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Transformation of urban mobility during COVID-19 pandemic – Lessons for transportation planning

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ABSTRACT

Introduction: The coronavirus disease (COVID-19) pandemic is a global threat that started in Wuhan, China, in 2019 and spread rapidly to the globe. To reduce the spread of the COVID-19, different non-pharmacological control measures have been conducted in different countries, which include social distancing, distance working, and stay-at-home mandates. These control measures had affected global transportation and mobility significantly. This study investigated the short-term changes in urban mobility, tropospheric air pollution, and fuel consumption in two major cities of Saudi Arabia, namely, Riyadh and Jeddah.

Methods: In this study, the dynamics of the number of trips and trip purposes in different provinces of the country were analyzed, focusing on the pandemic period and the lockdown program. These changes impacted fuel consumption and, consequently, air pollutants. The quantity of fuel consumption and its trend was projected considering a few possible fuel consumption and emission scenarios. It is also expected that fuel price plays a role in fuel consumption. The spatial and temporal distributions of the remote sensed tropospheric Nitrogen Dioxide (NO2) levels in different provinces were presented to depict the short and long-term impact on the air quality due to the changes in mobility.

Results: The significant reduction in urban mobility has been observed since the beginning of the first partial curfew in March 2020 compared to that in 2019. The air pollutant levels (such as NO2) in 2020 after the pandemic were generally less than those of 2019. The fuel consumption has been following a decreasing trend in 2020 starting from January due to dynamic fuel price and the additional influence of pandemic. Based on the current online shopping pattern, it is argued that there will be some permanent behavioral changes in urban mobility, which will decrease some shopping trips at least immediately after the recovery from the pandemic.

Conclusions: This study concluded that the availability of global urban mobility data, remote sensed based tropospheric air pollution data, and global fuel consumption database are important sources of information to investigate the impact of COVID pandemic, especially for the developing countries which suffer from scarcity of pertinent urban mobility information. It seems that, at least in the study area, the spread of COVID-19 is a complex phenomenon in which several exogenous factors, in addition to the curfew protocols, affect the spread of the virus.
1. Introduction

Global pandemics are known to spread on a broader scale and to significant levels due to the mobility of people (Merler and Ajelli, 2010). The last example of such pandemic is H1N1 influenza, which affected many regions of the world, including Asia, Europe, and the USA in 2009 (Momonaka et al., 2014). This pandemic started in June 2009 from Mexico, which resulted in a 40% reduction in the trips to/from it (Bajardi et al., 2011). Some studies linked the spread of this pandemic to the local and international mobility patterns (Merler et al., 2011). Despite this fact, there were limited restrictions on routine travel in most parts of the world except Mexico, consequently having a negligible effect on the mobility patterns (Kraemer et al., 2020).

The coronavirus disease (COVID-19) pandemic is a global threat that started in Wuhan, China, in 2019 and spread rapidly to the globe (Jiang et al., 2020; Lipsitch et al., 2020). As of August 4, 2020, the number of confirmed cases, deaths, and recovered cases were 18, 664, 940, 702,562, and 11, 884, 307, respectively. To reduce the spread of the COVID-19, different non-pharmaceutical control measures have been conducted in different countries which include social distancing, distance working, and stay-at-home mandates (Kraemeret al., 2020).

These control measures had affected global transportation and mobility significantly (Falchetta and Noussan). There was a significant fall in traffic volumes and global economic activities. As a result, the oil demand has significantly dropped, which lead to the price of a barrel of West Texas Intermediate (WTI) crude oil, reaching 11.57 US Dollar on April 21, 2020. Engle et al. (2020) conducted a study to investigate the effects of COVID-19 outbreak and stay at home policy on people’s mobility in the USA. They found that an increase in the infection rate from 0 to 0.003% resulted in a reduction in mobility by 2.31% and stay at home policy reduced mobility by 7.87%. The effect was more pronounced in metropolitan cities of the USA. According to Gao et al. (2020), stay at home has reduced the transit ridership and traffic volume in New York by 94% and 72%, respectively.

Similar trend was observed in Seattle, USA, where the reduction in commuting journeys and journey times was 60% and 26%, respectively (Understanding the, 2020). Klein et al. (Klein et al., 2020) found a reduction of 60% and 50% in inter-city mobility and total commutes in the major cities in the USA. In New York City, traffic levels during the Covid-19 outbreak were found to be less by 35% compared to the same period of the last year (BBC, 2020). Moreover, based on the TomTom traffic index, the congestion levels nowadays are less than 10% in many cities around the world, which is probably due to the effect of COVID-19 (TomTom, 2020). Aloī et al. (Aloī et al., 2020) found that car usage fell by 68% in Santander, Spain, due to the spread of COVID-19.

Beck and Hensher (2020) conducted a questionnaire survey study to investigate the effect of restrictions imposed by the Australian government in response to COVID-19 on Australian residents’ mobility. The participants were asked about their daily activities such as travel, employment, and shopping before and during the COVID-19 outbreak. The analysis of survey results revealed that people’s mobility reduced by more than 50% due to the COVID-19 pandemic. The trend was same for all modes of transport and household trips. The recent Official Airline Guide (OAG) aviation report stated that commercial flight operations had reduced significantly to less than one-third of its volume as compared to the same period of 2019 (Worldwide). In another report (Impact of Coronavirus), it revealed that the demand for public transport declined by more than 60% in many countries compared with the pre-COVID-19 period.

Researchers around the world have been estimating the possible effects on human mobility due to the restrictions on travel which were imposed to reduce the spread of the virus. They have provided significant insights about the mobility and spread of COVID-19 infections relationships. Kraemer et al. (Kraemer et al., 2020) showed that travel restrictions are useful at an early stage of an outbreak if the spread is confined into a locality; however, such measures have less effect when the outbreak is widespread. Askitas et al. (2020) revealed that the demand for public transport declined by more than 60% in many countries compared with the pre-COVID-19 period. A reduction of 60% reduction in NOx was recorded during the pandemic (Aloī et al., 2020). Global emissions of CO2 due to transportation have been reported to decline by 17% (average) in April 2020 compared to those in 2019 (Le Quéré et al., 2020). Another aspect of reduction in mobility is the decline in fuel consumption. It had affected the oil market significantly with a decrease in prices (Fernandes, 2020; Ozili and Arun, 2020).

Previous studies have also shown that whenever people are forced to reduce their travel due to any policy, then they develop new travel habits with reduced mobility even after the restrictions are lifted (Henriques, 2020). Concerning future changes in mobility, New Zealand can be taken as a case study to foresee the changes since it is considered as a COVID free country. It has been reported that some of the air carriers have been wholly immobilized, and demand for labor has reduced even after the revocation of restrictions. It is predicted that demand for the transport sector may not be the same as the pre-COVID period in the coming 2–3 years (De Morel et al., 2020). Tourism has been on a decline as well, which has asked for an exploration of other sources of income for communities and
countries relying on it (Carr, 2020). It has also been hypothesized that the tourists’ destinations (local as well as international) would see a shift in preference as people would try to avoid overcrowded places (Wen et al., 2020).

One of the concerns, when life goes back to normal, is how people will travel and how driving behavior or mode choice will be altered. If people choose to use their cars instead of using public transportation, pollution rates and collisions may increase. The new rules and restriction orders affected the individuals’ mobility and the transport sector significantly. Furthermore, working from home and online shopping is expected to reduce the home-based work trips and shopping trips, which will negatively affect the freight and mass transportation sectors. Moreover, it has been revealed that COVID-19 caused social stigma towards using specific transport modes such as buses, trains, and planes due to its high risks of infection attributed to proximity with other travelers (Falchetta and Noussan; De Vos, 2020).

The previously mentioned studies pertinent to the COVID-19 pandemic and urban mobility have mainly focused on developed countries due to the availability of data. However, similar research, related to mobility and its impacts, becomes difficult for developing countries where continuous data is scarcely available for mobility. Hence, the present study presents an investigation into changes in urban mobility and consequent effects on tropospheric air pollution levels and fuel consumption for Saudi Arabia mainly based on publicly available information. The study would be useful to investigate the country-level effects on mobility due to the COVID-19 pandemic or any other event of similar nature especially for developing countries.

The rest of the paper is organized as follows. Section 2 describes the study area. Section 3 explains the research methodology followed in this study. Analysis and results are discussed in section 4. Finally, section 5 summarizes the conclusions and recommendations for the future.

2. Study area

2.1. COVID-19 pandemic in Saudi Arabia

Saudi Arabia is the second-largest country in the Arab world, with a population of approximately 34 million of which 37% consists of nationals from different countries other than Saudis (General authority of stat). The middle age group of 15–64 make up approximately 65% while the rest belongs to the age groups of 0–14 (32.4%) and over 65 (2.8%) (General authority of stat). Private hospitals across the country also contribute to the healthcare service. The number of beds per 1000 population in Saudi Arabia is at 2.2 (Algaissi et al., 2020).

The World Health Organization (WHO) declared and labeled the COVID-19 as Public Health Emergencies of International Concern (PHEIC) on January 30, 2020, and subsequently, as a pandemic on March 11, 2020 (Elhassan and Gaafar, 2020). Building upon that, the whole world currently has been battling against the unprecedented and catastrophic repercussions from the COVID-19 pandemic. This pandemic almost invaded the lives and disrupted the daily routines of people across nations, including Saudi Arabia. Until August 4, 2020, the COVID-19 has spread over 213 countries. In Saudi Arabia, 281,456 cases were reported with more than 2984 deaths due to the COVID-19. The consequence of this deadly peril unfolded on people, their business, and mainly on the mobility of the citizens and residents in Saudi Arabia.

Saudi Arabia is one of the few potential candidate countries that fall under the severe threat of havoc during the global pandemic. Millions of Muslims across the world visit Saudi Arabia for the pilgrimage (Umrah and Hajj), which happens to be the most significant global mass gatherings on earth. Umrah is an Islamic ritual performed by thousands of Muslims daily in the city of Makkah. At the same time, Hajj is an annual five days pilgrimage (mandatory to all able Muslims for a once in all lifetime event) to the holy sites in Makkah. An estimated 7 million people perform Umrah, and about 2 million pilgrims perform Hajj annually. Additionally, Kingdom’s Vision 2030 envisages a proliferation of businesses, international investments, growing tourism, and requires preparation for it to be an active travel destination. Despite the enormous efforts the government of Saudi Arabia set forth to ensure the healthliness, safety, and security of pilgrims, Umrah and Hajj remain to be the events of possible spread of infectious diseases (Hashemet al., 2019; Memishet al., 2014).

Responding to the possible spread of the novel COVID-19 pandemic in the country, on 6 February, approximately a month before the first case appeared in the country, all flights to and from China were stopped. The government enacted the suspension of all international pilgrims and tourists on 27 February, and checkpoints were established to monitor the movement to the holy cities of Makkah and Medina. The prerogative of using national I.D. cards other than passports to travel to the Gulf Cooperation Council (GCC) countries by Saudi Nationals and entry of other nationals to the country was also revoked. However, exemptions were given to those who had already exited the country using the I.D. cards and were waiting to return. By 28 February, Saudi Arabia banned inbound travelers from COVID-19 affected countries, including GCC citizens who have traveled to affected countries. Even with the strict measures, Saudi Arabia reported its first COVID-19 confirmed case on 2 March. Umrah (pilgrimage) was entirely suspended by 4 March, and the entry to the two holy mosques in Makkah and Medina were closed for sterilization on 5 March. Physical attendance to the school and universities across the country was shut off on 8 March; however, the teaching and learning activity continued to function through virtual classrooms. On 12 March, social gatherings and events were banned, with all international summits being postponed for an uncertain time. All types of air travel, sports event, and attendance to workplaces were suspended until further notice.

The most remarkable decision was to stop the daily five times prayer at mosques to curb the spread of the virus.

Furthermore, other mass transits, for example, the Kingdom’s metro services have also been suspended. The famous Riyadh-Dammam line through Abqaiq and Hofuf, the Riyadh-Jouf line through the Majmaa, Al-Qassim, and Hail, and the Haramain Express all have been docked and remain without functioning. Nevertheless, freight trains between King Abdulaziz Sea Port in Dammam and the Riyadh land Port and the mining train of the Saudi Railways Company “Saar” are in operation to transport daily necessaries.

As the number of cases reached 500 in the last week of March, the government imposed a curfew and hefty financial penalties for
violators. By the end of March, the Saudi government announced a lockdown on its major cities in Riyadh, Jeddah, Makkah, and Medina, and all inter-province travel was banned. Apart from increasing the number of tests per day in its stricter measures, Saudi Arabia went for a 24-hr curfew throughout the Kingdom, enforced lockdown and isolation of several severely affected suburbs and districts in major cities in April 2020. During the first three-quarters of May, the majority of the cities were under partial curfew measures with a hope to reduce the spread of the virus. The congregation 

\textit{Taraweeh} prayer at the mosques other than the two holy mosques was called off in the holy month of Ramadan for Muslims, and people were instructed to pray at home. The authority went for 24 h full lockdown from 23 May to 27 May, which also includes the Eid festival for Muslims (Algaissi et al., 2020).

Saudi Arabia started re-opening the regular activities in phases at the end of May. Return to “normalcy” was announced to take place on June 21, 2020, everywhere in the country except Makkah. On 22 June, the authority officially declared that the Hajj pilgrimage in 2020 would be performed in a limited capacity to minimize the number of people permitted.

At the onset of the pandemic, the medical consultancy and advice through digital channels were quickly introduced, and health service mobile applications were developed to seek health prescriptions. These measures allowed the residents not to visit the hospitals for minor reasons to help reduce the burden of health service providers. All these measures were taken at a time when the number of active cases was still below 300. The social media had an impeccable role in disseminating relevant information and preventive measures against the virus spread.

![Daily Confirmed COVID-19 cases and Curfew measures taken in Riyadh](image1)

![Daily Confirmed COVID-19 cases and Curfew measures taken in Jeddah](image2)

**Fig. 1.** Fig. 1a. Daily confirmed COVID-19 cases in Riyadh. Fig. 1b. Daily confirmed COVID-19 cases in Jeddah.
2.2. Background of Riyadh and Jeddah cities

Riyadh and Jeddah have been selected for studying and predicting mobility patterns in this study. These are the major cities of Saudi Arabia that have experienced exponential growth over the years. Riyadh is the capital and largest city of Saudi Arabia, which is located in the central region of Saudi Arabia. It has grown in population from 5 million (in 2008) to more than 6 million in 2017, with an area of 300,000 ha (Alotaibi, 2017; Alqhatani et al., 2013). The current population of Riyadh is 8 million (Al-Shammari and Bendak, 2020).

Jeddah is the second largest and the first commercial city in Saudi Arabia (Aljoufie, 2016). Jeddah is located in the western region of Saudi Arabia on the Red Sea eastern coast. The population of the city was recorded approximately 4.5 million in 2018 (UN-Habitat, 2018).

The impact of government actions on the spread of COVID-19 in Riyadh and Jeddah is shown in Fig. 1a and b, respectively. The government of Saudi Arabia acted promptly with the first discovered cases of COVID-19 in March 2020. Although schools were off for the summer break at that time, partial curfew was imposed on Riyadh and Jeddah in the third week of March (Fig. 1). Between 21 March and 21 June, four different protocols of curfew were imposed on Riyadh versus three different curfew protocols for Jeddah (Fig. 1a and b). The curfew protocols on Jeddah were more stringent than Riyadh, especially at the beginning of the pandemic and before lifting the curfew and returning to normal mobility. It should be mentioned that the authorities conducted active screening (testing random samples of the population) for the COVID-19, only in Riyadh during the first three weeks of June. This is presumably the cause of the dramatic jump in the number of cases during that period compared to the number of cases in Jeddah during the same period. There was a general tapered spread of the virus toward the end of the three months curfew in both cities (Fig. 1).

3. Methodology

3.1. Approach

The scarcity of mobility data is prevalent in developing countries, including Saudi Arabia. However, the availability of some global datasets pertinent to urban mobility and remote sensed air quality parameters provide opportunities to investigate the multi-faceted effects of the COVID-19 pandemic. In this study, the dynamics of the number of trips and trip purposes in different provinces of the country were analyzed, focusing on the pandemic period and the lockdown program. These changes impacted fuel consumption and, consequently, air pollutants. The quantity of fuel consumption and its trend was projected considering a few possible fuel consumption and emission scenarios. It is also expected that fuel price plays a role in fuel consumption. The spatial and temporal distributions of the remote sensed tropospheric Nitrogen Dioxide (NO$_2$) levels in different provinces were presented to depict the short- and long-term impact on the air quality due to the changes in mobility.

One of the most common air pollutants emitted from urban and industrial activities include nitrogen oxide (NO$_x$) which is a combination of Nitrogen Dioxide (NO$_2$) and Nitric Oxide (NO). It is produced by combustion of fossil fuels. It is regarded as one of the
main indicators to assess environmental pollution level (Bauwens et al., 2020; Wang and Su, 2020). It is harmful to human health and may cause damage in lung tissues and respiratory diseases (Wang and Su, 2020). In the urban areas of Saudi Arabia, it can be assumed that Nitrogen Dioxide is generated mainly due to anthropogenic activities including road transportation.

The framework of the study is to analyze the urban mobility dynamics due to the COVID-19 pandemic is presented in Fig. 2. It is based on observations of qualitative and limited quantitative information during the COVID-19 pandemic and the associated changes in different spheres of the human world. The human health, governmental policy and regulations, socioeconomic behavior, and economic activities will affect each other. It is assumed that these changes will cause short- and long-term impacts on urban mobility, which will also affect the factors. However, this study mainly emphasized on the impact of the COVID-19 pandemic on urban mobility and other associated consequences including air pollution.

4. Datasets

In this study, the community mobility report developed by Google LLC is used. The main objective of the report is to portray the changes due to the policies, including work-from-home and shelter-in-place, at flattening the curve of the COVID-19 pandemic. Google adopted an anonymization process to protect personal data, including an individual’s location, movement, or contacts (Aktay et al., 2020). It prepared a set of metrics using the information of its users who selected specific location services. The changes in these metrics were calculated considering a baseline depending on historical data.

The dataset presents the percent change in visits to different place categories. The categories are grocery and pharmacy, parks, transit stations, retail and recreation, residential, and workplaces. The grocery and pharmacy category include grocery markets, food warehouses, farmer’s markets, specialty food shops, drug stores, and pharmacies. The parks category includes local parks, national parks, public beaches, marinas, dog parks, plazas, and public gardens. The transit stations category includes public transport hubs such as subway, bus, and train stations. The retail and recreation category are restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters. The dataset provides the changes for each day compared to a baseline value for that day of the week. The baseline is the median value, for the corresponding day of the week, during the five weeks between 3 January and February 6, 2020 (GoogleC and “GoogleD-, 2020).

This study also used near real-time high-resolution imagery of NO\textsubscript{2} concentrations provided by the satellite Sentinel-5 Precursor, which was launched by the European Space Agency in 2017 (Babic et al., 2017). The satellite carries the Tropospheric Monitoring Instrument (TROPOMI) that measure NO\textsubscript{2} by finding total column concentrations of Nitrogen Dioxide. TROPOMI’s spectrometers measure the ultraviolet–visible backscattered solar radiation measurements in the wavelength range between 405 and 465 nm. The details of the instrument, the retrieval and assimilation method, and the data are provided in (Babic et al., 2017) and (Van Geffen et al., 2020). The land surface temperature (LST) of Riyadh and Jeddah were generated using the Moderate Resolution Imaging Spectroradiometer (MODIS) data retrieved from the Land Processes Distributed Active Archive Center (LP, 2020), which operates as a partnership between the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA). The MODIS which is onboard of the NASA Terra Earth Observing System satellites provides day- and night-time LST products on a daily basis. The product provides LST with 1 km (km) spatial resolution (LP, 2020).

![Percent change in mobility from baseline for different category in Riyadh City](image-url)

Fig. 3. Urban mobility changes for different place categories from the baseline condition during the COVID-19 pandemic in Riyadh City (GoogleC and "GoogleD-, 2020).
5. Analysis and results

5.1. Mobility and COVID cases

In contrary to the number of COVID-19 cases, curfew had a strong effect on mobility for Riyadh and Jeddah (Figs. 3 and 4). An apparent increase in residential trips versus a reduction in all of the other trips during the curfew duration was observed. The increase in residential trips was up to 30% during the full curfew period in both cities. The transit trips have shown the highest reduction, which is more 70%, since March 2020 in both cities. The mode share of transit trips is small in Saudi Arabia which could be the reason that these trips have shown the highest change. Hence, it could be expected that the future changes in mobility will also be reflected in the mode share. More dependence on cars could be seen in future due to the risk of exposure to infection. The trips for grocery and shopping have a reduction, by approximately 30%, since March which could be attributed to the cautiousness of the travelers and the increase in online shopping. However, these trips were almost same as the baseline for few days just before the full curfew as the residents prepared for the curfew period. The reduction in these trips was comparatively less as compared to trips for retail, parks, transit, and work.

5.2. Air pollutant emissions and land surface temperature

The spatial distributions of tropospheric NO\textsubscript{2} concentration for four months of 2019 and 2020 between February and May for Riyadh and Jeddah are presented in Figures A1 and A2 (in appendix A). Overall, the spatial distributions of NO\textsubscript{2} concentration follow similar trend and there is little improvement in NO\textsubscript{2} concentrations in 2020 compared to that of 2019. In Riyadh, the areas with high concentrations for 2019 cover comparatively larger areas than that of 2020. However, the high concentration areas towards the North-East of Riyadh during April of 2020 was slightly prominent. There is no significant indication of a pronounced reduction during April and May of 2020 in which curfews were enforced as compared to February and March (curfew started on 21 March), as shown in Figure A1. In Jeddah, the areas with high concentrations cover almost same extent for 2019 and 2020 as shown in Figure A2. The high concentration areas toward the North of Jeddah during March of 2020 was slightly prominent. In fact, the NO\textsubscript{2} concentrations in those cities depend on fossil fuel combustion, meteorological conditions, and atmospheric chemistry. Fig. 5 shows that the fuel demand in Saudi Arabia during the period between February and May in 2020 were lower than the same period in 2019. The monthly fuel demand was the lowest in April of 2020. This might be, in part, due to the fact that the fuel price was increased at the middle of April 2020 (Global petrol prices. Ava).

The time-series data of NO\textsubscript{2} concentrations shown in Fig. 6 typically exhibit a decrease in 2020 compared to that of 2019 with exceptions in number of days. During the full curfew periods for both cities, the NO\textsubscript{2} concentrations for 2020 were mostly less than that of 2019. There is no significant indication of a pronounced reduction NO\textsubscript{2} concentrations for both cities during the curfew period. The changes in NO\textsubscript{2} concentrations in 2020 could be attributed to the interactions among fuel price, meteorological conditions, atmospheric chemistry, and the pandemic which ultimately affect the generation and dispersion of air pollutants.

The effect of curfew on land surface temperature is shown in Figs. 7 and 8 for Riyadh and Jeddah. The figures indicate no noticeable effect even at night for both cities.

Fig. 4. Urban mobility changes for different place categories from the baseline condition during the COVID-19 pandemic in Jeddah City (GoogleC and ‘GoogleD’, 2020).
5.3. Fuel consumption pattern

The different policies that the Saudi government implemented, including full and partial curfews, have limited the movements of the citizens. As shown in the previous Fig. 5, fuel consumption decreased slightly in March and significantly reduced in April. The first COVID-19 case was reported in early March, and the first government policy was implemented in the second week of March, which is the suspension of all schools and universities. In March, the fuel consumption dropped to 13,361 KBBL (thousand barrel) (17.7% reduction from the previous month). In March, the government started to implement a series of policies. On 8 March, the government suspended all schools and universities, as mentioned above. However, the most significant reduction in fuel consumption began in April. The reduction in fuel consumption was magnified by the increase in fuel price which took place in the middle of April 2020. The fuel consumption dropped significantly to 6930 KBBL (48.1% reduction from the previous month). By comparing the fuel consumption between April and February, the percentage of reduction was about 57.3%. In April, the government started its first 24-h curfew for most cities, with movement restricted to only essential neighborhood travel between 6 a.m. and 3 p.m.

5.4. Projected changes in mobility and policy implications

This study currently highlights the following facts observed during COVID-19; the mode share for public transport has reduced, and restrictions imposed during COVID-19 has resulted in significant decrease in NO\textsubscript{2} concentrations and fuel consumption. This clearly shows the need to rethink the policy in terms of the planned public transport projects. The COVID-19 may create social stigma towards using public transport modes due to the risk of infection. In the absence of appropriate measures to address the public concerns with public transportation, this mode may suffer even after the pandemic. Therefore, it is essential to explore other options, such as less occupancy and better ventilation in public transportation, to reduce the possibility of being infected with COVID-19 in public transit. This will increase the confidence of transit and consequently reduce personal car trips. Similar to public transport, the aviation sector will also face similar challenges. It is also likely that the crowded destinations including tourists’ places will be avoided which may also impact transportation demand and mobility pattern. This means that tourism development will be hampered and governments may have to focus on other areas of economic development to cover this shortcoming.

The spread of the COVID-19 pandemic has also resulted in growth in online shopping. For instance, in the study area, online shopping for everyday needs rose by 400% (Bashraheel, 2020), and ten new mobile delivery applications were introduced to deal with the sudden hike in online purchases (Communication and Information Technology Commission, 2020). Similarly, more than 50% increase has been reported for online shoppers, while the proportion of people doing only online shopping has doubled in Japan (Watanabe and Omori, 2020). However, there are conflicting views if these effects will last long after the pandemic (Chang and Meyerhoefer, 2020; Richards and Rickard, 2020). Based on the users’ satisfaction in online shopping and the extent and varieties of online services, the transport demand may decrease after the pandemic. The increase in online shopping and delivery systems, during COVID-19, is most likely the reason for reduction in fuel consumption and NO\textsubscript{2}. Therefore, it is highly recommended that government devises policies to expand these services and encourage their use, so that the resulting positive environmental impacts continue in future.
6. Conclusions and recommendations

This study was aimed at studying the changes in mobility and environmental emissions due to COVID-19 restrictions in two main cities of Saudi Arabia, namely Riyadh and Jeddah. There were three different types of curfew protocols implemented from March to June 2020. In each curfew, the number of residential trips increased while all other types of trips decreased. The increase in the residential trips was up to 30% during the full curfew period. The highest reduction was seen in transit trips which would indicate a shift in mode choice in future as well. There was some general trend of reduction in the NO\textsubscript{2} levels in both cities during the full curfew protocol. Apparently, the pandemic, curfew protocols, and the increase in fuel price contributed to a clear decrease in fuel consumption during the same period. There was no significant change in surface temperature during the curfew. There was some indication of an increase in online shopping activities during the pandemic. This is consistent with findings from other countries of the world who reported a considerable increase in online shopping. It has been foreseen that the effect of COVID-19 on the transportation sector and the labor market will be long-lasting as people may change their travel habits. This study concluded that the availability of global urban mobility data, remote sensed based tropospheric air pollution data, and global fuel consumption database are important sources of information to investigate the impact of COVID pandemic, especially for the developing countries which suffer from scarcity of pertinent urban mobility information. It seems that, at least in the study area, the spread of COVID-19 is a complex phenomenon in
which several exogenous factors, in addition to the curfew protocols, affect the spread of the virus.

Correlation analysis between COVID-19 cases, curfew protocols, mobility changes, congestion levels, NO$_2$ concentrations were conducted. This was done with different time lags between COVID-19 cases and the values of the other variables. The investigated time lags ranged between one day to 21 days. A similar procedure was also tried using Principal Component Analysis (PCA). All these efforts were unsuccessful and did not add any extra insight to problem. A sophisticated holistic approach based on machine learning appears to be more promising to investigate this phenomenon. Consequently, the authors are planning to reinvestigate this problem by using such techniques in the future.

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Syed Masiur Rahman: Conceptualization, Methodology, Data curation, Writing – original draft, preparation. Nedal Ratrout: Conceptualization, Methodology, Writing – original draft, preparation. Khaled Assi: Methodology, Data curation, Visualization, Writing – original draft. Ibrahim Al-Sghan: Data curation, Methodology, Writing – original draft, preparation. Uneb Gazder: Methodology, Writing – original draft, preparation, Validation. Imran Reza: Visualization, Writing – review & editing. Omer Reshi: Visualization, Writing – review & editing.

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Appendix A

Figure A1a Monthly variations of tropospheric NO2 levels in Riyadh city for February and March of 2019 and 2020.
Figure A1b. Monthly variations of tropospheric NO2 levels in Riyadh city for April and May of 2019 and 2020.
Figure A2a Monthly variations of tropospheric NO2 levels in Jeddah city for February and March of 2019 and 2020.
Figure A2b. Monthly variations of tropospheric NO2 levels in Jeddah city for April and May of 2019 and 2020.
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