO and CMCO at all stations. The BTEX concentrations at all stations, especially at Cheras, were also recorded as being higher during the night. This may be due to atmospheric stability conditions, particularly in the areas within Kuala Lumpur’s urban environment. The lowest BTEX concentrations occurred at midday which may be due to the high air temperature (around 34 °C as shown in Fig. 4) and low stability conditions whereby pollutants move towards the upper part of the atmosphere.

3.2. Ratios between individual BTEX compounds

The mean of toluene/benzene (T/B) and m,p-xylene/ethylbenzene (m,p-X/E) ratios are presented in Table 3. The T/B and m,p-X/E ratios can indicate their potential sources and the chemical age of air parcels (Guo et al., 2007). The T/B ratio is widely used to indicate the influence of vehicular or traffic sources on ambient air (Alfoldy et al., 2019; Bretón et al., 2017; Miller et al., 2011; Tiwari et al., 2010; Tsai et al., 2020). T/B ratios at Shah Alam, Cheras and Seremban during the BMCO period were found to be 3.48 ± 2.20, 3.76 ± 5.50 and 1.84 ± 0.580, respectively. The T/B ratios observed in Shah Alam and Cheras were found to be almost similar to the T/B ratios reported by Latif et al. (2019) (3.26 ± 1.02) and Fandi et al. (2020) (3.81 ± 2.02) in urban areas of Kuala Lumpur. Other studies by Lan and Binh (2012) and Hamid et al. (2019) at Kuala Lumpur road sides also indicated similar results with T/B ratios between 2.20 and 2.22, respectively. T/B ratios which are lower than 2 (T/B < 2) indicate that the source of toluene is mainly traffic emissions, as shown by Bruno et al. (2006) and Hui et al. (2018) under industrial conditions (Taranto, Italy) in 2003 and in an urban area (Wuhan, Central China) in 2017, respectively. T/B ratios that are >2 (T/B > 2) indicate that the sources of toluene are from both traffic and industrial activities (Bruno et al., 2006; Hui et al., 2018). The T/B ratios at all stations showed a clear indication of vehicle emissions with an additional source of industrial activities at Shah Alam and Cheras.

Further investigation found that Shah Alam station showed an increased pattern in the T/B ratio: 3.48 ± 2.20 (BMCO) < 3.96 ± 3.94 (MCO) < 4.71 ± 3.34 (CMCO). The increased pattern for the T/B ratio for Shah Alam is presumably due to lower benzene emissions from gasoline-fuelled cars as a result of the MCO. The continuous operations of several industrial activities in this industrial area during the MCO and CMCO are expected to contribute to the concentration of toluene (Zulkifli et al., 2022). The T/B ratio in Cheras showed a decreasing pattern of 3.76 ± 5.50 (BMCO) > 2.47 ± 0.740 (MCO) > 1.92 ± 1.44 (CMCO), indicating that toluene from traffic and local industrial activity was reduced due to limited operation. However, the T/B ratio in Seremban showed minor changes: 1.91 ± 0.790 (CMCO) > 1.84 ± 0.580 (BMCO) > 1.63 ± 0.590 (MCO). The lowest T/B ratio in Seremban clearly shows that BTEX concentrations in the area were predominantly affected by vehicular emissions.

The m,p-X/E ratio can be used to indicate the age of air parcels based on the photochemical reactivity of xylene and ethylbenzene (Roukos et al., 2009; Ueda and Tomaz, 2011). As m,p-xylene are more reactive than other compounds, a lower m,p-X/E ratio indicates the ageing of VOCs in the atmosphere. According to Ueda and Tomaz (2011), higher values of m,p-X/E ratios (m,p-X/E > 3.28) imply fresh pollutants. Previous studies by Latif et al. (2019) and Fandi et al. (2020) found the m,p-X/E ratios recorded in Kuala Lumpur were 2.73 and 1.54, respectively. The values may indicate the influence of photochemical reactions on m,p-X/E ratios in the tropical urban environment.

The m,p-X/E ratio at Shah Alam indicated a consistent trend: 2.44 ± 5.94 (BMCO), 2.53 ± 4.12 (MCO) and 2.24 ± 0.740 (CMCO). The m,p-X/E ratio at Seremban indicated a decreasing trend: 1.65 ± 1.11 (BMCO) > 1.09 ± 0.990 (MCO) > 0.670 ± 1.06 (CMCO). Meanwhile, the m,p-X/E ratio in Cheras showed an increasing trend in the order of: 1.40 ± 1.25 (BMCO) < 1.78 ± 1.51 (MCO) < 3.21 ± 4.02 (CMCO). A comparison of Cheras and Shah Alam stations, both of which are located in the Klang Valley region, shows that Cheras recorded a lower m,p-X/E ratio compared to Shah Alam except for during the CMCO. It is expected emissions from essential industrial activities in the nearby upwind areas may have contributed to the higher concentrations of xylene isomers in Shah Alam. The concentration of ethylbenzene may influence the higher m,p-X/E ratio recorded at Cheras.

3.3. Correlation between BTEX concentrations

The correlations between BTEX concentrations during the BMCO, MCO and CMCO periods at the three stations are presented in Table S2. Overall, the correlations between BTEX compounds at all three sampling stations were significant (p < 0.01). There were no clear trends of strong correlation (r > 0.70) between BTEX compounds at the sampling stations during the three time periods (BMCO, MCO and CMCO). The BTEX compounds recorded at Cheras station during the BMCO period showed strong correlations between each other, indicating that the compounds originate from similar sources. The number of strong correlations recorded at this station was reduced during the MCO and CMCO. For the other stations, strong correlations were found between toluene and ethylbenzene; between benzene with m,p-xylene and o-xylene; and between ethylbenzene with m,p-xylene and o-xylene.

Table 3
Toluene to benzene (T/B) and m,p-xylene to ethylbenzene (m,p-X/E) ratios at each station during the BMCO, MCO and CMCO periods.

| Ratio | Shah Alam | Cheras | Seremban |
|-------|-----------|--------|----------|
|       | BMCO      | MCO    | CMCO     | BMCO      | MCO    | CMCO     | BMCO      | MCO    | CMCO     |
| T/B   | 3.48 ± 2.20 | 3.96 ± 3.94 | 4.71 ± 3.34 | 3.76 ± 5.50 | 2.47 ± 0.740 | 1.92 ± 1.44 | 1.84 ± 0.580 | 1.63 ± 0.590 | 1.91 ± 0.790 |
| m,p-X/E | 2.44 ± 5.94 | 2.53 ± 4.12 | 2.24 ± 0.740 | 1.40 ± 1.25 | 1.78 ± 1.51 | 3.21 ± 4.02 | 1.65 ± 1.11 | 1.09 ± 0.990 | 0.670 ± 1.06 |
Table 4
Principal Component Analysis (PCA) results for each station during the BMCO, MCO and CMCO periods.

| Variables     | BMCO          |        | MCO          |        | CMCO          |        |
|---------------|---------------|--------|--------------|--------|---------------|--------|
|               | Shah Alam     | Cheras | Seremban     | Shah Alam | Cheras        | Seremban |
|               | F1  | F2  | F3  | F1  | F2  | F3  | F1  | F2  | F3  | F1  | F2  | F3  | F1  | F2  | F3  | F1  | F2  | F3  | F1  | F2  | F3  |
| Benzene       | 0.93 | 0.04 | 0.08 | 0.91 | 0.26 | 0.93 | 0.26 | 0.89 | 0.15 | 0.88 | 0.25 | 0.87 | 0.34 | 0.90 | 0.15 | 0.07 | 0.23 | 0.77 | 0.34 | 0.90 | 0.25 | -0.20 |
| Toluene       | 0.93 | 0.05 | 0.06 | 0.92 | 0.30 | 0.94 | 0.19 | 0.78 | 0.00 | 0.93 | 0.19 | 0.93 | 0.19 | 0.77 | 0.12 | -0.01 | 0.05 | 0.92 | -0.04 | 0.85 | 0.26 | -0.27 |
| Ethylbenzene  | 0.92 | 0.02 | 0.09 | 0.74 | 0.25 | 0.80 | 0.18 | 0.89 | 0.01 | 0.72 | 0.16 | 0.82 | 0.18 | 0.84 | -0.01 | 0.21 | 0.16 | 0.82 | 0.05 | 0.87 | 0.19 | -0.22 |
| m,p-Xylene    | 0.96 | 0.05 | 0.14 | 0.76 | 0.06 | 0.74 | 0.08 | 0.96 | 0.07 | 0.75 | 0.00 | 0.55 | 0.01 | 0.95 | 0.06 | 0.20 | 0.30 | 0.46 | 0.57 | 0.70 | -0.06 | 0.28 |
| o-Xylene      | 0.86 | 0.06 | 0.09 | 0.92 | 0.21 | 0.92 | 0.15 | 0.90 | 0.07 | 0.96 | 0.18 | 0.88 | 0.11 | 0.94 | 0.07 | 0.18 | 0.50 | 0.07 | 0.70 | 0.12 | -0.03 |
| PM10          | 0.05 | 0.07 | 0.12 | 0.21 | 0.94 | 0.11 | 0.94 | 0.03 | 0.95 | 0.11 | 0.92 | 0.05 | 0.92 | 0.16 | 0.96 | 0.05 | 0.94 | 0.10 | 0.02 | 0.06 | 0.92 | 0.04 |
| PM2.5         | 0.03 | 0.96 | 0.11 | 0.20 | 0.94 | 0.07 | 0.95 | 0.00 | 0.95 | 0.00 | 0.95 | -0.04 | 0.95 | 0.13 | 0.97 | 0.05 | 0.95 | 0.10 | -0.07 | 0.02 | 0.94 | 0.20 |
| O3            | -0.06 | 0.17 | -0.85 | -0.69 | 0.45 | -0.57 | 0.40 | -0.40 | 0.22 | -0.67 | 0.34 | -0.40 | 0.31 | -0.21 | 0.03 | -0.69 | 0.13 | -0.01 | -0.88 | -0.12 | 0.01 | 0.89 |
| CO            | 0.16 | 0.42 | 0.72 | 0.77 | 0.40 | 0.62 | 0.45 | 0.03 | 0.61 | 0.49 | 0.52 | 0.27 | 0.65 | -0.05 | 0.54 | 0.51 | 0.67 | 0.25 | 0.39 | 0.20 | 0.72 | -0.30 |
| NO2           | 0.11 | 0.42 | 0.72 | 0.59 | 0.49 | 0.36 | 0.57 | 0.33 | 0.25 | 0.58 | 0.42 | 0.34 | 0.50 | 0.13 | 0.14 | 0.82 | 0.60 | 0.33 | 0.32 | 0.27 | 0.56 | -0.09 |
| Eigen values  | 4.6 | 2.5 | 1.2 | 5.9 | 1.8 | 5.2 | 2.1 | 4.2 | 2.3 | 5.1 | 2.0 | 4.3 | 2.1 | 4.5 | 2.1 | 1.2 | 4.5 | 1.7 | 1.4 | 4.6 | 2.1 | 1.0 |
| Variance (%)  | 45.7 | 24.6 | 12.4 | 59.4 | 18.4 | 51.9 | 20.8 | 42.4 | 22.7 | 50.9 | 20.4 | 42.9 | 21.5 | 44.7 | 20.8 | 11.7 | 44.7 | 16.8 | 14.0 | 45.7 | 21.1 | 10.3 |
| Cumulative (%)| 45.7 | 70.2 | 82.6 | 59.4 | 77.8 | 51.9 | 72.7 | 42.4 | 65.1 | 50.9 | 71.4 | 42.9 | 64.4 | 44.7 | 65.6 | 77.3 | 44.7 | 61.5 | 75.5 | 45.7 | 66.8 | 77.1 |

Note: BMCO = Before Movement Control Order (1st January to 17th March 2020), MCO = Movement Control Order (18th March to 3rd May 2020), CMCO = Conditional Movement Control Order (4th May to 31st May 2020). Bold values are loading values that are >0.7.
Fig. 5. The polar plot based on total BTEX concentrations with wind speed and wind direction at three stations; 1. Shah Alam during a) BMCO, b) MCO and c) CMCO, 2. Cheras during d) BMCO, e) MCO and f) CMCO, 3. Seremban during g) BMCO, h) MCO and i) CMCO.
PCA was applied to the hourly dataset using SPSS software and the retrieved results are presented in Table 4. Before the MCO (BMCO), Shah Alam showed three factors, while Cheras and Seremban showed two factors with cumulative variances of 82.6%, 77.8% and 72.7%, respectively. The first factor (F1) for Shah Alam, Cheras and Seremban during the BMCO period showed strong factor loadings for benzene, toluene, ethylbenzene and xylene with variances of 45.7%, 59.4% and 51.9%, respectively. All three stations showed strong loading for particulate matter for the second factor (F2), with variances of 24.6%, 18.4% and 20.8%, respectively. Shah Alam showed an additional factor (F3) with strong loading for O3 and NO2. The major source of these air pollutants in the urban environment is industrial activity and the burning of fossil fuels by vehicles (Marč et al., 2016; Hamid et al., 2020; Muhammad et al., 2020; Popitanu et al., 2021). Hence, traffic emissions and industrial activities could be the primary source of BTEX concentrations during the BMCO period.

During the MCO period, Shah Alam, Cheras and Seremban stations showed strong factor loadings for F1 on all BTEX compounds except for m,p-xylene at Seremban station. The variances for F1 in Shah Alam, Cheras and Seremban were 42.4%, 50.9% and 42.9%, respectively. All stations showed strong loadings for particulate matter for F2 with variances of 22.7%, 20.4% and 21.5%, respectively. Regardless of a lower percentage of variance recorded during the MCO period, the sources of studied pollutants were industrial activity and traffic emissions.

During the CMCO period, all three stations recorded three factors. The Shah Alam and Seremban stations showed strong factor loadings for F1 on all BTEX compounds with variance values of 44.7% and 45.7%, respectively. Cheras station recorded strong factor loadings for particulate matter (44.7%) for F1. Both Shah Alam and Seremban recorded strong loading for particulate matter for F2 with an additional strong loading for CO for Seremban station. Meanwhile, Cheras station showed strong loading for F2 (16.8%) for benzene, toluene and ethylbenzene. Cheras and Seremban stations recorded strong loadings for F3 on O3 whereas Shah Alam station recorded strong loading for NO2. A higher percentage of variance was recorded during the CMCO compared to the MCO due to most rules being relaxed with more economic sectors allowed to open compared to the MCO. Once again, the possible sources of studied pollutants were industrial activities and traffic emissions, as supported by monthly GDP and mobility data (Fig. S1 and Fig. 2).

3.5. Influence of meteorological variables

The meteorological variables (relative humidity, air temperature, wind speed and solar radiation) during the BMCO, MCO and CMCO periods are presented in Fig. S2. Overall, the relative humidity and air temperature recorded at Shah Alam, Cheras and Seremban are quite similar at each station during the BMCO, MCO and CMCO periods. Malaysia is a tropical country that records consistent values of relative humidity and air temperature throughout the year. The meteorological variables within the different lockdown periods (BMCO, MCO and CMCO) are expected to not influence the BTEX concentrations in this study significantly. Further detailed analysis of the correlations between BTEX compounds and meteorological variables is presented in Table S2. In general, the BTEX concentrations recorded during the BMCO, MCO and CMCO periods at all stations had positive correlations with relative humidity and negative correlations with wind speed, solar radiation and air temperature. Most of the significant correlations between meteorological variables were recorded at Cheras and Seremban stations, especially during the BMCO period. The results showed that relative humidity influenced the existence of BTEX, while wind speed, air temperature and solar radiation reduced the BTEX concentrations. These results suggest that the atmospheric instability and dilution processes, as indicated by high wind speeds, photo-degradation, high solar radiation and air temperature, may have reduced BTEX concentrations, especially during the BMCO period. The different characteristics of BTEX emissions at Shah Alam and lower BTEX concentrations during the MCO and CMCO may influence the correlations between BTEX and meteorological variables.

The influence of wind direction on BTEX concentrations at the different stations is presented via polar plots, as shown in Fig. 5 and Figs. S3 – S5. The results show different patterns of polar plots at all stations during the BMCO, MCO and CMCO periods. During the BMCO period, higher concentrations of BTEX were measured coming from the surroundings of each station, especially for Cheras and Shah Alam. Cheras station is located in Kuala Lumpur’s city centre, so it is expected that this area will experience a high number of motor vehicles which, in turn, contribute to the high BTEX concentrations. Even though there are several potential sources of BTEX on the west coast of Klang Valley that can affect Shah Alam, the local wind speed and wind direction show that Shah Alam station is also influenced by BTEX sources that surround the station. Shah Alam station has an airport located nearby and is also surrounded by industrial and residential areas, as well as highways which will lead to higher BTEX concentrations during the BMCO period.

The BTEX concentrations during the MCO were found to be influenced by northeasterly winds for Cheras and Shah Alam as shown in Fig. 5, Fig. S3 and Fig. S4, respectively. However, Seremban followed the same northwesterly wind pattern for the BMCO period with lower concentrations during the MCO compared to the BMCO and CMCO periods (Fig. 5 and Fig. S5). Local emissions originating from around the stations contributed to the BTEX concentrations at this particular time. However, lower BTEX concentrations were observed during the MCO with different wind patterns and sources at Cheras and Shah Alam but not at Seremban. Seremban station maintained the same direction of sources, from a northeasterly wind during the BMCO, MCO and CMCO periods. As for Shah Alam, the high number of motor vehicles within the residential area and highways from northeast of the station contributed to the high BTEX concentrations at this station during the MCO. The wind pattern and sources of BTEX during the CMCO are almost similar to the wind pattern and sources of BTEX during the MCO for Cheras and Seremban. The increased number of motor vehicles and industrial activities surrounding the sampling station during the CMCO increased the BTEX concentrations in the study areas.
4. Conclusion

The results of the study clearly show that BTEX concentrations reduced significantly during the MCO in an urban area in Malaysia. The percentage reduction ranged from ~38% to ~46%, with the highest reduction recorded at Cheras station in Kuala Lumpur. The BTEX concentrations increased after the MCO and returned to the concentrations they had originally been at during the CMCO. The ratios between individual BTEX compounds indicated that the concentrations were contributed to by motor vehicle emissions and other anthropogenic sources relating to industrial and human activities during these different periods as well as meteorological variables.

This study suggests that BTEX concentrations in ambient air in the urban environment in Malaysia can be controlled by reducing the levels of emissions originating from anthropogenic sources, notably from motor vehicle emissions. Since BTEX compounds, especially benzene, are very toxic and long term exposure can lead to carcinogenic effects to humans, policies aimed at effectively reducing emissions from motor vehicles therefore need to be implemented in Malaysia in order to reduce BTEX concentrations in ambient air, particularly in urban environments.

CRediT authorship contribution statement

Nor Syamimi Suffiera Limi Hawari: Conceptualization, Data analysis, Writing – original draft. Mohd Talib Latif: Review & editing, Supervision, Funding acquisition. Haris Hafizal Abd Hamid: Review & editing, Supervision. Teoh Hwai Leng: Writing – Data analysis. Murnira Othman: Conceptualization, Writing, Review & editing. Anis Asma Ahmad Mohtar: Data analysis, Review & editing. Azliyana Azhari: Writing, Review & editing. Doreena Dominick: Data analysis, Review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2022.101238.

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