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Assessing the impact of COVID-19 pandemic on urban transportation and air quality in Canada

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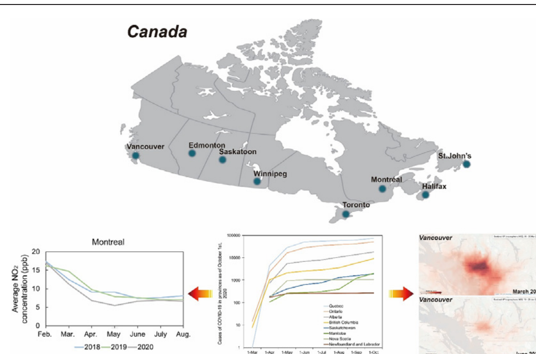
HIGHLIGHTS

- The consumption of motor gasoline decreased from March and rebounded in May 2020.
- The urban traffic volume and congestion level changed after COVID-19 outbreak.
- The concentrations of NO_2 and CO had strong relevance with the COVID-19 period.
- Emissions from urban vehicles accounted for a large proportion air pollutant emission.
- AQHI of most cities declined to varying degrees after February 2020.

GRAPHICAL ABSTRACT



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ABSTRACT

The global outbreak and spread of COVID-19 had a significant impact on the environment of urban areas. This study aimed to provide a new insight into the urban transportation and air pollutant emission of representative Canadian cities impacted by this pandemic. The consumption of urban transportation fuel was analyzed and the corresponding CO_2 emissions was evaluated. The changes in urban traffic volume and air pollutant concentrations before and after the outbreak of this pandemic was investigated. Due to the lockdown after the outbreak of COVID-19, the domestic consumption of motor gasoline and estimated CO_2 emissions from urban vehicles in Canada has continuously decreased with a lowest level in April 2020, and rebounded in May 2020. It will still take a long time to recover to pre-pandemic levels because of the upcoming second wave of pandemic and further change. The Air Quality Health Index (AQHI), level of urban congestion and concentration level of NO_2 and CO had strong relevance with the COVID-19 period while SO_2 did not show significant relation. The comprehensive analysis of changing fuel consumptions, traffic volume and emission levels can help the government assess the impact and make corresponding strategy for such a pandemic in the future.

1. Introduction

The global outbreak and spread of COVID-19 have brought serious threat to public health and major disruption to global economic activities. The impact on global supply chains and trade lasted for a long time, which also caused the anxiety not only in public health environment but also in global economic growth (Wang and Su, 2020; Smith

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et al., 2020). During this pandemic, different levels of restrictions on the movement of people in various countries also had significant impact on daily life (Fernandes, 2020). With the downturn in economy and reductions in daily travel caused by COVID-19, there was the reduced environmental pollutant emission, which could be “a blessing in disguise” (Muhammad et al., 2020).

It was found that the daily global CO_2 emissions decreased during the pandemic (Le Quéré et al., 2020). Zambrano-Monserrate et al. (2020) analyzed the indirect effect of COVID-19 on the air quality, beaches and environmental noise reduction, especially in China, USA, Italy and Spain. Bauwens et al. (2020) compared the dynamic changes in NO_2 concentration level over China, South Korea, western Europe and the United States during the coronavirus disease outbreak based on data from the spaceborne NO_2 column observations. In addition, the changes in air pollution at different cities during the epidemic were reported (Dai et al., 2020; Wang et al., 2020). In terms of the changes in urban vehicle emissions, Xiang et al. (2020a) evaluated the impact of this pandemic on the traffic-related air pollution in downtown of Seattle, and compared the median traffic volume, road occupancy and the pollutants before and after lockdown. Tanzer-Gruener et al. (2020) compared concentrations of $PM_{2.5}$, CO and NO_2 between closure and business-as-usual periods in Pittsburgh.

From the perspective of energy consumption and emissions, the impact of unexpected disaster on energy consumption was studied previously. For example, Taghizadeh-Hesary et al. (2017) compared the elasticity of oil consumption with crude oil price before and after the Fukushima Daiichi nuclear disaster. During the present pandemic, fuel demand and oil price plummeted in April 2020. Ou et al. (2020) incorporated the pandemic scenarios and the trip activities for projecting future fuel usage in the United State based on a machine-learning-model. In a global scale, fossil fuel consumption and CO_2 emissions are expected to return to pre-crisis levels in a two-year extent (Smith et al., 2020, Alberta Capital Airshed, 2020).

Although there were some studies about the impact of COVID-19 on environmental problems, the relation between this pandemic and urban air pollution is still not clear. This study aims to provide a new insight into the urban air pollutant emission of representative Canadian cities impacted by the pandemic. The consumption of urban transportation fuel will be analyzed and the corresponding CO_2 emissions will be evaluated. The changes in urban traffic volume and air pollutant concentrations before and after the outbreak of this pandemic will be investigated.

2. Methods

2.1. Study area

The COVID-19 virus in Canada was firstly reported in January 2020 and then the community transmission was confirmed in mid-March 2020, followed by the states of emergency in all Canadian provinces. In summer, the new cases steadily declined across the country, while the whole country experienced a resurgence of cases in autumn. The long-lasting pandemic had a significant impact on the environment of urban areas in Canada. In order to investigate the impact of the COVID-19 pandemic on urban transportation and air quality, some representative cities including Vancouver in British Columbia, Edmonton in Alberta, Saskatoon in Saskatchewan, Winnipeg in Manitoba, Toronto in Ontario, Montréal in Quebec, Halifax in Nova Scotia and St. John's in Newfoundland and Labrador, were chosen. Considering the time when different cities declared the state of emergency and relaunch strategy, the time frame in this research was from February to September 2020.

The changes of air quality in different provinces of Canada were studied. Fig. 1 shows the overall emissions of SOx, NOx and CO in British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Montréal, Nova Scotia and Newfoundland and Labrador in 1990 and 2017 (Environment and Climate Change Canada, 2019a). In 2017, Ontario and Alberta accounted for 44% of national SO_X emissions. Between 1990 and 2017, Ontario experienced the largest reduction and SO_X emissions decreased by 84%, while the only increase (24%) was observed in Saskatchewan (Chen et al., 2020). The reduction in SO_X emissions in Ontario from 1990 to 2017 was mainly due to the technological upgrades and new air pollution control measures for the non-ferrous smelting and refining industry. For example, the closure of major smelter and the phase-out of coal electricity generation in Ontario both resulted in the decrease in SO_X emissions. The increasing electric utilities has become the most important source of emissions in Saskatchewan (Environment and Climate Change Canada, 2019b). In terms of NO_X emissions, Alberta accounted for 36% of national emissions which wat the highest NO_X emission among provinces in 2017. The most important source of NO_X emissions in Alberta was the oil and gas industry, accounting for 59% of the province's NO_X emissions in 2017. In recent years, the reduction in NO_X emissions from transportation and electric utilities sectors has been offset by the continuous increase in emissions from the oil and gas industry sector (Environment and Climate Change Canada, 2019a). Therefore, NO_X emissions in

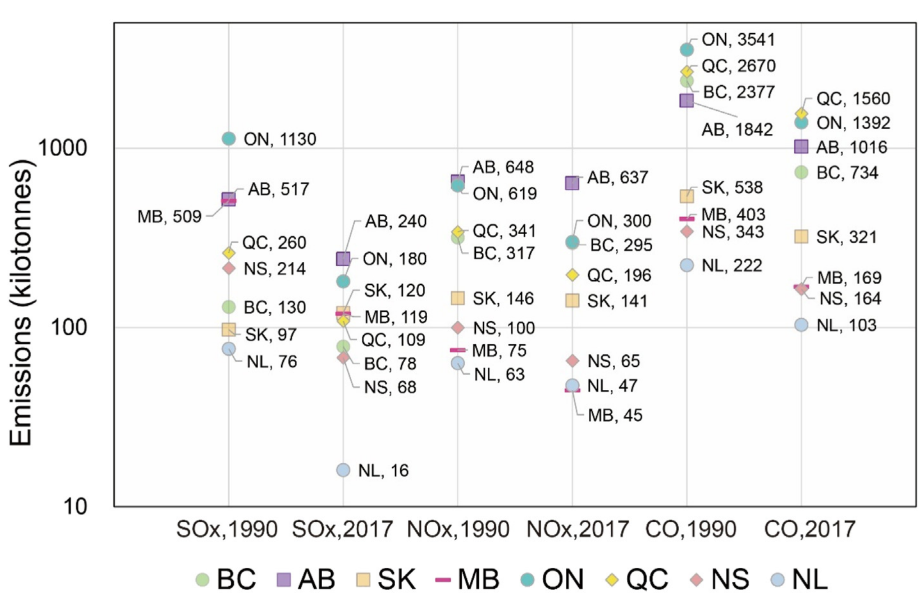
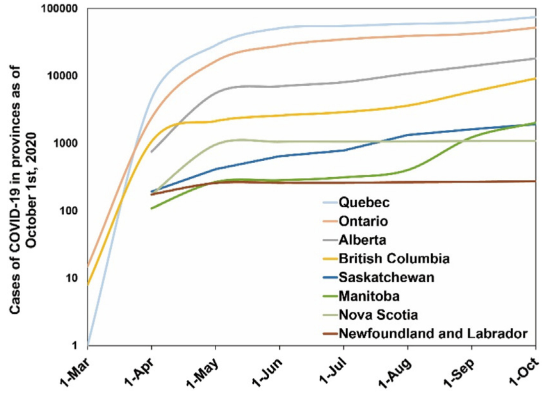


Fig. 1. Ranking of SOx emissions, NOx emissions and CO emissions by province, Canada, 1990 and 2017 (Environment and Climate Change Canada, 2019a).



Province	State of emergency declared	Reopening in stage 1
Quebec	2020/3/12	2020/5/11
Ontario	2020/3/17	2020/5/8
Alberta	2020/3/17	2020/5/14
British Columbia	2020/3/18	2020/5/16
Saskatchewan	2020/3/18	2020/5/4
Manitoba	2020/3/20	2020/5/4
Nova Scotia	2020/3/22	2020/5/1
Newfoundland and Labrador	2020/3/18	2020/5/11

Fig. 2. Cases of COVID-19 in eight provinces as of October 1st, 2020 and policies related COVID-19 declared by provincial and territorial governments (Government of Canada, 2020).

Alberta have been ranking first for many years in Canada. Ontario ranked the second largest proportion of NO_X emissions in 2017, accounting for 17% of the country's total emissions. Transportation, including roads, rail, aviation and marine, was the most important source, followed by off-road vehicles and mobile equipment. However, the NO_X emissions in Ontario decreased by 52% from 1990 to 2017 as a result of emission reductions from transportation, electric utilities, off-road vehicles and mobile equipment. In addition to NO_X emissions, CO emission reduction from transportation was also a main factor attributing to significant decrease in CO emissions between 1990 and 2017 in these eight provinces. During this period, the larger reductions of 69%, 61%, and 42% took place in British Columbia, Ontario, and Quebec, respectively. CO emissions was mainly from the home firewood burning in Quebec and from the transportation (road, rail, air and marine) in Ontario.

2.2. Data sources and processing

The air quality data of eight cities from February to August in 2018, 2019 and 2020 were collected. The hourly pollutant concentrations monitored on each day was used to calculate the corresponding monthly average levels. The pollution data in Vancouver, British Columbia were taken from Robson Square monitoring station (B.C. Air Quality Data, 2020). The air quality data in Edmonton, Alberta were accessed from both Alberta Air Data Warehouse and Alberta Capital Airshed (ACA) (Government of Alverta, 2020, Alberta Capital Airshed, 2020). The data were from the core long term program in Central station and McCauley station of Edmonton. The real-time and historic air quality data in Saskatoon, Saskatchewan was from the National Air Pollution Surveillance (NAPS) network on the Air Quality Index (AQI) website (Government of Saskatchewan, 2020). The monitoring station in Winnipeg, Manitoba was on the Ellen Street which was close to downtown area. In Ontario, the station chosen for O_3 and NO_2 data was Toronto Downton station. Due to the lack of data in Toronto Downton station, the Toronto West station was chosen for the supplementary data of CO. The website didn't provide the daily average data of air quality and thus the hourly data was collected and calculated to get the daily average data. The station chosen in Montréal, Quebec was Station 31 St-Dominique located in downtown area. The station chosen in Nova Scotia was the Halifax station located in Johnston Building (Nova Scotia Environment, 2020). The air monitoring sites located in St. John's, Newfoundland and Labrador was one of the NAPS stations (Environment and Climate Change Canada, 1969, Government of Newfoundland and Labrador, 2020). The Air Quality Health Index (AQHI) monthly data from February to September in 2019 and 2020 were collected. Due to the lack of historical data in Montréal, the representative cities including Vancouver, Edmonton, Saskatoon, Winnipeg, Toronto, Halifax and St. John's were chosen for the comparison of AQHI (Environment and Climate Change Canada 2019).

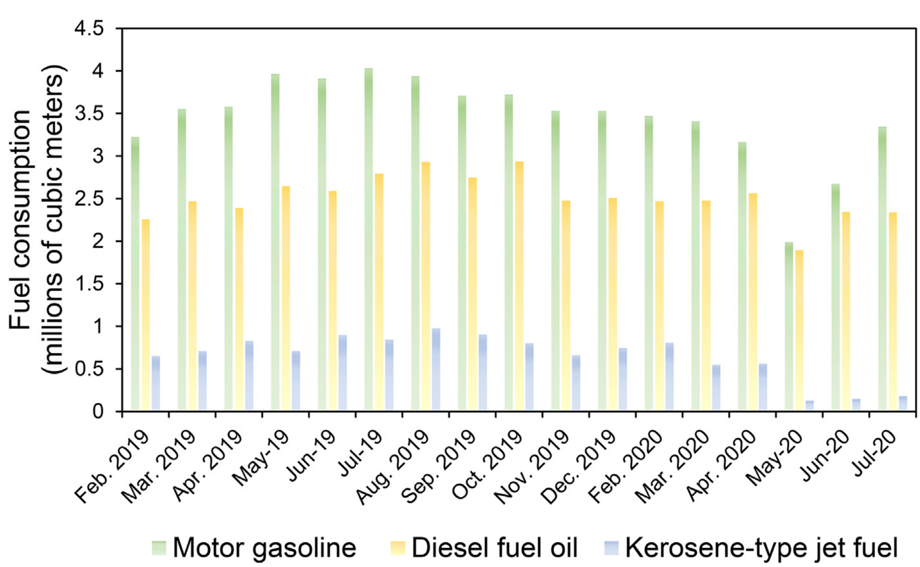


Fig. 3. Domestic consumption of motor gasoline, diesel fuel and kerosene-type jet fuel in Canada, monthly (Statistics Canada, 2020a; Statistics Canada, 2020b).

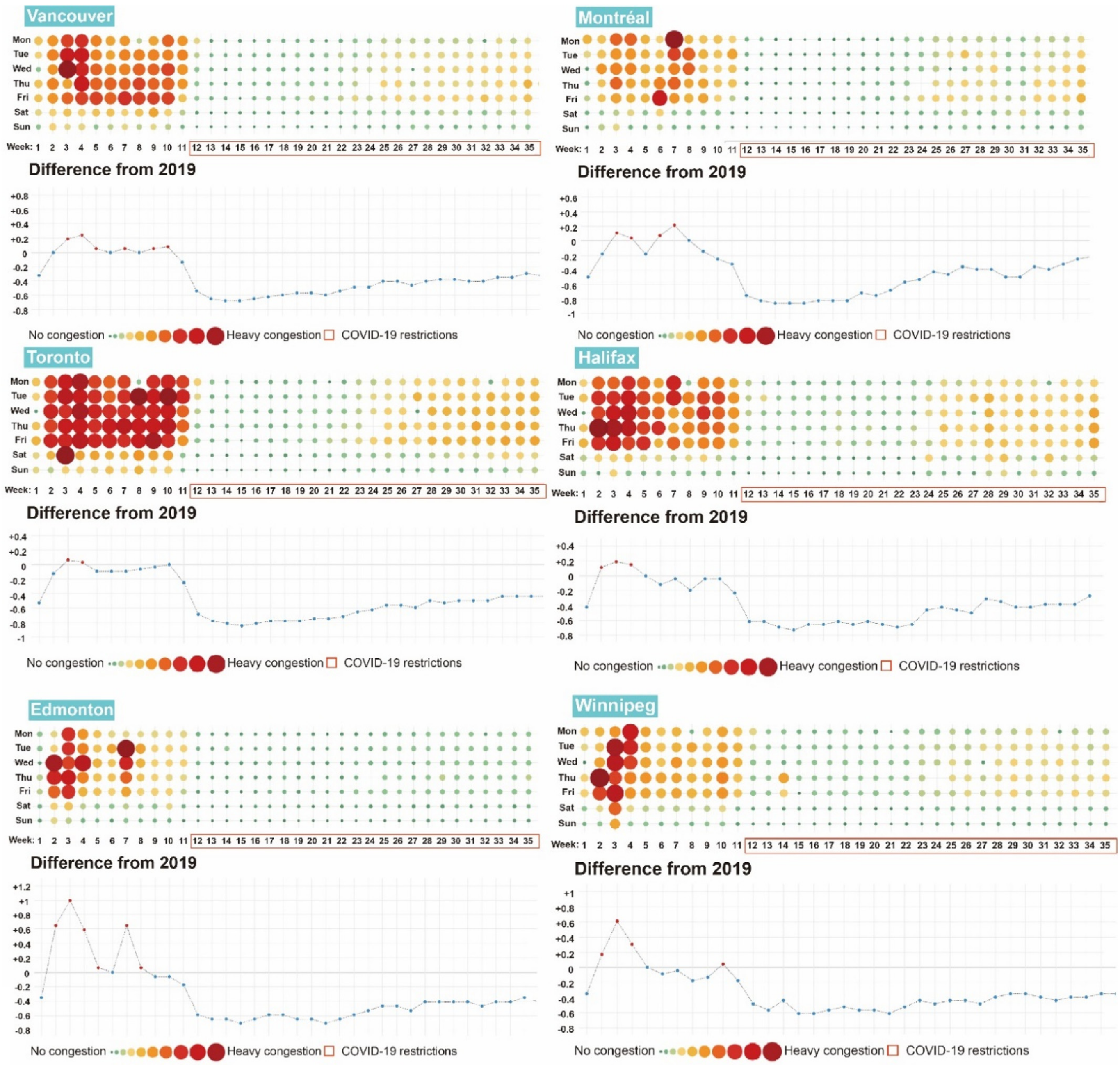


Fig. 4. Average congestion level in 2020 and the relative difference of average congestion levels in 2020 from standard congestion levels in 2019 in Vancouver, Edmonton, Winnipeg, Toronto, Montréal and Halifax.

The consumptions of domestic motor gasoline in different months were from a monthly cross-sectional designed survey which collected data on the activities of all Canadian refineries and oil sands processing plants involved in the production of refined petroleum products and of selected major blending terminals of these products (Statistics Canada, 2020b). The level of average traffic congestion in different cities was a representation of traffic volume in this study. The traffic index data was obtained from TOMTOM (2020), covering six cities in Canada, namely Vancouver, Edmonton, Winnipeg, Toronto, Montréal and Halifax. The baseline was calculated per city by analyzing free-flow travel times of all vehicles on the entire road network which was recorded 24 h a day and 365 days a year. The whole data source came from 600 million drivers around the world who used their tech in navigation devices, in-dash systems and smartphones. The satellite imagery of averaged NO_2 concentrations were collected on an online platform which used data from the Copernicus Sentinel-5P satellite (European Commission and European Space Agency, 2020). These satellite maps show the concentration of NO_2 in the lowest km of the atmosphere. The changes and trends of concentrations can be better presented by this 14-day moving average than shorter time periods because the average of concentrations gives an overview over the whole time period. LabelMe (MIT, US) was used first to outline the administrative boundaries of Vancouver and Toronto by continuous points in the scene of the NO_2 satellite images. The coordinates of points associated with the boundaries were saved and overlaid on top of NO_2 satellite images. Then the MATLAB (Mathworks, US) was used to segment the images under three different threshold levels and calculate the pixels of each threshold in the whole city. The percentage of the pixels with NO_2 concentration higher than thresholds to the pixels of the whole city were calculated.

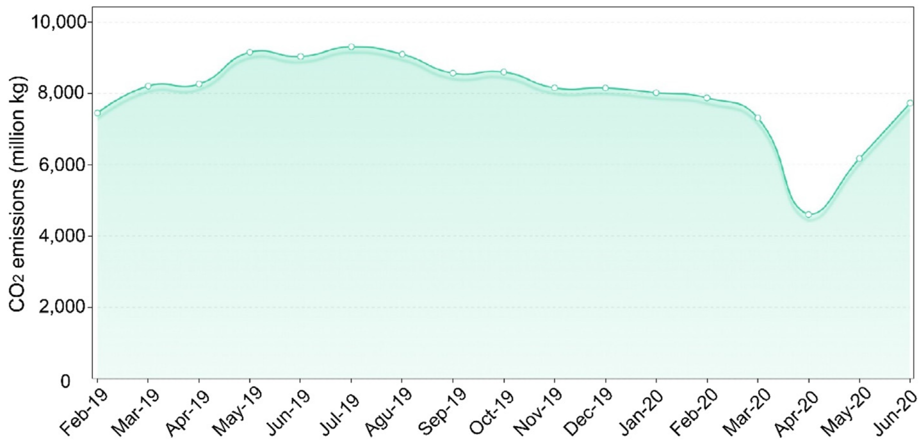


Fig. 5. Estimated CO_2 emission from the motor gasoline consumption from February 2019 to June 2020 in Canada, monthly.

3. Results and discussion

3.1. Situation of COVID-19 in Canada

As of October 9, 2020, there have been 178,117 confirmed COVID-19 cases and 9585 deaths in Canada. Most COVID-19 cases in Canada are in Ontario and Quebec, which are two most populous provinces. After the first case of community transmission confirmed in British Columbia, all provinces in Canada declared state of emergency in mid-March and prohibited gathering with varying degrees. The emergency orders included the closure of non-essential workplaces, outdoor amenities in parks and recreational areas and public places. Residents were encouraged to stay at home and keep social distance when going out. These emergency orders allowed provinces to ban gathering and different provinces have their own gathering banned policies. For example, on March 12, Quebec required banning gatherings of 10 people in a private location and 250 people in a public location. Soon after, on March 17, Ontario had their banning gatherings of 50 people indoors and over 100 people outdoors. This pandemic had a deep impact on the Canadian economy. For the economic recovery, gradual and stage-by-stage approaches to loosen emergency measures were put in place in different provinces in May 2020. The total cases in each province on the first of each month were counted as logarithmic numbers in Fig. 2. Quebec, Ontario and British Columbia had 1, 15 and 8 COVID-19 cases on the first of March, representatively. There was zero COVID-19 case on the first of March in Alberta, Saskatchewan, Manitoba, Nova Scotia and Newfoundland and Labrador. As a result, in Fig. 2, the curves of Quebec, Ontario and British Columbia start from March and the rest curves of other provinces start from April.

3.2. Changes in domestic consumption of transportation fuels

Due to the global lockdowns caused by the COVID-19 pandemic, the demand and consumption of fuel have plummeted since March 2020. It has become the most severe plunge in energy consumption since the Second World War which has been on pace to trigger multi-decade lows for the world's consumption of oil, gas and coal (Bakx, 2020). During this period, several studies have assessed the impact of COVID-19 on fossil fuel consumption. Güngör et al. (2020) collected the daily gasoline consumption data during 2014 to 2020 and forecasted the effects of COVID-19 pandemic on Turkish gasoline market. In their estimation, there was 0.8% difference compared with the actual gasoline consumption data before the COVID-19 outbreak while there was approximately 30% difference after the COVID-19 outbreak. Ou et al. (2020) quantified and forecasted the US demands of motor gasoline in varying pandemic scenarios. Under the optimistic scenario, the projected motor gasoline demand was about 98% of the demand compared with the non-pandemic scenario in late September 2020. The projected proportion number under the pessimistic scenario was about 78% of the demand under the non-pandemic scenario. From global scale, Smith et al. (2020) assessed the impact of COVID-19 on coal, natural gas and oil consumption and estimated CO_2 emissions worldwide over a two-year range. The samples were divided into advanced economics like Canada and European Union (EU) countries and emerging economies like China and Mexico. The EU countries appeared to be impacted most than the advanced group and emerging economies due to the spread of COVID-10, displaying significant negative drops in oil and natural gas consumption. Only the top three populous metropolitans in Canada were included. Therefore, a comparison of transportation fuel consumption indifferent provinces during pandemic in Canada was included in this research to know how the outbreak of COVID-19 impacted the demand for fossil fuels.

Fig. 3 shows the monthly consumption of transportation fuels, namely motor gasoline, diesel fuel and kerosene-type jet fuel, in Canada from February 2019 to June 2020 (Statistics Canada, 2020a; Statistics Canada, 2020b). The domestic consumption of each petroleum product was calculated as production plus imports minus the sum of stock change, inputs and exports. All three types of transportation fuels decreased from February to March 2020 and remained at historically low levels in May 2020. Since December, 2019, the domestic consumption of motor gasoline has been continued downward. In May 2020, it fell 49.8% while the consumption of diesel fuel oil was down 28.4% compared with 2019 (Statistics Canada, 2020b). The demand for transportation fuels remained low in June 2020 compared with the same period in 2019. Although overall refining activity increased from May to June in 2020 in Canada along with economies reopening, it would still take long time to recover to pre-pandemic levels.

In the first quarter of 2020, there was a 57% decrease in global oil demand from mobiles compared with the same period in 2019, which was the consequence of lockdown measures globally. During the confinement period, the gasoline demand was declined by 70% in both France and the United Kingdom. The decline for road gasoline consumption in Canada is less than that for the world as well as other developed countries (International Energy Agency, 2020). In 2017, the vehicles in Canada have the highest fuel consumption and CO_2 emissions with an average consumption of 8.9 L of gasoline per 100 km driven (L/100 km) and a value of 206 g per kilometer, respectively. For other developed countries, the fuel consumption averaged 8.6 L/100 km in the United States, 5.9 L/100 km in Germany and 4.9 L/100 km in Portugal (International Energy Agency, 2019). Canadians are much more dependent on vehicles than many other countries and less fuel-efficient vehicles such as SUV and trucks are often preferred in Canada. In 2017, trucks, which gradually became the preferred vehicle choice of Canadians, even accounted for 70% of newly registered vehicles in Canada (Canada Energy Regulator, 2019). Such vehicle preference is also one of the main reasons for the higher average fuel economy in Canada. The current study presents the impact of this pandemic on the cities with high fuel-economy vehicles. The air pollution and emissions from vehicles can be further reduced by strengthening green stimulus policies in adjusting vehicle purchase and promoting the fuel-efficient vehicles (Ji et al., 2020).

3.3. Changes in urban traffic volume

The reduction in traffic volume impacted by this pandemic has been seen in cities all over the world. The effect of self-isolation, social distancing, and the shuttering of shops, restaurants and offices from the pandemic could be seen in the traffic data (Parr et al., 2020). The condition of traffic flows also has the relation with air pollutant emission (Sadullah et al., 2003). In Canada, there was a slow downward trend followed by a large and fairly sudden drop in traffic congestion. In the

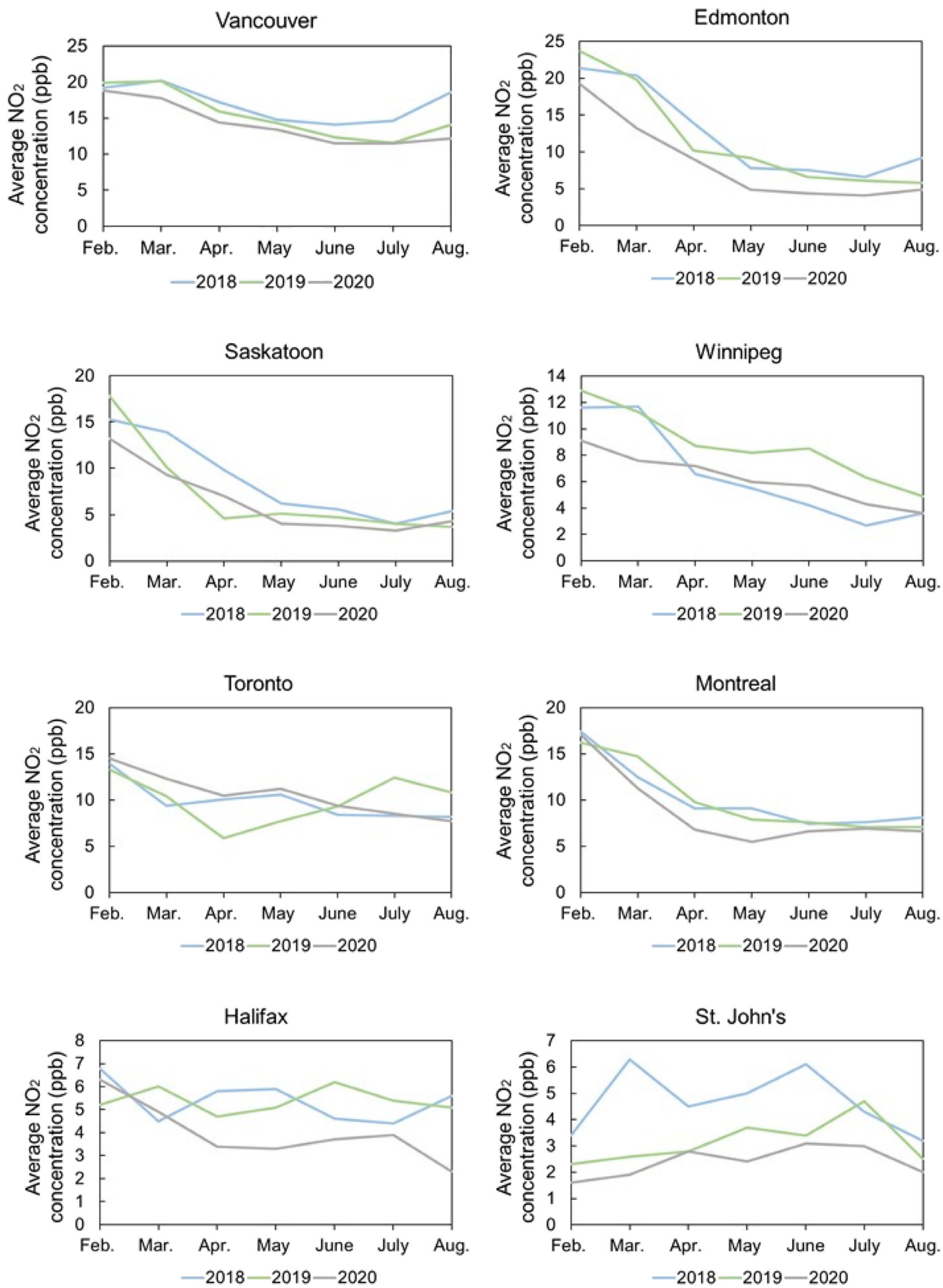


Fig. 6. Change in average NO_2 concentration from February to August in 2018, 2019 and 2020 (ppb).

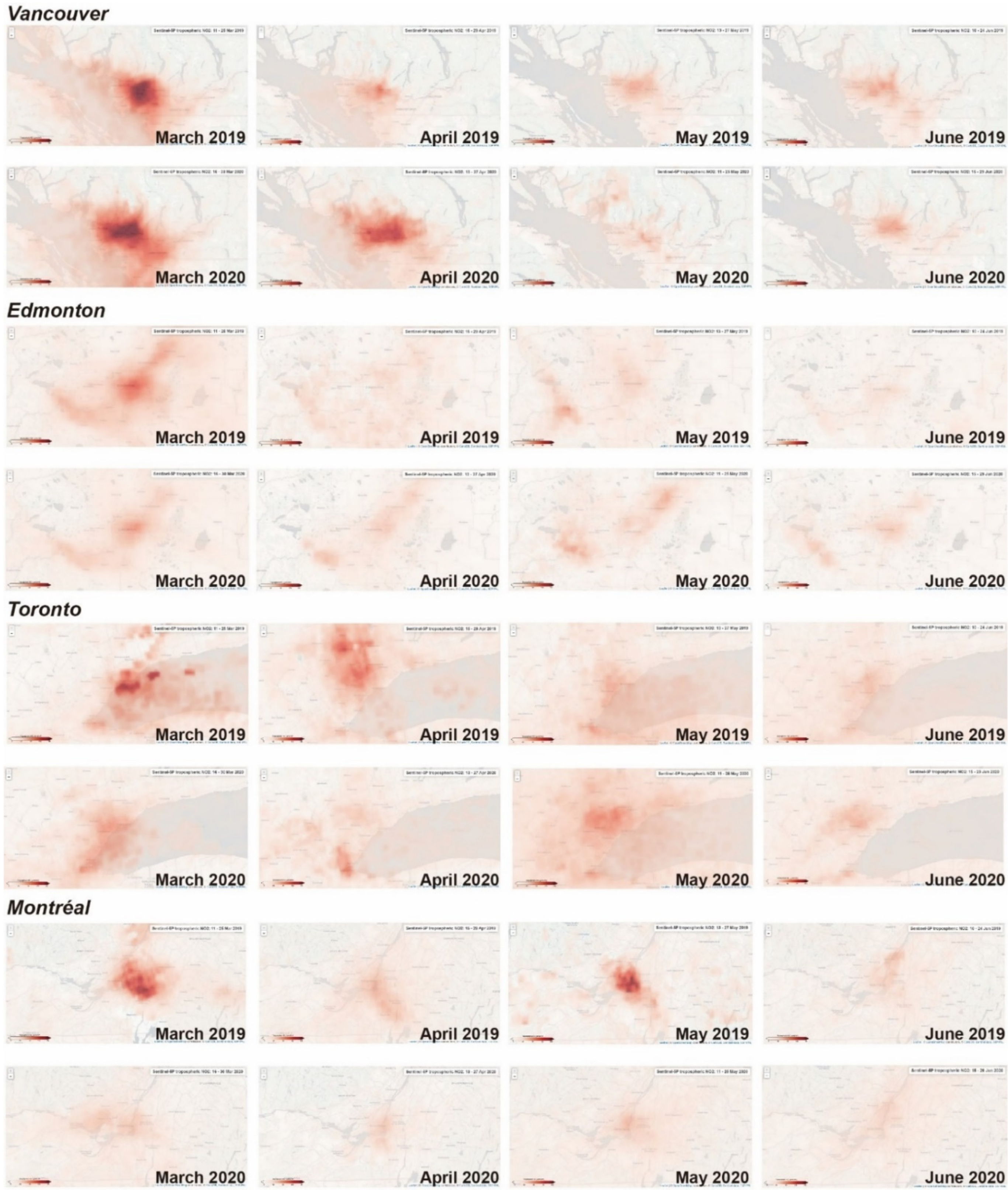


Fig. 7. Changes in NO_2 emission levels in representative cities in Canada (European Commission and European Space Agency, 2020).

present study, the average congestion condition was used to represent the traffic volume of urban transportation. The levels of daily and weekly congestion were calculated based on the hourly data, with each week starting from Monday and ending on Sunday in this data collection (TOMTOM, 2020). The daily and weekly standard congestion levels were considered. The cut-off date in this research is the end of August 2020 which is also the week 35 in the figure.

Fig. 4 shows the average congestion level of Vancouver, Edmonton, Winnipeg, Toronto, Montréal and Halifax in 2020 and the relative difference of average congestion levels in 2020 from corresponding standard congestion levels in 2019. In Vancouver, the peak rush-hour congestion decreased 54% compared to the average weekday rush hour in week 12, which was the start of COVID-19 restrictions. Compared with the other five cities, the trend of decline during restriction and the trend of recovery during reopening period in Vancouver was relatively moderate. In week 12, the traffic congestion level decreased 69% and 75% in Toronto and Montréal, respectively, compared with 2019. In the first week after the restriction policy declared in Toronto, the traffic congestion level dropped significantly, while in Montréal, the congestion was reduced 32% in the first week and dropped significantly until the second week. During the pandemic period, the traffic congestion level in Edmonton showed the largest drop of 71% in week 15, while the congestion level in week 35 was 35% less than standard weekly level in 2019. The impact on traffic from this pandemic in Winnipeg was the smallest among these six cities, with the lowest decrease of 60%. Toronto and Halifax are the only two cities in which the traffic congestion levels began to decline before week 12 compared to 2019. After the opening policy was announced, the traffic congestion in Halifax has returned to levels before the pandemic on the Friday of week 35. Among these six cities, Montréal and Halifax are the top two cities where traffic volume levels have the fastest recovery after the reopening. As of week 35, the congestion level declined by 25% in Montréal and 27% in Halifax compared with the standard weekly congestion level in 2019. Although it can be seen that the traffic volume was gradually recovering, the change for the remaining time of the year will be contingent on the duration and extent of the restriction (Le Quéré et al., 2020).

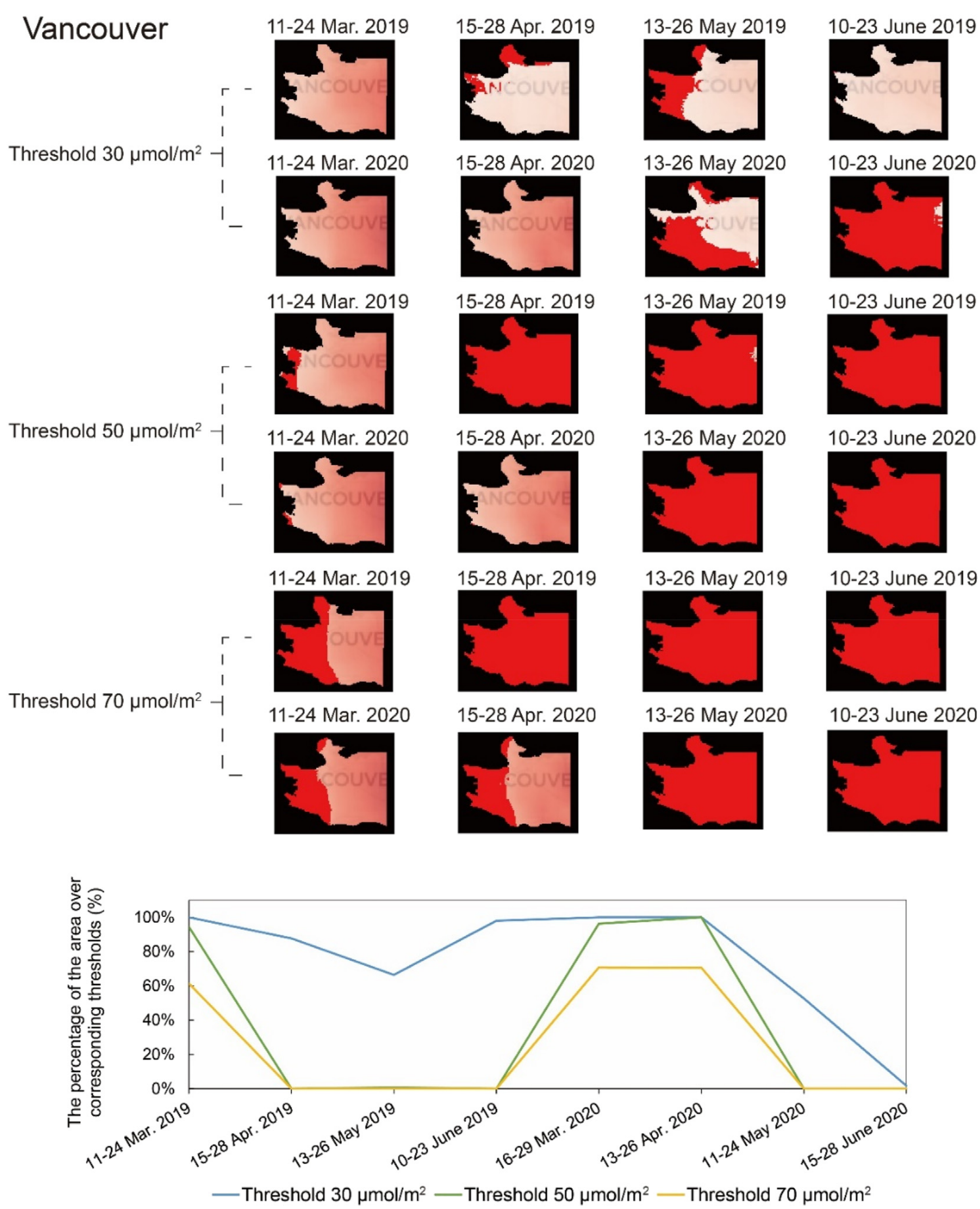


Fig. 8. Area with NO_2 concentration and the percentage of aera over corresponding thresholds in Vancouver from March to June in 2019 and 2020 (the red area is the area with the NO_2 concentration less than corresponding threshold level and the remaining area is the area that meets the threshold with the NO_2 concentration higher than certain level.)

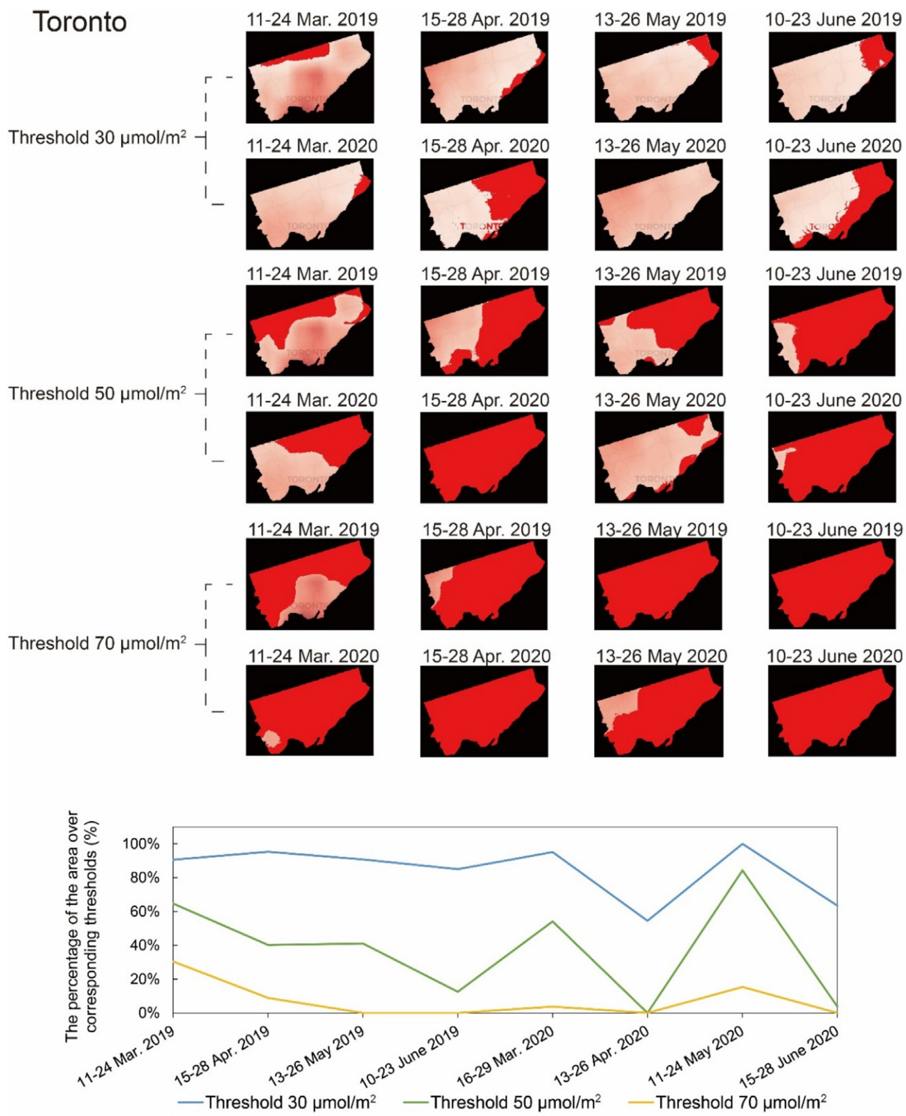


Fig. 9. Area with NO_2 concentration and the percentage of aera over corresponding thresholds in Toronto from March to June in 2019 and 2020 (the red area is the area with the NO_2 concentration less than corresponding threshold level and the remaining area is the area that meets the threshold with the NO_2 concentration higher than certain level.)

3.4. Changes in CO_2 emissions from vehicle fuel consumption

Vehicle emissions can be estimated and calculated according to either the fuel consumed or the distance travelled by the vehicles. Generally, the first approach represented by fuel consumption is appropriate for the estimation of CO_2 emissions (Eggleston et al., 2006). The Tier 1 approach recommended by Intergovernmental Panel on Climate Change (Eggleston et al., 2006) as used to calculate the CO_2 emissions based on the domestic consumption of motor gasoline with a CO_2 emission factor. The calculation of CO_2 emission for fuel consumption is shown in Eq. (1).

$$Emission = \sum_{a} [Fuel_a * EF_a] \tag{1}$$

where *Emission* is the total emission of CO_2 (kg); $Fuel_a$ is the fuel sold (L); EF_a is the emission factor for refined petroleum products (kg/L); a is the type of fuel. The CO_2 emission factors are mainly influenced by the fuel properties, followed by combustion technology. To ensure consistency with the guidelines from IPCC in 2006, Environment and Climate Change Canada (2016) directed and developed the value of the major class of refined petroleum products using data provided by industry to the Canadian Industrial Energy End-Use Data Analysis Centre (CIEEDAC).

Fig. 5 presents an estimation of the CO_2 emissions from the motor gasoline consumption from February, 2019 to June 2020 in Canada. There was a significant drop in estimated CO_2 emissions from 7303.73 million kg in March to 4593.01 million kg in April in 2020 due to the lockdown in different provinces. The estimated CO_2 from motor gasoline consumption in April 2019 is 8253.52 million kg, which is almost twice that in April 2020. With the implementation of reopening policy, CO_2 emissions gradually rebounded in May 2020. Different from previous economic crises, the economic critical stage concomitant by COVID-19 was more deeply anchored in constrained individual behavior. At present, even though the emissions level rebounded, it is still unclear how the second wave of COVID-19 in Canada will affect CO_2 emissions. Being aware of changing emission levels can be helpful for the government to determine the future emissions trajectories in carbon-intensive pathways through the post-pandemic period (Le Quéré et al., 2020; Feng et al., 2020; Yao et al., 2020; Richards et al., 2016).

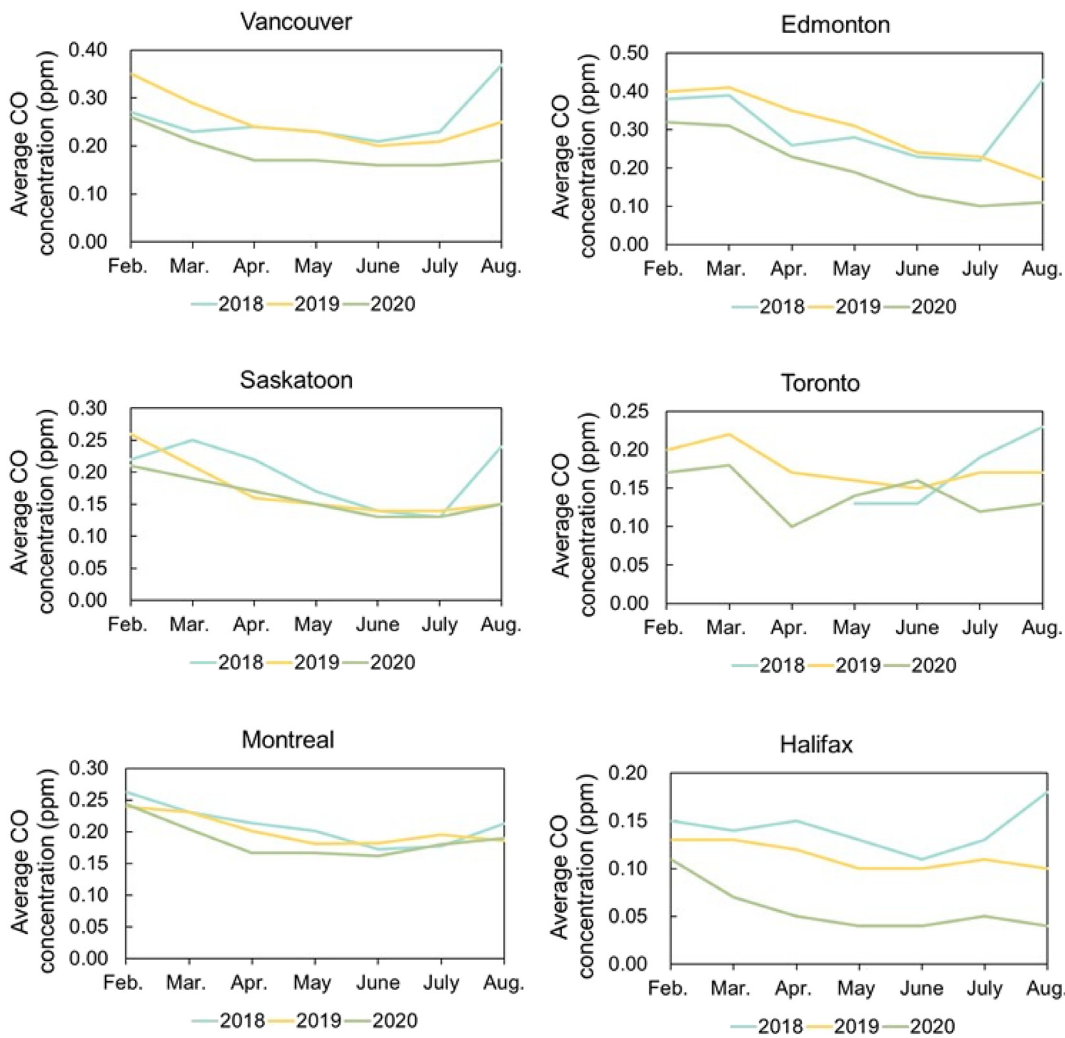


Fig. 10. Change in average CO concentration from February to August in 2018, 2019 and 2020 (ppm).

3.5. Changes in urban air pollution indicators

3.5.1. NO_2 concentration

Most NO_2 emissions come from burning of fossil fuels, especially from vehicles. In 2018, about 51% of NO_x emission derived from the transportation mobile equipment in Canada (Environment and Climate Change Canada, 2020). The COVID-19 restriction could result in the change of average NO_2 concentration. It was found the NO_2 concentration in cities of China deceased 40% compared with the same period in 2019. Similar decrease (20% to 38%) was also observed in western Europe and the United States (Xiang et al., 2020b). However, the monitoring results in Iran didn't show less emissions from vehicles (Bauwens et al., 2020). In this study, the NO_2 concentrations at the same time period in 2018, 2019 and 2020 were compared among eight cities in Canada and the results are shown in Fig. 6. It can be seen these cities experienced NO_2 decreases in 2020 compared with the same period in 2019 and 2018 except for Toronto and Winnipeg. During the period in 2020, the most significant change was in Edmonton with a 78.6% decline from February to July. Although the date of emergency declared in Toronto was earlier than that of other cities apart from Montréal, Toronto was the only city that had consistently exceeded pollution levels from April to June. From February to August in 2020, Vancouver, Edmonton and St. John's were the cities with NO_2 concentration level not exceeding the previous two years. British Columbia had good pandemic control since the outbreak. Among the most populous provinces with serious pandemic, the changes in the level of pollutant concentrations can also reflect the level of public health and control measures in different regions.

3.5.2. Spatial–temporal variation of NO_2 concentration

The maps in Fig. S1 based on the data from the Copernicus Sentinel-5P satellite of European Space Agency (ESA) can show a 14-day average NO_2 concentration across Canada (European Commission and European Space Agency, 2020). The variations of air pollutants such as NO_2 are not only the manifestation of changes in emissions, but also the indicators of economic and urban development (Ye et al., 2020; Tian et al., 2020). In Fig. 7, the satellite images of four cities, Vancouver, Edmonton, Toronto and Montréal, are presented. The satellite images showing the amount of NO_2 from March to June in 2019 and 2020 in four cities were compared. The average levels of atmospheric NO_2 in these major Canadian cities and their surrounding areas have plummeted during this pandemic compared to a year ago. Since The change in NO_2 concentration is consistent in these four cities. In April, the month after the emergency declared, the concentrations of pollutants in these cities of Canada have decreased to a certain extent. As there was a gradual control for the pandemic and a need for economy recovery, the stage-by-stage reopening was put on the agenda in May in different cities. The NO_2 concentration level had a certain degree of rebound after July 2020. In fact, it can be seen that the effect of short-term quarantine

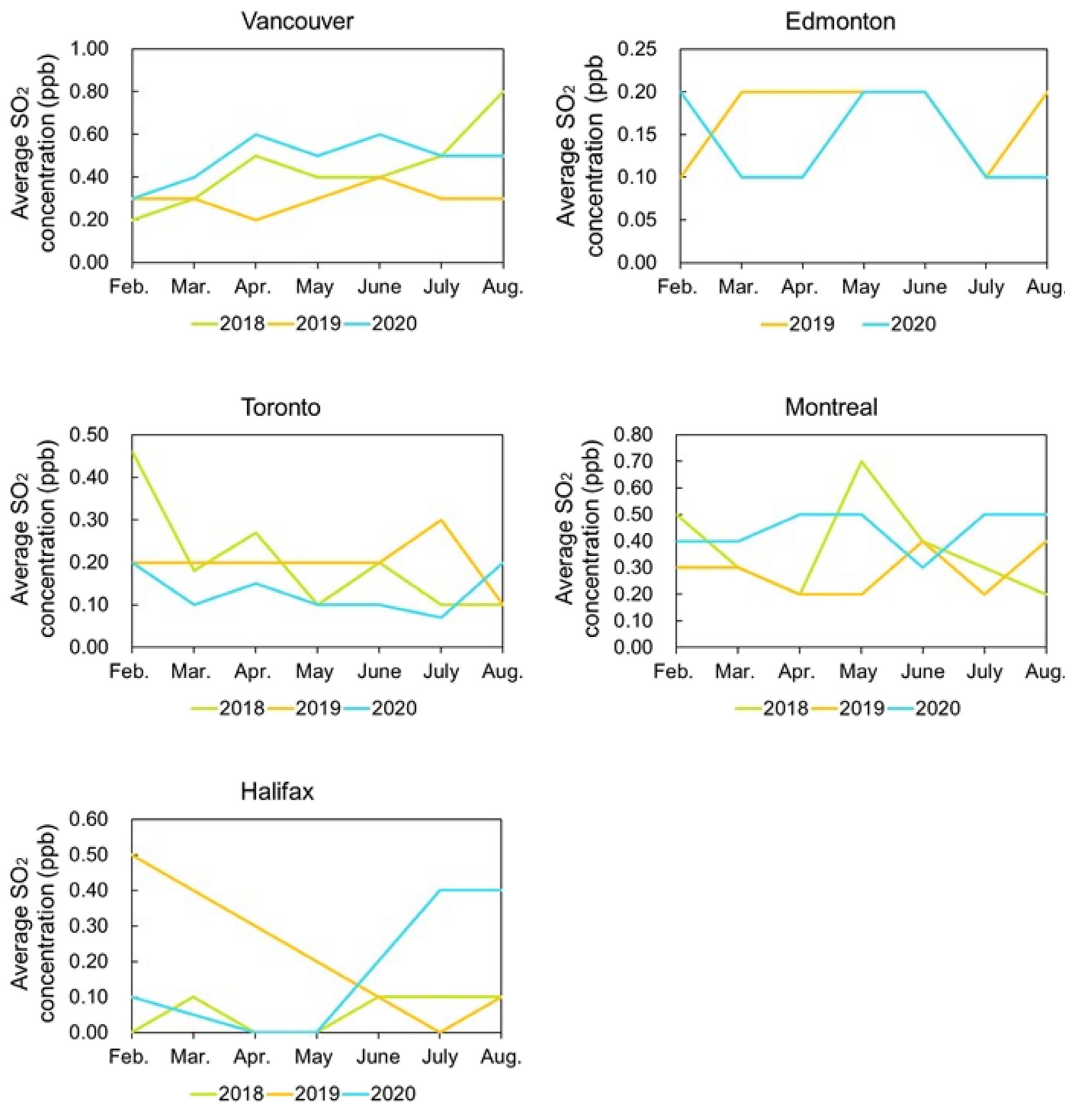


Fig. 11. Change in average SO_2 concentration from February to August in 2018, 2019 and 2020 (ppb).

in reducing air pollution was significant, but could be only temporary (Yang, 2020). The changes in NO_2 emission levels at Saskatoon, Halifax, Winnipeg and St. John's were not significant (Fig. S1).

In order to better reveal the changes of NO_2 concentration in the urban areas, the image binarization was conducted for further analysis based on the satellite images in Fig. 7. Image binarization is a thresholding method, which is a form of segmentation to divide the image into constituent objects. In this study, the pollutant analysis based on image binarization could help analyze the area variation under different thresholds of NO_2 concentration. The concentration range of tropospheric NO_2 in the Copernicus Sentinel-5P satellite is from 0 to 180 μmol/m^2. 30, 50 and 70 μmol/m^2 were selected as the threshold levels. Vancouver and Toronto were chosen as the representative cities to compare the NO_2 changes from March to June in 2019 and 2020. Fig. 8 to Fig. 9 show the results of image binarization analysis. It can be seen for both Vancouver or Toronto from March to May in 2019, the above-threshold area percentage exhibits an overall downward trend. In April 2020, due to the start of emergency measures in Toronto, the above-threshold area ratios all dropped sharply. At the same time in Vancouver, due to the impact of wildfires, the above-threshold area ratio did not decrease even during the lockdown period. With the start of the first-stage reopening in Toronto, the areas above different NO_2 threshold concentrations rapidly expanded in May 2020 due to increasing travel and retaliatory consumption behaviors (Wang and Wang, 2020). However, in Vancouver, there was a continuous downward trend from May 2020.

3.5.3. CO concentration

CO in the air can enter the bloodstream and reduce oxygen delivery, which is the cause of fatal poisoning reported in many countries (Raub et al., 2000). In northern United States, the rate of accidental death resulted from CO emitted from motor vehicles is high in the northern and usually peaks in the winter (Ernst and Zibrak, 1998). Most CO is produced by the incomplete combustion of fossil fuels. Approximately 5.8 Mt. of CO were emitted in Canada in 2018, which decreased by 54% compared with that in 1990. The Air Pollutant Emissions Inventory Report in 2020 in Canada (Environment and Climate Change Canada, 2020) indicated that transportation and mobile equipment sector accounted for 56% of total CO emissions. Fig. 10 presents the change in average CO concentration from February to August in 2018, 2019 and 2020 at Vancouver, Edmonton, Saskatoon, Toronto, Montréal and Halifax. Winnipeg and St. John's were not included due to the lack of monitoring data or negligible magnitude of CO concentration level. The line graphs were not shown for several months in Toronto due to the lack of monitoring data for CO concentration. The CO concentration level of six cities all decreased from March 2020. The average CO concentration in Edmonton dropped from 0.14 to 0.07 ppm in March from 2018 to

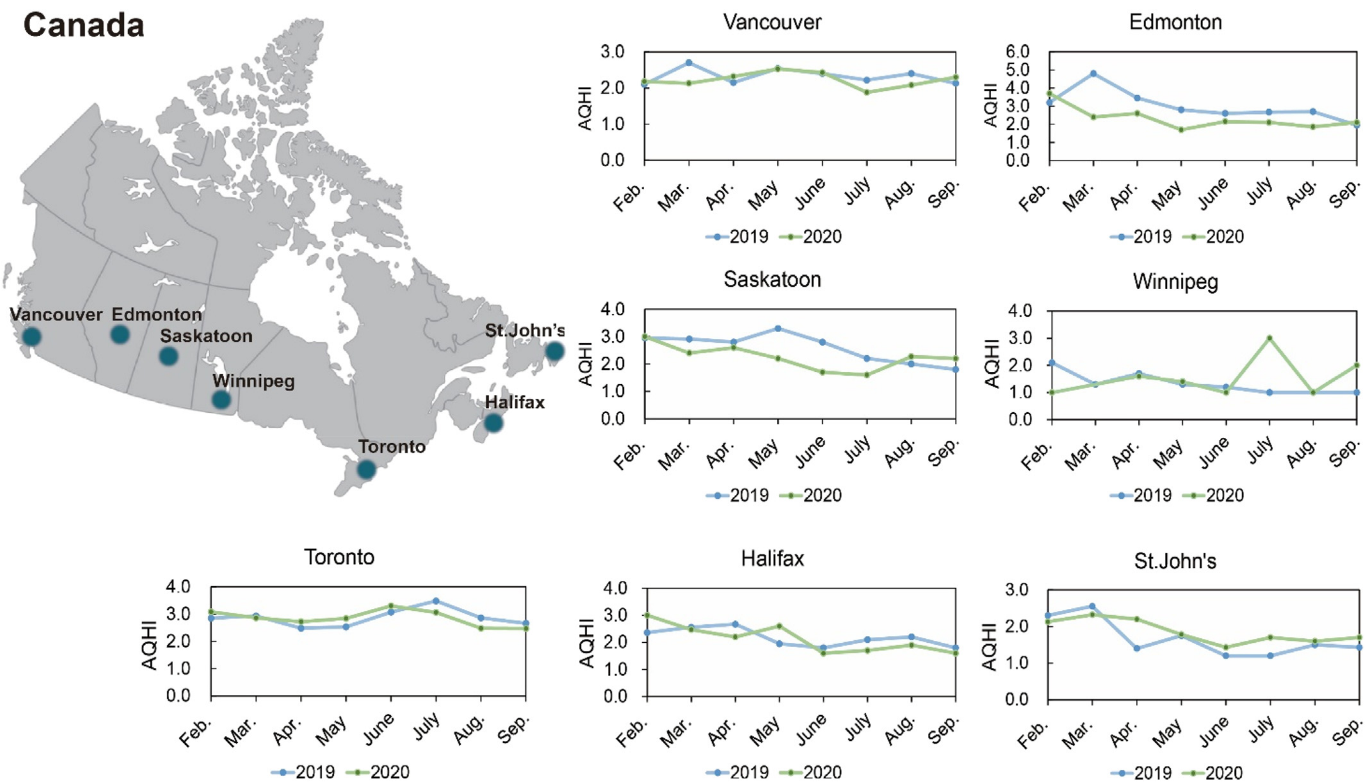


Fig. 12. Comparison of Air Quality Health Index (AQHI) in representative cities of Canada in 2019 and 2020 (Environment and Climate Change Canada, 2019).

2020, with a highest decreasing ratio of 50% among these cities. From May to August, the average concentration in this city remained around 0.04 ppm. Different from other cities, the average CO concentration level in Toronto had a significant rebound from 0.10 ppm in April to 0.16 ppm in June 2020. Before the pandemic began, the average CO concentrations of Vancouver, Halifax and Edmonton in 2020 were significantly lower than those in 2018 and 2019. During the period of lockdown, the decrease of CO concentration in these three cities was much faster. Based on the analysis aforementioned, the traffic congestion in Halifax during the pandemic has been reduced compared with same period in previous years, while the changes in Vancouver fluctuated without a decreasing trend. It indicated that the CO concentration in Halifax was more affected by residents' travel while Vancouver did not.

3.5.4. SO_2 concentration

The variation of SO_2 concentration in different Canadian cities are shown in Fig. 11. Due to the limited data, only Vancouver, Edmonton, Toronto, Montréal and Halifax were included in this analysis. The Alberta Air Data Warehouse and Alberta Capital Airshed (ACA) lacks SO_2 concentration data in 2018 in Edmonton and thus only the data of 2019 and 2020 were collected. It can be seen that the impact of this pandemic on SO_2 concentration in each city was not significant. From 1990 to 2018, the whole SO_X emissions in Canada decreased by 73%. Ore-mineral and oil-gas industries are two of the largest contributors, each accounting for 32% of total SO_X emissions in Canada (Environment and Climate Change Canada, 2020). Smaller anthropogenic sources of SO_2 emissions involve locomotives, ships and vehicles with heavy equipment that burn fuel with a high sulfur content. The concentration changes from 2018 to 2020 in Fig. 11 did not show clear correlation between SO_2 concentration and this pandemic.

3.5.5. AQHI impacted by the pandemic

The AQHI is a scale designed to provide hourly air quality and related health information (Lerner et al., 2019). It is calculated based on a comprehensive consideration of various pollutants, including ozone at ground level, particulate matter and NO_2 (Xiao et al., 2020). Different from the Air Quality Index (AQI) which communicates the air quality based on a single worst pollutant, the AQHI can reflect the health risk based on a mixture of pollutants associated with air pollution (Chen et al., 2013).The AQHI helps people to know the levels of air pollution in their surrounding environment on a scale ranging from 1 to 10+. The health risk associated with the air quality increases as the AQHI rises (Asif and Chen, 2020). There are four groups of the index reading which are low risk (1–3), moderate risk (4–6), high risk (7–10) and very high risk (10+). Fig. 12 presents the AQHI from February to September in Vancouver, Edmonton, Saskatoon, Winnipeg, Toronto, Halifax and St. John's in 2019 and 2020. The AQHI of most cities declined to varying degrees after February 2020, except for Winnipeg and St. John's. Among these cities, Edmonton showed the largest decline which dropped from 3.7 in February to 2.4 in May. In Halifax, Edmonton, and Saskatoon, the AQHI during pandemic period in 2020 was lower than that in 2019.

4. Conclusions

This study proposed a new perspective regarding the dynamic impacts of the COVID-19 pandemic on the urban transportation and emission. Due to the lockdown after the outbreak of COVID-19, the domestic consumption of motor gasoline and estimated CO_2 emissions from urban vehicles in Canada has continuously decreased with a lowest level in April 2020, and rebounded in May 2020. Although the overall refining activity increased from May to June in 2020 along with reopening, it will still take a long time to recover to pre-pandemic levels duo to the upcoming second wave of pandemic and further change. The pandemic significantly reduced the traffic volume and congestion level in Vancouver, Edmonton, Winnipeg, Toronto and Montréal compared with the same period in 2019. The AQHI and concentration level of NO_2 and CO had strong relevance with the COVID-19 period while SO_2 did not show significant relation. The urban air quality throughout the country improved a lot during the pandemic period, which will be still unclear how the rebound will be. It also indicates that emissions from urban vehicles account for a large proportion air pollutant emission in urban areas. It is expected to further promote the development of public transportation facilities and use the energy-saving and emission-reducing vehicles in these cities. The comprehensive analysis of changing fuel consumptions, traffic volume and emission levels will help the government assess the impact and make corresponding strategy for such a pandemic in the future.

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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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