The impact of COVID-19 on emissions from the transport sector in low- and middle-income countries: A rapid review of the evidence

Produced for the Gauteng Department of Agriculture and Rural Development

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LIST OF ACRONYMS

μm^3	micrometre
CH4	methane
CO	carbon monoxide
CO2	carbon dioxide
GHG	greenhouse gas
LMICs	low- and middle-income countries
N2O	nitrous oxide
NH3	atmospheric ammonia
NOx / NO2	nitrogen oxide / nitrogen dioxide
O3	ozone
PM2.5	fine particulate matter
PM10	particulate matter
SO2	sulphur dioxide
VOCs	volatile organic compounds

INTRODUCTION

In December 2019, news broke of a new virus that caused illness and death in Wuhan, China. This novel and contagious human coronavirus was named severe acute respiratory syndrome coronavirus 2, with the phrase COVID-19 quickly catching on. Due to its alarming spread worldwide, the World Health Organisation (2020) declared the COVID-19 outbreak as a pandemic on 11 March 2020. Governments across the world responded with unprecedented measures to limit the spread of the virus. COVID-19 and the efforts of governments to deal with it have been massively disruptive to every aspect of our societies.

Government responses included restrictions about social gatherings, a minimum distance between people in public spaces, temporary closure of numerous economic activities, travel restrictions for non-essential reasons, and covering of mouth-and-nose through face masks in public spaces. One of the widespread government responses worldwide has been to opt for lockdowns that restrict people's movements. These lockdowns (and possibly some aspects of fear of infection) have led to a unique situation where people radically, in a very short period, changed their daily lives regarding where they work and how (and how often) they travel. National and local lockdowns limited all non-essential travel, including air and road transport,[1] and closed numerous economic activities temporarily in those spaces where lockdowns were applied. International, national and local mobility of people were affected, reducing the number of trips and distances travelled. Due to the massively reduced movement of people throughout the world, we saw massively reduced traffic. Under strict lockdowns, road traffic – of both public and private vehicles – and air travel came to a standstill just about, and whilst under partial lockdowns traffic increased, it was less than during pre-COVID times. In Beijing, for example, average daily traffic volume decreased by 62% during the strict lockdown and by around 38% in 2020 (Cao et al. 2021:1). And in Vienna, road traffic was reduced by 43% in April 2020 (Brancher 2021:4). People being less keen on using public transportation might be a legacy of the COVID-19 pandemic in some parts of the world (OECD 2020:2).

Reduced traffic means lesser burning of fossil fuels, which affects short-term greenhouse gas (GHG) and air pollutant emissions from the transport sector. Worldwide the transport sector contributes just less than a quarter to all GHGs emissions. Road and aviation transportation respectively make up 72% and 11% of the transport sector's contribution to GHG emissions

[1] Water (including marine) transport has also been affected, of course, but given the purpose of this rapid review in the context of a research project about air emissions from the transport sector in Gauteng, where we hardly have water transport, we did not search for studies on water transport. Whilst rail transport is relevant for Gauteng, and we did search for it, we did not find any study on emissions from rail transport in the context of COVID-19.

(IPCC 2018).[2] The impact of COVID-19 measures on air quality did then not go unnoticed (Mahato et al. 2020; Monks 2020; NASA 2020; OECD 2020; Schiermeier 2020; Ventera et al. 2020). The Global Carbon Project (2020) reported on carbon emissions for 2020 going down by a record 7%, road transport emissions down by 10%, and aviation emissions down 40%. In Ireland, for example, transport emissions are estimated to have fallen by almost 17% in 2020, compared to 2019 (Sustainable Energy Authority of Ireland and Environmental Protection Agency 2021:6).

The burning of fossil fuels through transport is a significant source of GHGs (such as carbon dioxide) and numerous other air pollutants (such as carbon monoxide, nitrogen oxides, sulphur, and particulates). These pollutants pose health risks to humans, including chronic acute respiratory problems, cardiovascular diseases and carcinogenic illnesses (Banerji & Mitra 2021:2). According to the World Health Organisation (2016), air pollution is responsible for the deaths of nearly seven million people annually. They also contribute to climate change and the considerable threat of this to life on earth. The reduction of these air pollutants during COVID-19 lockdowns should thus interest us, to see what we can learn from this so-called 'natural experiment' for our mitigation and adaptation strategies.

Numerous studies have been conducted worldwide on changes in air quality due to the transport sector in the context of the COVID-19 pandemic (e.g., Brown et al. 2021; Burns et al. 2021; Cárcel-Carrasco et al. 2021; Clemente et al. 2022; Ravina et al. 2021; Tian et al. 2021; Xiang et al. 2020; Yang et al. 2021). Whilst these studies were undertaken mainly in high-income countries, there are also studies in low- and middle-income contexts. We then focus on the impact of COVID-19 – and governments' responses to it – on emissions from the transport sector in low- and middle-income countries.[3] We applied a rapid review methodology, as an evidence synthesis approach, to find relevant studies, extract data, and synthesise the data.

In this report, we describe the evidence base of 18 studies – see Appendix B for a list of these studies – in low- and middle-income countries (LMICs) focused on the emissions of GHGs and other air pollutants from the transport sector in the context of COVID-19. We synthesise the findings from these studies and group the presentation of findings in four broad groups of pollutants, namely GHGs, ozone precursor gases, aerosols, and acidifying gases. We discuss

[2] In South Africa direct emissions from the transport sector account for 10.8% of total GHG emissions, the second highest sector contributor after the energy sector (Department of Transport 2018:8). Road transport contributes a massive 91.2% to the transport sector's total emissions (Department of Transport 2018:18).

[3] As is explained in the Methodology in Appendix A, we searched for studies everywhere, and applied a first round of inclusion/exclusion criteria to the studies found. This delivered just over 60 relevant studies that have been conducted worldwide. Given that this was to be rapid review, delivered within three months, we had to reduce the number of included studies. When focusing on countries with broadly similar development levels, we only included low- and middle-income countries in the rapid review.

what the results mean and conclude. A detailed description of the methodology followed in this rapid review can be found in Appendix A.

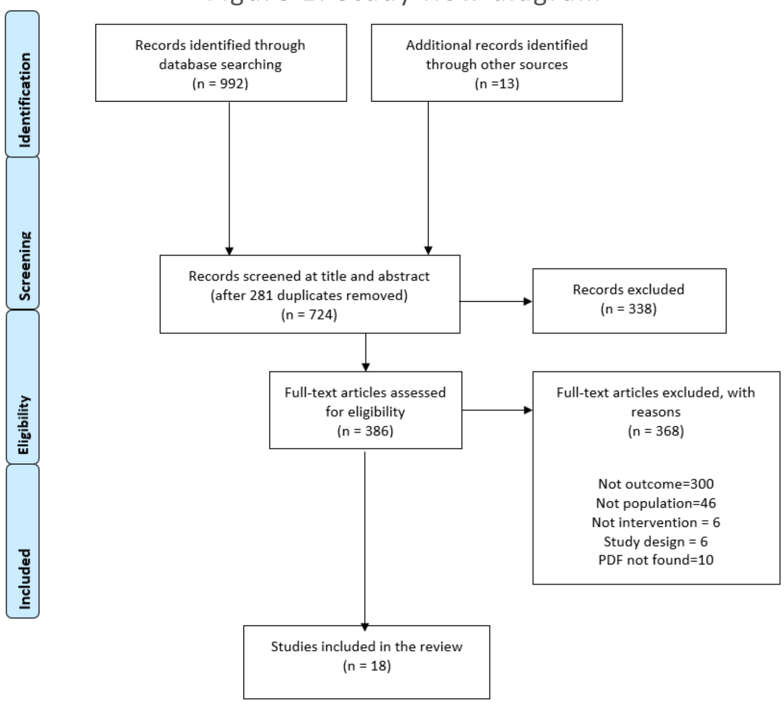
DESCRIPTION OF THE EVIDENCE BASE

This section indicates how we came to the 18 studies included in this rapid review and then indicate key characteristics of these 18 studies.

Search results

Initial search results identified a total of 1005 potential studies. Following duplicate removal (n=281) and screening at title and abstracts (n=338) for studies meeting the inclusion criteria,[4] the total number of studies was reduced to 386. Screening at full text removed an additional 368 studies, mainly because the excluded studies were not focusing on emissions related to the transport sector (indicated as 'not outcome' in Figure 1), which was not evident from titles and abstracts. Regarding population, i.e., studies from which countries to include, we initially did not have this as an exclusion criterium, as we wanted to consider studies throughout the world. But after applying our initial inclusion/exclusion criteria, we had 64 studies to review. This is simply too many studies to conduct a rapid review with (to be completed within three months). We then revised the inclusion criterium for 'population' to only include studies from LMICs (as per the definition of the World Bank). This meant that 46 studies were excluded from the relevant population, leaving us with 18 studies forming the evidence base for this rapid review. Figure 1 provides the complete study flow of this process.

Figure 1: Study flow diagram



[4] The methodology followed in this rapid review is discussed in detail in Appendix A.

Study characteristics

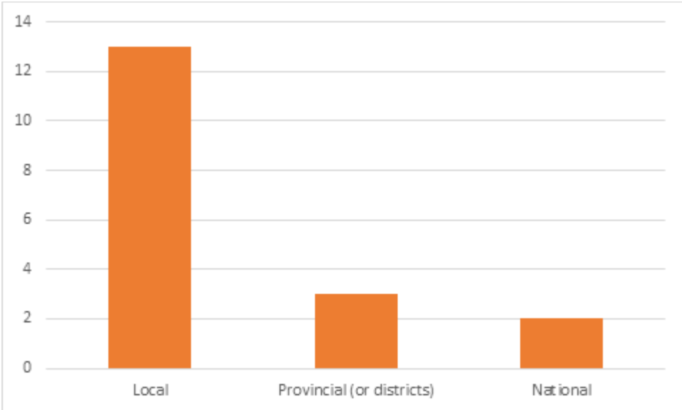
Most of the included studies were published in 2021 (n=12), with only six published in 2020. The evidence base only constitutes academic journal articles, although any research report, government report, dissertation or online book chapter could have been included. We did not find such publication types. The studies were mainly conducted in Asia (n=14), with two in Latin American and one in Europe and one study from Africa. The overwhelming majority of the studies were conducted in China (n=12), followed by Colombia (n=2) and one in each of Algeria, Thailand, India, and Turkey. Figure 2 below highlights the geographic coverage of the included studies. In terms of country income classification, the evidence base comprises sixteen studies from upper-middle-income countries and two from low-middle-income countries. This means that the evidence base, in terms of income, is similar to South Africa.

Figure 2: Geographical coverage of the include studies

Overall, an analytical quantitative approach was the most popular study design, with eleven studies adopting it. Seven studies applied a quasi-experimental research design. The studies mainly draw on emissions data from roadside and/or traffic monitoring stations. One study uses air quality sensors on taxis and one drawing on monthly passenger volume of road transportation, then deducing NOx. All the studies in the evidence base have a comparative aspect, comparing air quality data during COVID-19 to a pre-COVID-19 period. In such comparisons, the studies account for any changed meteorological conditions (such as wind speed, wind direction, air temperature, atmospheric pressure and precipitation) that could have affected emissions. This is crucial because air quality levels result from chemistry and meteorological conditions (Brancher 2021:2).

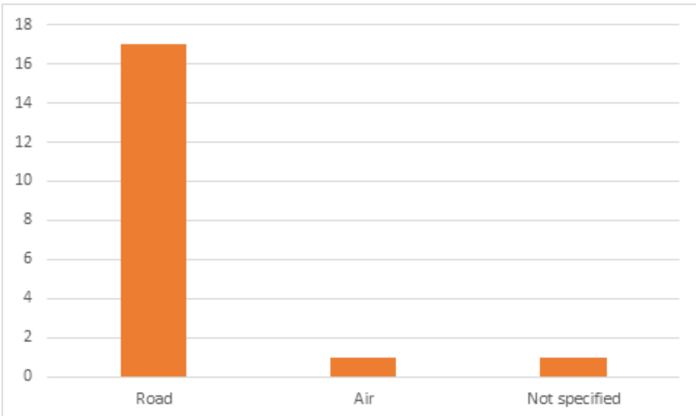
Most of the studies in the evidence base assessed the variations in the emissions or pollutants at a local level (n=13), predominantly city-wide variations based on distributed air monitoring stations. Three studies considered variations across a region/province/district, and two studies assessed emission changes at a national level, as shown in Figure 3.

Figure 3: Level of assessment of emissions



Nearly all the studies (n=17) included in the evidence base assessed emissions from road transport, with one study considering both road and air transport emissions. One study did not specify the transport sector which caused the emissions. Whilst we did include in our search strings concepts for rail transport, we found no studies covering air pollutant emissions from rail transport – see Figure 4.

Figure 4: Type of transport sector assessed



In terms of the action taken in the context of COVID-19, we looked out for two broad categories of interventions regarding transport. The one is government responses to reduce the spread of COVID-19; these were typically strict or partial lockdowns and included travel restrictions at international, national, regional and / or local levels. The other category of intervention is changes in individual or societal behaviour due to COVID-19, leading to changes in transport use, for example, less use of public transport. All 18 studies in the evidence base are about government lockdowns; in our searching, we found no study on individual / societal behavioural changes. We do anticipate, though, that studies focused on this will be forthcoming.

FINDINGS OF THE RAPID REVIEW

In this section, we report the emissions findings from the included studies. We structure our indication into four groupings, namely aerosols (fine particulate matter and particulate matter), ozone precursor gases (carbon monoxide, non-methane volatile organic compounds, and nitrogen oxides), acidifying gases (sulphur dioxide and atmospheric ammonia), and greenhouse gases (carbon dioxide, methane, nitrous oxide, and ozone). Our coding tool included data for emissions of nitric oxide, benzene, ethylbenzene and toluene, but none of the studies in the evidence bases reported on these specifically.

Aerosols

Regarding aerosols, the evidence base reports on concentrations of fine particulate matter and particulate matter.

Fine particulate matter

There are fourteen studies in the evidence base that consider the impact of changes in the transport sector – due to lockdowns at a national level (n=9) and local level restrictions (n=5)- on concentrations of fine particulate matter (PM2.5).[5] All fourteen studies look at changes in PM2.5 concentrations resulting from changes in road transport patterns. These studies were conducted in China (n=10), Colombia (n=2), India (n=1) and Thailand (n=1). One study also assesses changes in PM2.5 concentration levels due to air transport; they find PM2.5 concentrations declined by 80% and 60% in the Level 1 and Level 2 response periods in China's Yangtze River Delta Region (Li et al. 2020).

In eleven of the fourteen studies focusing on the effects of road transport on ambient air quality, PM2.5 concentration levels decreased during the respective lockdown or restriction periods compared to pre-lockdown levels. Overall, the reported decreases fell between a 1% and 80% decline in concentrations of PM2.5. Specifically, PM2.5 reductions related to road transport were:

- Jia and colleagues (2021) report an average reduction of 15.2 $\mu g/m^3$ for PM2.5 across 361 cities in China during the traffic period compared to the pre-traffic control period;
- 12.5% reduction (Dejchanchaiwong & Tekasakul 2021) as measured on two road site stations in Bangkok, Thailand, when comparing the daily average PM2.5 mass concentration immediately before lockdown (March 2020) and during lockdown (April 2020);
- 17% reduction across five air quality traffic stations in Bogota, Colombia (Camargo-Caicedo et al. 2021). Camargo-Caicedo and colleagues (2021:6) also have specific findings on black carbon (also called soot) emissions.[6] They found a decrease of 15%

[5] PM2.5 indicates particulate matter with an aerodynamic diameter of less than 2.5 micrometre (μm^3).
[6] Black carbon is a short-lived PM2.5 pollutant.

in black carbon emissions at five air quality traffic stations in Bogota, Colombia, between January and June 2020 compared to comparative periods in 2018 and 2019;

- a range between 23% and 29% from 17 highway monitoring stations across Beijing, China (Cao et al. 2021);
- 5% and 35% reduction in Bogotá and Medellín (Colombia), respectively, during strict lockdown from (25 March to 26 April 2020) compared to a pre-COVID period (Mendez-Espinosa et al. 2020). In the partial lockdown period (27 April to 30 June 2020), the reductions were 31% in Bogota and 34% in Medellín;
- 35% and 29% reductions in Shanghai during the full lockdown (23 January to 9 February 2020) and partial lockdown (10 February to 23 March 2020) in comparison to the same period in 2018-2019, respectively, based on roadside data (Wu et al. 2021);
- an average of 37.8% decrease in PM2.5 concentrations in the period of intense government interventions (24 January to 29 February 2020) relative to the period before lockdown (between 1 and 23 January 2020) (Gu et al. 2021);
- 39.3% reductions across 49 cities in the four Chinese provinces (Chen et al. 2021);
- a range between 1% and 44% reductions across three roadside monitoring stations in Hong Kong (Huang et al. 2020);
- 54% reduction across 52 locations in Hyderabad, India (Eregowda et al. 2021); and
- Li and colleagues (2020) show that PM2.5 concentrations related to vehicle exhaust emissions decreased by 75% in the Level 1 response period and 50% in the Level 2 response period in China's Yangtze River Delta Region.

Two studies report mixed results on the effect of lockdown measures on PM2.5 concentrations due to road transport. Dejchanchaiwong and Tekasakul (2021) find that relative to the normal period (April 2019), the daily PM2.5 concentrations at road sites during the strict lockdown (April 2020) in Bangkok (Thailand) were not significantly different, as the small observed reductions could be attributed to normal random variations. However, comparing the daily average PM2.5 mass concentration immediately before lockdown (March 2020) and during lockdown (April 2020) at two road site monitoring stations shows that PM2.5 concentrations decreased by 12.5% (Dejchanchaiwong & Tekasakul 2021). Depending on the city of investigation, the Gao (2021) study also indicates mixed results on PM2.5 concentrations from the transport sector during the lockdown period across Wuhan, Beijing, Shanghai, and Guangzhou, relative to the pre-lockdown period. The PM2.5 concentrations decreased or slightly increased in the four Chinese cities in May 2020, owing to meteorological conditions being more conducive to the dispersion of air pollutants. The study notes that the abnormal increase of PM2.5 in Beijing was probably caused by transported pollutants produced by uninterrupted industrial emissions and fireworks during New Year's Eve and the Lantern Festival, as well as the influence of adverse weather conditions.

One study, Brimblecombe and Lai (2020), indicates insignificant differences between the average PM2.5 concentrations during the lockdown period and a pre-lockdown period due to road transport. The researchers compare the daily average concentrations of PM2.5 in and around Beijing, focusing on two-week periods before lockdown (29 May to 12 June) and the lockdown period (13 May to 26 June). They find overall no significant difference between the daily average concentrations of PM2.5. This lack of significant differences noted in the study could be attributed to the shortness of the time between the pre-lockdown and the lockdown period used for comparison in this study.

Particulate matter

Seven studies in the evidence base indicate changes in particulate matter (PM10)[7] concentrations due to the transport sector. Five of these studies took place in China, and two in Colombia. Four studies conducted their measures at a local level, two at provincial/regional level, and one at the national level. All the studies looked at PM10 concentrations due to road transport changes, with one study (Li et al. 2020) also measuring PM10 concentration levels caused by air transport. Five studies looked at PM10 concentrations in the context of lockdown measures that affected national mobility, while local mobility was affected by lockdown measures in the other two studies.

All the studies show a decrease in the concentrations of PM10 from vehicle emissions during the COVID-19 period, compared to a pre-COVID-19 period.

- 17% reduction in Bogota in Colombia (Camargo-Caicedo et al. 2021:6).
- 28.9 % reduction across 49 Chinese cities in the light of private vehicle restriction policies (Chen et al. 2021:5).
- 31% reduction across 361 cities in China (Jia et al. 2021:3).[8]
- 37% reduction in Hong Kong, based on measures at roadside monitoring stations (Huang et al. 2020:3).[9]
- 28% reduction in Bogotá and 33% reduction in Medellín in Colombia during strict lockdown (20 March to 26 April 2020), and 38% and 19% reduction in the respective cities during relaxed lockdown (27 April to 30 June 2020), compared to a pre-COVID period (Mendez-Espinosa et al. 2020:4).
- 46% reduction during strict lockdown (23 January to 9 February 2020) and 22% reduction during partial lockdown (10 February to 23 March 2020) in Shanghai, based

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[7] PM10 is PM2.5 plus coarser particles. PM10 is not a singular pollutant, but a mixture of aerosols varying widely in size (although all have a diameter of 10 microns or less), shape and chemical compositions. It has multiple emission sources, including the combustion of oil, gasoline, diesel or wood, but also dust from landfills and construction sites, wildfires, and industrial sources. It can also be formed in the atmosphere through chemical reactions between, for example, NOx, SO2, and organic compounds.

[8] The average reduction, after controlling for meteorological factors and traffic control type, was 22.1 (17.9, 26.2) $\mu g/m^3$ (Jia et al. 2021:3).

[9] When measuring ambient air quality, PM10 concentrations were slightly lower than concentrations at roadside, with a 38% reduction compared to a pre-COVID-19 period (Huang et al. 2020:4).

on roadside measurement, compared to the same periods in 2018 and 2019 (Wu et al. 2021).
- 75% reduction (during Level 1 restrictions) and 50% reduction (during Level 2 restrictions) across 41 cities in the Yangtze River Delta Region of China (Li et al. 2020:8).

The only study in the evidence base that considered PM10 concentration from air traffic is Li and colleagues (2020:8). They found a reduction of 80% and 60%, respectively, during Levels 1 and 2 of restrictions compared to pre-COVID concentrations in China's Yangtze River Delta Region.

Ozone precursor gases[10]

In the evidence base, we have studies reporting on emissions from the transport sector related to carbon monoxide, nitrogen oxides, and volatile organic compounds, comparing pre- and during-COVID periods.

Carbon monoxide

Nine of the included studies assess changes in concentrations or emission intensity of carbon monoxide (CO) in China (n=7), Thailand (n=1) and India (n=1). All the studies assessed road transport-related CO emissions, with one of the studies also considering CO emissions from the air transport sector (Li et al. 2020). In six studies the context was national level lockdowns, and in three studies it was government responses affecting local mobility.

All the studies report evidence of decreased CO concentrations or intensity that ranged from 8% to 80% during the respective lockdown periods as compared to pre-lockdown periods.

- Across 361 cities in China, the Jia study (2021) indicates that CO reduced by an average of 0.18 $\mu g/m^3$ during the traffic control period compared to the normal traffic period.
- CO concentrations in Bangkok (Thailand) decreased by 8.3% at road sites during the lockdown period, compared to the same period in 2019, and with the same percentage compared to the pre-lockdown level in 2020 (Dejchanchaiwong & Tekasakul 2021).
- Chen and colleagues (2021) indicate a 10.1% decrease in concentrations of CO in 49 cities from four Chinese provinces.
- In Hong Kong, the Huang study (2020) compares data from three roadside air quality monitoring stations for the first four months of 2020 with data from the preceding three years (2017 to 2019). Comparing February 2020 with the same months in previous years, the study shows a reduction of CO emissions of between 7% and 21%. But for April 2020, compared to previous years, CO emissions reduced by between only two percent, and an increase of 40% (Huang et al. 2020:4).

[10] These gases are oxidising agents, meaning they are very reactive with other compounds.

- The emission intensity of CO decreases by between 23% and 29% across 17 highway monitoring stations in Beijing (Cao et al. 2021).
- Compared to the same periods in 2018 and 2019, Wu and colleagues (2021) find CO emissions in Shanghai (China) declining by 34% and 26% during the full lockdown period (23 January to 9 February 2020) and partial lockdown (10 February to 23 March) (Wu et al. 2021).
- In Nanjing (China), CO concentrations decreased by 44.9% during the COVID-lockdown periods (24-31 January 2020 and 17-24 February 2020) in comparison to the pre-COVID period (1 October to 23 January 2020) (Wang et al. 2021).
- Findings from Eregowda and colleagues (2021) show that vehicular CO emission in Hyderabad, India reduced by 61% during the lockdown period compared to usual traffic emissions.
- Li and colleagues (2020) find that vehicle-related CO emissions decreased by 75% in the Level 1 response period and 50% in the Level 2 response period in the Yangtze River Delta Region. CO emissions from aircraft decreased by 80% in the Level 1 response period and 60% in the Level 2 response period.

Nitrogen oxides

The evidence base holds 13 studies that consider nitrogen oxide (NOx)[11] emissions from the transport sector in the context of the COVID-19 pandemic. Nine of the studies indicate measuring nitrogen dioxide (NO2) emissions, with the other four studies showing NOx emissions. For purposes of this report, we group reporting on NO2 and NOx together, given that NO2 is one of two NOx gases (with nitric oxide the other). Where a study specified NO2, we report it as such.

Most of the studies were conducted in China (n=10) and one each in Colombia, India, and Thailand, respectively. Ten studies focused on a local level, two on provincial/regional level, and one on the national level. All but one study looked at NOx emissions from road traffic, one study did not specify the transport sector, and one study (Li et al. 2020) also looked at emissions from air traffic. In nine of the studies, the government response to COVID-19 included lockdown measures that affected national mobility; in three studies, the lockdown measures only affected local mobility; and in one study, both national and local mobility was affected (Cao et al. 2021).

Regarding the impact on NOx emission, nearly all the studies in the evidence base found a reduction (and many a significant reduction), with only one study showing a mixed impact on NOx emissions. The twelve studies that show reduction compared to a pre-COVID-19 period report the following reduced NOx concentrations:

[11] The main source of NOx emissions is the transport sector. As an air pollutant NOx contributes to the formation of smog and acid rain, and at very high concentrations can cause lung damage.

- In Beijing (China), Brimblecombe and Lai (2020:6) report a reduction (from 46.6 ± 11.1 $\mu g/m^3$ to 36.4 ± 7.4 $\mu g/m^3$) in NO2 concentrations when comparing two weeks before the June 2020 localised lockdown (around Xinfadi Market) with two weeks after this lockdown.
- Still, in China, Chen and colleagues (2021), focusing on private vehicle restriction policies, also find a reduction in ambient NO2 concentrations after controlling for meteorological factors between 1 August 2019 and 7 February 2020.
- In the same city and in the context of the same localised lockdown restrictions that led to a decline in traffic flows by about 23%, Cao and colleagues (2021) found NOx emission reduced by a third during the strict lockdown level, as compared to the same period in 2019. Comparing the pollutant measures from 17 highways in Beijing, they find that the spatial distribution of the pollutant radiates outward from the central urban area (Cao et al. 2021:9).
- In Bangkok (Thailand), Dejchanchaiwong and Tekasakul (2021) draw on the one-hour average of NO2 ambient concentrations from five roadside monitoring stations pre- and during COVID-19 lockdown. They find a reduction in NO2 concentrations of 23.5% at road sites (Dejchanchaiwong & Tekasakul 2021:7).
- In their study in Hong Kong, drawing from air quality monitoring data from three roadside stations and comparing data from January to April 2020 with data for the same months in 2017 to 2019, Huang and colleagues (2020) found a reduction in NO2 emissions in most months, of between 1% and 28%. In April 2018 and April 2019, though, NO2 roadside concentrations were lower than in April 2020. Meteorological conditions explain this: April 2020 were unfavourable for air movements to disperse these pollutants (Huang et al. 2020:3).
- From Hyderabad in India, we learn of a 38% reduction in NOx from vehicle concentrations during the lockdown period (Eregodwa et al. 2021:9).
- Gu and colleagues (2021) found a reduction in NO2 concentrations from transport in Shanghai during various periods; the most drastic decrease was that of 46.2% in the period of intense restrictions, to a 37.9% reduction during gradual recovery, compared to the same months from 2017 to 2019 (Gu et al. 2021:3).
- Jia and colleagues (2021) collected data from 361 cities across China in the context of nationwide traffic restrictions due to the COVID-19 pandemic and compared concentrations post-traffic control with pre-traffic control. They found a substantial reduction – and the largest decrease in the numerous air pollutants measured – in NO2 emissions from road traffic: a reduction of 40.5% (Jia et al. 2021:3). After controlling for meteorological factors and traffic control type, the average decrease was 9.9 (9.1, 10.8) $\mu g/m^3$.
- NO2 concentrations from road traffic decreased significantly in Nanjing (China) during the COVID-19 lockdown period, by 47.1%, Wang and colleagues (2021) found. They utilised air quality sensors on a taxi fleet pre-COVID (October 2019 to 23 January 2020), during COVID-19 lockdown (24 January to 14 February 2020), and post-

lockdown (1 March to 30 September 2020) to collect the data. They also found that NO2 (and CO) concentrations reflected a pattern reflecting traffic volume – high concentrations with higher traffic volumes (Wang et al. 2021:1).

- The study by Wu and colleagues (2021) in Shanghai found significant reductions in NO2 concentrations in the context of COVID-19 lockdowns. To measure NO2 emissions from road transport, they drew on data from four roadside stations in busy traffic spots, comparing data from 2018 to 2020. NO2 concentration at roadside sites decreased by 48% during strict lockdown and 32% during partial lockdown, compared to the same periods in 2018 and 2019 (Wu et al. 2021:7).
- The study by Mendez-Espinosa and colleagues (2020) found reductions in NO2 concentrations in Bogotá and Medellín in Colombia during strict lockdown from 25 March until 26 April 2020, compared to the same periods in the previous five years (2015-2019), and a before lockdown period (21 February – 19 March 2020) and a relaxed lockdown period (27 April-30 June 2020). During the strict lockdown period, NO2 concentrations in Bogotá reduced substantially by 62% and in Medellín by 69%, as measured at the traffic stations, compared to previous years (Mendez-Espinosa et al. 2020:5).
- In the study by Li and colleagues (2020) in the Yangtze River Delta region of China, they collected data on NOx concentrations from road and air transport. NOx emissions from vehicles reduced by 75% in the Level 1 response period, and by 50% in the Level 2 period, whilst for NOx emissions from air transport, the reductions were 80% and 60% respectively for the two periods, compared to pre-lockdown (Li et al. 2020:9).

As indicated, one study in the evidence base had mixed results regarding NO2 emissions in the context of the COVID-19 pandemic. Gao and colleagues (2021) looked at data from four megacities in China – Wuhan, Beijing, Shanghai, and Guangzhou – from January to May between 2016 and 2020. During the strict lockdown period of 24 January to 8 February 2020 (the Chinese New Year Festival period), NO2 concentrations reduced sharply, compared to the pre-COVID period, by 49.4%, 42%, 50.3%, and 66.1%, respectively in Wuhan, Beijing, Shanghai, and Guangzhou (Gao et al. 2021:4). In the period 9-29 February 2020 though – with lockdown still in place – NO2 concentration decreased further in Wuhan, remained relatively stable in Beijing, and increased in Shanghai and Guangzhou.

Volatile organic compounds

Four studies from China investigated the variations in volatile organic compounds (VOCs)[12] in the context of COVID-19. Three studies look at how VOCs were affected by local lockdown measures, and one assessed any changes in the context of national lockdown. Two studies

[12] VOCs include an array of chemical gases emitted from burning fossil fuels, but also other sources. VOCs are an important pollutant for its role in the formation of ground-level ozone. In the atmosphere VOCs interact with nitrogen oxides to create ozone molecules. On hot days, due to higher UV radiation from the sun, this reaction is sped up, leading to more production of ground-level ozone.

focus on road transport-related emissions, one study explores aircraft-linked emissions, and one study does not specify the transport sector.

Overall, VOCs display a negative trend during the lockdown or traffic control periods compared to regular periods. In the Yangtze River Delta Region of China, Li and co-authors (2020) find that vehicle-related emissions decreased by 75% in the Level 1 response period and 50% in the Level 2 response period. Compared to previous years' emission levels, aircraft-related emissions declined by 80% and 60% in the Level 1 and the Level 2 response periods. At Shanghai's Pudong and the regional Dianshan Lake Supersites (monitoring stations), the amounts of VOCs from vehicle exhaust showed significant reduction rates of 27.6% and 60.4%, respectively (Jia et al. 2020). In the same city, Gu and colleagues (2021) report between 30% and 64% reduction in transport-related VOCs in the 17 weak transport affected days of intense government interventions relative to the pre-lockdown period. The emission intensity of hydrocarbons, as a VOC, in Beijing in 2020 was seen to decrease by a range of 23% to 29%, compared to 2019 (Cao et al. 2021).

Acidifying gases

The air pollutants making the largest contribution to the acidification of the environment are sulphur dioxide, NOx, and atmospheric ammonia.[13] As we have already indicated emission findings related to NOx, as an ozone precursor gas, we consider the other two gases in this section.

Sulphur dioxide

Nine studies in the evidence base show sulphur dioxide (SO2)[14] emissions from the transport sector; seven indicate emissions in China, and one each in Colombia and India, respectively. Regarding the level of measurement, six studies focused on a local level, two on provincial/regional level, and one was conducted at national level. Seven studies in the evidence base measure sulphur dioxide emissions from the transport sector during lockdown measures that affected national mobility, whilst two studies do so in the context of lockdown measures affecting local mobility.

A significant reduction in sulphur dioxide emissions from road traffic is reported in all the studies in the evidence base. The measure was typically in µg/m^3 at roadside stations. The reductions range from 13% across 361 Chinese cities (Jia et al. 2021:3), to 19% in Bogotá (Camargo-Caicedo et al. 2021:6), to 43% in Shanghai (Wu et al. 2021:7), to 50% in Hyderabad (Eregowda et al. 2021:9), to 52% in Hong Kong (Huang et al. 2020:3), to 75% in the Yangtze

[13] In terms of air quality, acidifying gases contribute to the formation of fine particles in the air, which in turn cause respiratory diseases.
[14] The sources of SO2 emissions are mostly energy production and manufacturing.

River Delta of China during Level 1[15] and 50% reduction during Level 2 (Li et al. 2020:9). Chen and colleagues (2021) also indicate a decrease in SO2 emissions between August 2019 and February 2020 in 49 Chinese cities, as do Gu and co-authors (2021), based on a Shanghai study. Whilst Gao and colleagues (2021) indicate significant decreases in SO2 emissions in Beijing, Shanghai and Guangzhou during the strict lockdown compared to pre-COVID, in Wuhan, SO2 emissions were similar during strict lockdown compared to pre-COVID and then increased slightly in April 2020. The authors explained this through high SO2 emissions from adjacent cities (Gao et al. 2021:5).

There is one study that also considers SO2 emissions from air transport. Li and colleagues (2021:9) found significant reductions in China's Yangtze River Delta region: SO2 emissions from air transport reduced by 80% in the Level 1 response period and 60% in the Level 2 period (Li et al. 2020:9).

Atmospheric ammonia

Only one study in the evidence base looks at changes in atmospheric ammonia (NH3)[16] concentrations due to the transport sector, namely Zhang and colleagues (2021). They draw on data from five air quality monitoring stations (four being roadside stations) in Beijing. In the context of the national lockdown, their data show higher concentrations of NH3 in 2020 compared to 2017: roadside sites had on average 7.9 $\mu g/m^3$ higher NH3 concentrations (Zhang et al. 2021:2). Interestingly, NH3 concentrations did not increase significantly after the lockdown ended (Zhang et al. 2021:1). They conclude that changes in regional transport patterns and unfavourable meteorological conditions of lower boundary layer heights likely influenced NH3 concentrations.

Greenhouse gases

Regarding greenhouse gases (GHGs)[17] emitted from the transport sector during the COVID-19 pandemic, the evidence base reports on emissions of carbon dioxide, nitrous oxide, methane, and ground-level ozone. One study, that of Gürbüz and colleagues (2021), in Turkey, estimates GHG emissions from road transport, based on road transportation fuel consumption data from January to October from 2017 to 2020. This study does not separate the specific emissions of separate GHGs, but combine estimates for CO2, CH4 and N2O. They found decreases in GHGs during lockdown – between 10% and 40% decreases – compared to the preceding three years (Gürbüz et al. 2021:9).

[15] Li and colleagues compared data across four periods: pre-lockdown, Level 1 response (of full lockdown from around 24 January to 25 February 2020), Level 2 response (roughly 26 February to 31 March 2020), and Level 3 response (after 31 March 2021).

[16] NH3 is the chief alkaline gas in the air and plays an important role in the formation of secondary inorganic aerosols / particulate matter. The major source of NH3 emissions is agriculture, with vehicle emissions also a source.

[17] The key issue with human-contributed GHGs is how it contributes to climate change.

Cardon dioxide

Carbon dioxide (CO_2) emissions pattern changes from the road transport sector resulting from lockdown measures that affect national mobility are evaluated in two other studies, aside from the Gürbüz (2021) study mentioned above. Camargo-Caicedo and colleagues (2021) highlight negative CO_2 variations of 28% between January and June 2020 due to the pandemic lockdown compared to the 2018-2019 period in Bogota, Colombia. Eregowda and co-authors (2021) report a 54% reduction in vehicular CO_2 emission during the lockdown period in Hyderabad, India, compared to a pre-COVID period.

Nitrous oxide

Only one study in the evidence base reports on nitrous oxide (N_2O) emissions during COVID-19 national lockdowns and how it relates to the transport sector. It was conducted in Colombia, drawing on data from five air quality roadside stations in Bogotá (Camargo-Caicedo et al. 2021). During the first half of 2020 compared to the same period in 2018. Camargo-Caicedo and colleagues (2021:6) found a reduction in N_2O emissions of 71% (the highest reduction of the GHG emissions in the study) in April 2020 after the implementation of vehicle restrictions nationally in late March 2020. Between January and June 2020, N_2O emissions reduced by 17% compared to the same period in 2018.

Methane

Additional to the Gürbüz study (2021) noted above, only Camargo-Caicedo and colleagues (2021) also evaluate the transport-related methane (CH_4) emissions during COVID-19 national lockdowns. After the government adopted vehicle restriction at the end of March 2020, the April CH_4 concentrations decreased by 40% relative to April 2018. Compared to January to June 2018, road transport-related CH_4 emissions decreased by 20% in Bogotá in the same months in 2020.

Ground-level ozone

Eight studies included in the evidence base analyse the impact of COVID-19 related lockdown measures on ground-level ozone (O_3)[18] emissions linked to changes in transport patterns due to national lockdown measures (n=7), with one study in the context of lockdown measures that affected local mobility. Most studies are conducted in China (n=5) and one in each of Colombia, Thailand, and Algeria.

All but two studies indicate significant increases in ground-level ozone (O_3) concentrations: up 106.32% in Bogota, Colombia (Camargo-Caicedo et al. 2021); 1% to 72% higher in Hong

[18] Ground-level O_3 should be clearly differentiated from stratospheric O_3; the first is a result of air pollution (thus a secondary air pollutant), with the other naturally occurring in the outer layer of the earth's atmosphere where it forms a layer of protection against UV light. Ground-level (or tropospheric) O_3 is not emitted directly into the air, but produced from photochemical reactions involving NOx and VOCs. Ground-level O_3 is a key pollutant that causes smog and have numerous impacts on human health, including irritation of the eyes, nose and throat, aggravating asthma and other lung diseases.

Kong (Huang et al. 2020); up 52% in Oran in Algeria (Rahal et al. 2020:242), and up 69.6% at road sites in Bangkok, Thailand (Dejchanchaiwong & Tekasakul 2021). Wang and colleagues (2021) found ozone concentrations increased by 35.7% in Nanjing (China), whilst in Shanghai (China), O3 concentrations increased by 64% during the full-lockdown period and 30% during the partial lockdown period at roadside stations (Wu et al. 2021). The average increase of O3 across 361 Chinese cities is 4.2 $\mu g/m^3$ during the traffic control period compared to regular traffic periods (Jia et al. 2021). The reasons provided for such O3 increases include the reduction of NOx emissions from road transport, which generally contributes to the degradation of O3 (Rahal 2020:6).

Interestingly, Chen and colleagues (2021) recorded a reduction of 11.4% ozone concentrations owing to private vehicle restrictions from 49 cities across China. Although Dejchanchaiwong and Tekasakul (2021) find evidence in increased O3 concentrations during the lockdown period in the year 2020 as compared to the same period in 2019, it is important to note that a 20% decrease in O3 concentrations at road sites during the lockdown period was observed, compared to the pre-lockdown period in the year 2020.

DISCUSSION OF FINDINGS

Our rapid review considers the impact of COVID-19 on emissions from the transport sector in LMICs. We identify two possible ways in which COVD-19 has an impact: through government responses of, for example, lockdowns; and through individual or societal behavioural changes related to transport. We found no study dealing with the second, so our discussion is only focused on government responses to COVID-19.

The evidence base on emissions from the transport sector in LMICs shows a significant impact on air quality due to governments' responses to curb the spread of COVID-19. The evidence base of 18 studies is dominated by studies from China and studies focusing on emissions from road transport. With only one study including emissions from air transport, and one study not specifying the sub-sector, we do not have sufficient evidence to further discuss emissions from air transport during the COVID-19 pandemic. Since emissions from air transport can spread over a large area and disperse further before reaching the surface, research should unpack this. Directly measuring air transport emissions through monitoring stations is more complicated, though, and emissions will likely have to be calculated instead. And one would expect significant reductions due to the considerable drop in air traffic during strict lockdown levels.

In discussing the findings in the evidence base, we then look at emissions from road transport during COVID-19 lockdown and travel restrictions. Table 5 summarises the evidence base in this review on road transport emissions / concentrations.[19] Note that our review found only one study each on the emissions of NH3,[20] N2O and CH4, and two studies on CO2 emissions; these are not sufficient for further discussion. More primary studies on these emissions are required before one can synthesise results. We discuss findings on the other air pollutants below.

Table 5: Air pollutant emissions / concentrations from road transport during lockdowns

Air pollutant	Size of evidence base	Direction of change in emissions / concentrations (amount of studies)
Aerosols		
PM2.5	14	Decrease (11 studies) Insignificant change (1 study) Mixed (2 studies)
PM10	7	Decrease (7 studies)
Ozone precursor gases		
Nitrogen oxides	13	Decrease (12 studies) Mixed (1 study)
Carbon monoxide	9	Decrease (9 studies)
VOCs	4	Decrease (4 studies)
Acidifying gases		
Sulphur dioxide	9	Decrease (9)
Atmospheric ammonia	1	Increase (1)
Greenhouse gases		
Ground-level ozone	8	Increase (6) Decrease (2)
Carbon dioxide	2	Decrease (2)
Nitrous oxide	1	Decrease (1)
Methane	1	Decrease (1)
Combined GHGs	1	Decrease (1)

For road transport, we note substantial reductions in ambient concentrations of air pollutants – especially of NOx/NO2, PM2.5, PM10, CO, VOCs and SO2 – during the COVID-19 pandemic, as compared to a period before, after accounting for meteorological conditions and other contextual issues. From our evidence base, such reductions were mainly due to massively reduced vehicle traffic and thus a reduction in the burning of fossil fuels.

[19] Note that in evidence synthesis methodology this kind of 'vote counting', according to the Cochrane handbook, is only "considered as a last resort in situations when standard meta-analytical methods cannot be applied" (Higgins et al. 2021), as is the case in this rapid review.

[20] We should look out specifically for studies looking at what happens to NH3 concentrations due to road transport; the one study in our evidence base on this finds an increase in NH3 concentrations during COVID-19 lockdowns, and also not significant further increases after the lockdown ended. This is not in line with what happened to other air pollutants (outside of ground-level O3).

The largest reduction in emissions was in NOx / NO2. Being a pollutant mainly produced from vehicle emissions, it makes sense that lockdowns with its restrictions on people's movement via both public and private transport would have led to massive reductions in NOx / NO2 emissions and concentrations. One study in the evidence base on NOx / NO2 (Gao et al. 2021) found mixed results in NO2 emissions. Different from the other studies that relied on roadside stations or air quality sensors on vehicles, the study by Gao and co-authors (2021) explored the relationships between traffic and NO2 emissions by drawing on monthly passenger volume of public transportation (as bus and rail transit) and monthly passenger volume of taxis. Whilst drastically reduced traffic volumes in three cities correlated with reduced atmospheric NO2 concentrations, in Beijing NO2 emissions remained stable from the second period, despite reduced traffic volumes (Gao et al. 2021:8). Not directly using NO2 emissions / concentrations data from the transport sector, but instead deducing it and relying on correlation, might explain the findings of this study being out of kilter with the other studies in the evidence base.

For airborne PM10, CO and VOCs, the evidence base consistently indicates significant decreases due to reduced road transport during COVID-19 lockdowns. All these air pollutants are emitted through the combustion of fossil fuels. When complete combustion of fossil fuels happens, all carbon would be turned into CO2, but combustion is always incomplete and produces CO, CO2, PM2.5 and VOCs. These pollutants significantly decreasing when road traffic is reduced substantially, makes sense then.

For PM2.5, the evidence base is convincingly indicating significant decreases in the aerosols of PM2.5 during COVID-19 lockdowns, compared to pre-COVID, from road transport. Given that the source of PM2.5 is primarily vehicle exhaust, it makes sense. However, one study in the evidence base shows insignificant changes – attributed to normal random variations – in PM2.5 during the COVID-lockdown period (Brimblecombe & Lai 2020), and two studies have mixed results (Dejchanchaiwong & Tekasakul 2021; Gao et al. 2021). Whilst there were reductions in PM2.5 concentrations in the other cities that formed part of these two studies, there was an increase in Beijing (also the city the Brimblecombe study focuses on). Gao and colleagues (2021) explain the increase of PM2.5 in Beijing through localised meteorological conditions, uninterrupted industrial emissions and fireworks during the New Year's Eve and the Lantern Festival. It reveals that whilst vehicle traffic is crucial for PM2.5 concentrations in ambient air, local meteorological conditions and other local events also have an impact.

The evidence base on emissions of SO2 from road transport also consistently shows significant reductions in the context of COVID-19 lockdowns. A few studies commented on SO2 emissions following the pattern of NO2 emissions, with SO2 reductions tending to be slightly lower. The explanation is likely that SO2 is emitted when sulphur-containing fuel burns, but the emission from this combustion happens in lower quantities. The primary source of SO2 emissions, rather than fossil fuel burning, is electricity generation.

The only air pollutant that has increased during COVID-19 lockdowns is ground-level O3. The evidence base has six studies showing increases, with two studies indicating a decrease. O3 in the troposphere is a GHG and a harmful secondary air pollutant. The reason for increases in ground-level O3 during lockdowns can be explained by how it is formed. In general, ground-level O3 is formed in complex photochemical reactions between CO and VOCs in the presence of NOx (Monks et al. 2015).[21] Seinfeld and Pandis (2006) explain that fossil fuel combustion leads to direct emissions of NOx into the air. NOx is easily oxidised to NO2. This is then photo-dissociated to NOx and ground state O(3P), which combines with oxygen to form O3 through a termolecular reaction with a third body (e.g., N2). O3 then reacts with NO to regenerate O2. NOx is then involved in both the formation and reduction of O3, with the net formation of O3 determined by the ratio of VOC/NOx. Bassani and colleagues (2021:22982) identify two sensitivity regimes regarding VOC/NOx ratios, namely NOx-limited and VOC-limited regimes. Under NOx-limited regimes, often found in rural and sub-urban areas, VOC/NOx ratios are high, and more NOx will result in more O3. Under VOC-limited regimes – typically found in urban areas – VOC/NOx ratios are low, with less NOx producing more O3. This is termed titration, when less NOx reduces the amount of O3 being destructed in reaction with NO, thus increasing O3 (Monk et al. 2015). Significantly reduced NOx emissions / concentrations due to COVID-19 lockdowns, then resulted in substantial increases of O3.[22] This discussion reveals how important it is to consider the complex and non-linear photochemistry between several air pollutants.

Most of the studies in the evidence base compare data from COVID-19 lockdown periods (whether strict or partial lockdowns) with pre-COVID periods. It will be revealing to also compare post-lockdown data to the other periods to see what happens after mobility restrictions are removed. Studies on this are likely to come out soon.

CONCLUSION

The restriction on people's movement, and thus lesser use of motorised transport, as a government response to contain the spread of COVID-19, has presented the world with an unique opportunity to demonstrate the effect of transportation on air quality. In attempting to capture the lessons from this period for managing air pollution, and climate change mitigation and adaptation, we conducted this rapid review.[23]

[21] Being formed by chemical reactions in the air between specific pollutants means that ground-level O3 is mainly human-caused. Weather though also plays a role in the lebels of ground-level O3, with O3 concentrations typically higher on warm/hot days with low humidity and light/stagnant wind.

[22] Some authors (Agami & Dayan 2021; Sicard et al. 2020) compare the increases of ground-level O3 during COVID-19 lockdowns with ozone weekend effect (OWE), the phenomenon of higher O3 levels in urban areas on weekends, when road traffic, and other sources of NOx and hydrocarbon emissions – such as fuel refining electricity plants and industrial pants – are reduced.

[23] This review is part of a broader research project on how the short- and long-term changes in transport patterns due to COVID-19 has affected emissions of GHGs and air pollutants in Gauteng.

The rapid review is about the impact of COVID-19 on air pollutant emissions / concentrations from the transport sector in LMICs. But in essence, given the nature of the studies found, the evidence base is actually about the impact of COVID-19 lockdown measures on air pollutant emissions and concentrations due to road transport specifically. The so-called 'natural' experiment of lockdown levels in response to the COVID-19 pandemic clearly show traffic-related emissions as a crucial contributor to air pollution.

From the studies in the review, we learn how crucial it is to unpack and consider specific contextual realities rather than assume general patterns in air quality due to increased / decreased road traffic. Not only are localised meteorological conditions crucial, but also other contextual factors, such as the ratios of small passenger vehicles to large passenger vehicles to medium/large trucks on roads, the proportion of new-energy vehicles to vehicles with high-emissions ones, and the energy and industrial structure in the region (Cao et al. 2021; Chen et al. 2021; Li et al. 2020). Possible policies to restrict traffic, encourage low-emitting vehicles, ban high-emitting vehicles, or develop clean public transport have to fit the specific context to be effective.

From this review, we should also learn that we have to consider the complex non-linear relations between numerous pollutants for designing interventions to respond to air pollution. For example, we acknowledge the likely challenge of reducing the formation of secondary pollutants, such as ground-level O3, if we only consider measures to control primary pollutant emissions. Holistic policies in terms of all air pollutants and GHGs are then necessary.

It would be crucial to also look at what happens to air quality once lockdowns are fully lifted, and no traffic restrictions are in place, and traffic possibly increases, but maybe at a slower rate (if more people can opt to work from home). Given that this review did not focus on (or found) studies with a comparison period after the complete lifting of COVID-19 traffic restrictions, we have no evidence base to comment on this. But this is crucial matter to look out for in further studies.

Whist COVID-19 had received much public attention during 2020, the other global crisis of climate change did not go away. And whilst the evidence base shows reductions in numerous air pollutants, how long-term these are beyond the full and partial lockdowns are not known, and its impact on climate change is also not obvious. However, government responses to the COVID-19 pandemic have demonstrated very clearly that air pollution can be reduced by humans and their actions, and actions by governments. Such awareness should be a call for action on air pollutants and climate change. We are provided with an opportunity to rethink our transport policies and planning transport infrastructure for a new future post-COVID, rather than resume' business as (previously) normal'.

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APPENDIX A: METHODOLOGY USED IN THIS RAPID REVIEW

We conducted a rapid review in this study given a short time (three months) to provide evidence on air emissions from the transport sector in the context of the COVID-19 pandemic. A rapid review is a form of knowledge synthesis that streamlines or accelerates systematic review steps, represented by limiting certain aspects of the methodology to produce evidence in a timely manner (Garritty et al. 2020; Grant & Booth 2009). Evidence synthesis (also called systematic reviewing) is a family of methodologies that allow for the systematic, comprehensive, rigorous and transparent configuration of available scientific evidence on a topic or question. Whilst systematic reviews and other forms of evidence synthesis are often used to inform policy guidelines (Bosch-Capblanch et al. 2012; Oxman et al. 2010), the high-level methodological rigour tied to systematic reviews means that they take from six months to two years to conduct (Khangura et al. 2012) and require a considerable amount of skill to execute. The extended timeline for producing systematic reviews (Tricco et al. 2015) is usually misalignment with policy-making and decision-making cycles.

Through a rapid review methodology, also called rapid evidence assessment or rapid evidence synthesis, a systematic review is sped-up to produce timely, reliable, relevant and accessible evidence for stakeholders in a resource-efficient manner (Hamel et al. 2021:81; Khangura et al. 2012; Mijumbi-Deve et al. 2017). Rapid reviews have become a valuable tool in providing actionable and relevant evidence that is timely and cost-effective. They are an efficient approach to give the policy-makers relevant and state-of-the-art evidence on policy and systems challenges. And they remain aligned to the principles of systematic reviewing in terms of methodology rigour, comprehensiveness, and transparency (Tricco et al. 2017). Rapid reviews then present an exciting potential in addressing emerging needs for contextualised evidence to inform pressing decisions (Tricco et al. 2017). On average, rapid review are completed in a period of six to twelve weeks (depending on the size of the evidence base), thereby providing evidence in a shorter timeframe for policy- and decision-making (Tricco et al. 2015).

The methodology of our rapid review follows the internationally-agreed Cochrane Rapid Review Guide (Garritty et al. 2020) and the practical guide for rapid reviews to strengthen health policy and systems (Tricco et al. 2017). The methods and results are reported following the Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) Statement (Moher et al. 2009). The process involved five core tasks, including (1) setting the research question/ topic refinement, (2) setting the eligibility criteria, (3) searching for evidence, (4) screening the evidence, and (5) synthesis. We conducted the five-step process between August and October 2021.

Setting the research question

The first step in a systematic review is to determine the focus and precise framing of the question(s) the review seeks to answer. Well formulated questions guide numerous aspects of the review, including eligibility criteria, searching for evidence, collecting data from the included studies, structuring the synthesis and presenting the findings (Oliver et al. 2017). For this rapid review, the clarification of the research question was a collaborative process between the African Centre for Evidence, Gauteng Department of Agriculture and Rural Development (GDARD) and the University of Johannesburg's Process, Energy and Environmental Technology Station (UJ PEETS). In a few meetings during August, we refined and agreed on the question for the review.

This review is part of a broader research study that seeks to understand how short-term and long-term changes in transport patterns due to the COVID-19 affect emissions of GHGs and air pollutants in the Gauteng province. To that end, our review initially focused on global evidence on the impact of COVID-19 on GHG emissions and air pollutants from the transport sector. Focusing on the global evidence yielded an evidence base constituting a total of 64 studies, with 46 studies from high-income countries and 18 from low-middle-income countries. In light of time and resource constraints, this rapid review only considered and synthesised studies from LMICs.

Eligibility criteria

We generated eligibility criteria using the PICOS (Population, Intervention, Comparator, Outcome, Study Design) framework (see Table 1). Eligible populations included studies from low-middle income countries. We considered two broad types of interventions. First, government responses affecting local, provincial, national mobility or international travel restrictions in response to the COVID-19 pandemic. The second category of interventions is individual or societal behaviour changes due to the risk profiles (e.g., less use of public transport). Studies analysing trends in emissions during the response period without a corresponding pre-reference period were excluded. Only original studies with primary data related to our research question were included, thus excluding modelling studies from a design perspective. In terms of publication type, it excludes opinion pieces, newspaper articles or blog postings. Publication dates were limited to 2020 and 2021, as the pandemic started towards the end of 2019. Only studies in English were included.

Table A1: PICOS framework for the rapid review

Population	Low-and middle-income countries
Intervention	COVID-19 and associated isolation or protective measures such as lockdowns
Comparator	Pre-lockdown or post lockdown level of emissions or air pollutants
Outcome	The level of GHG emissions and air pollutants from the transport sector limited to road, rail, or air transport

Study design	Empirical studies that collect primary data from relevant monitoring stations

Searching for research evidence

We designed a scientific search strategy for relevant evidence and searched all scientific evidence in two extensive electronic academic databases, PubMed and Web of Science. A combination of key terms adopted included COVID-19 terms ("COVID*" OR "Coronavirus" OR "CoV" OR "severe acute respiratory syndrome coronavirus 2" OR "SARS-CoV-2"), emissions terms ("greenhouse gas*" OR "GHG "OR "n. HFC" OR "CO2" OR "NO_2 emissions" OR "NO_2 concentration" OR "air quality" OR "ozone" OR "O3" OR "nitrogen oxides") and transport terms ("Transport*" OR "vehicle" OR "aeroplane" OR "rail" OR "road"). Groups of terms were combined with the Boolean operator "AND" and applied in the two academic databases. To ensure maximum coverage of unpublished literature and reduce the potential for publication bias, we also conducted searches for grey literature in 13 websites identified from the Living hub of COVID-19 knowledge hubs,[24] by filtering for transport and environment. Table A2 and Table A3 below present the results from academic and grey literature sources, respectively.

Table A2: Search hits found in academic databases

Database	Search results
Medline/PubMed	389
Web of Science	603
TOTAL	**992**

Table A3: Searches for grey literature

Hub name	URL	Hits
Centre for the Prevention and Control of Diseases	https://www.cdc.gov/	0
COVID-19 CoronaVirus South African Resource Portal	https://sacoronavirus.co.za	0
Croatian Institute of Public Health	https://www.hzjz.hr/en/	0
Dalla Lana School of Public Health	https://ihpme.utoronto.ca/research/research-centres-initiatives/nao/covid19/	1
Full Fact	https://fullfact.org/health/coronavirus	0
GMCC Initiative	https://gmcc.alibabadoctor.com/?locale=en-us&entry=aliyungmcc_re_20200420__&	0
Hungarian Government	https://abouthungary.hu/	0
International Association for Dental Research	https://www.iadr.org/IADR/Publications/JDRCTR	0
Luxembourg Ministry of Health	https://covid19.public.lu/en.html	0
National Institute of Corrections	https://nicic.gov/coronavirus	0

[24] This hub – developed by McMaster University in Canada and ACE at UJ – has pull together all the major sources on COVID-19-related research into one platform. In this one-stop shop one can rapidly identify relevant knowledge hubs that contain research on the specific topic required. The living hub is updated regularly, and currently contains 343 knowledge hubs on COVID-19.

The National Academics of Sciences Engineering Medicine	https://www.nationalacademies.org/publications	5
Trace together	https://www.tracetogether.gov.sg/	0
United Nations Environment Programme	https://www.unep.org/covid-19	7
TOTAL		**13**

Study selection and data extraction

The data gathered from the databases and websites were exported to EPPI Reviewer 4 software (a specialist software for evidence synthesis) and used to identify duplicates from the identified records. The record was then exported to a Google Sheet to allow for a collaborative screening process. Two reviewers independently screened 20% of the studies at the title and abstracts and decisions were recorded on the same platform. One reviewer completed the screening of the rest of the studies. Two reviewers screened 28% of the selected papers, with the screening completed in the same fashion at title and abstract screening. In cases where reviewers disagreed on the inclusion of a study, they consulted one another to reach a consensus for both screening at title and abstract screening and full texts.

We developed and adopted a detailed data extraction tool to systematically extract data from the included primary studies. We translated the tool into a coding set on EPPI-Reviewer to extract the information required for the rapid review entered directly into the EPPI-Reviewer database. One reviewer conducted the data extraction process with verification by another reviewer. To allow for in-depth analysis and synthesis of study results full-text and studies coded on the following variables: title, year, authors, publication type, study design regions, country, country income classification, level of emission assessment, transport sector, interventions (response measures) and outcomes (emission type and variations).

Synthesis of findings

We performed a narrative synthesis to synthesise the findings of the different studies. Narrative synthesis is an approach in systematic reviewing to synthesise findings from multiple studies, reliant on the use of words and text to summarise and explain the findings of the synthesis (Popay et al. 2006). Due to the very different kinds of data and measures of the studies included in this rapid review, a narrative synthesis constitutes the best instrument to synthesise the findings of the studies. The synthesis structured the air emissions / concentrations into four categories: aerosols, ozone precursor gases, acidifying gases, and GHGs. We then pulled the coded information on each pollutant and GHG, and grouped similarities regarding directing of change in emissions / concentrations.

APPENDIX B: STUDIES INCLUDED IN THE RAPID REVIEW

Brimblecombe P, Lai Y (2020) Effect of sub-urban scale lockdown on air pollution in Beijing. *Urban Climate* 34: 100725.

Camargo-Caicedo Y, Mantilla-Romo LC, Bolaño-Ortiz TR (2021) Emissions reduction of greenhouse gases, ozone precursors, aerosols and acidifying gases from road transportation during the COVID-19 lockdown in Colombia. *Applied Sciences* 11(4): 1458.

Cao X, Tian Y, Shen Y, Wu T, Li R, Liu X, Yeerken A, Cui Y, Xue Y, Lian A (2021) Emission variations of primary air pollutants from highway vehicles and implications during the COVID-19 pandemic in Beijing, China. *International Journal of Environmental Research and Public Health* 18(8): 4019.

Chen Z, Hao X, Zhang X, Chen F (2021) Have traffic restrictions improved air quality? A shock from COVID-19. *Journal of Cleaner Production* 279*:* 123622.

Dejchanchaiwong R, Tekasakul P (2021) Effects of coronavirus-induced city lockdown on PM2.5 and gaseous pollutant concentrations in Bangkok. *Aerosol and Air Quality Research* 21.

Eregowda T, Chatterjee P, Pawar DS (2021) Impact of lockdown associated with COVID19 on air quality and emissions from transportation sector: Case study in selected Indian metropolitan cities. *Environment Systems and Decisions* 1-12.

Gao C, Li S, Liu M, Zhang F, Achal V, Tu Y, Zhang S, Cai C (2021) Impact of the COVID-19 pandemic on air pollution in Chinese megacities from the perspective of traffic volume and meteorological factors. *Science of The Total Environment* 773: 145545.

Gu Y, Yan F, Xu J, Duan Y, Fu Q, Qu Y, Liao H (2021) Mitigated PM2.5 changes by the regional transport during the COVID-19 lockdown in Shanghai, China. *Geophysical Research Letters* 48(8): e2021GL092395.

Gürbüz H, Şöhret Y, Ekici S (2021) Evaluating effects of the Covid-19 pandemic period on energy consumption and enviro-economic indicators of Turkish road transportation. *Energy Sources, Part A: Recovery, Utilisation and Environmental Effects* 1-13.

Huang Y, Zhou JL, Yu Y, Mok WC, Lee CF, Yam YS (2020) Uncertainty in the impact of the COVID-19 pandemic on air quality in Hong Kong, China. *Atmosphere* 11(9): 914.

Jia H, Huo J, Fu Q, Duan Y, Lin Y, Jin X, Hu X, Cheng J (2020) Insights into chemical composition, abatement mechanisms and regional transport of atmospheric pollutants in the Yangtze River Delta region, China during the COVID-19 outbreak control period. *Environmental Pollution* 267: 115612.

Jia C, Li W, Wu T, He M (2021) Road traffic and air pollution: Evidence from a nationwide traffic control during coronavirus disease 2019 outbreak. *Science of The Total Environment* 781: 146618.

Li L, Li Q, Huang L, Wang Q, Zhu A, Xu J, Liu Z, Li H, Shi L, Li R, Azari M (2020) Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: An insight into the impact of human activity pattern changes on air pollution variation. *Science of the Total Environment* 732: 139282.

Mendez-Espinosa JF, Rojas NY, Vargas J, Pachón JE, Belalcazar LC, Ramírez O (2020) Air quality variations in Northern South America during the COVID-19 lockdown. *Science of the Total Environment* 749: 141621.

Rahal F, Rezak S, Benabadji N (2020) Evaluation of the impact of the COVID-19 pandemic on photochemical pollution in urban areas. *Environmental Health Engineering and Management* 7(4): 237-243.

Wang S, Ma Y, Wang Z, Wang L, Chi X, Ding A, Yao M, Li Y, Li Q, Wu M, Zhang Y (2021) Mobile monitoring of urban air quality at high spatial resolution by low-cost sensors: Impacts of COVID-19 pandemic lockdown. *Atmospheric Chemistry and Physics* 21(9): 7199-7215.

Wu CL, Wang HW, Cai WJ, Ni AN, Peng ZR (2021) Impact of the COVID-19 lockdown on roadside traffic-related air pollution in Shanghai, China. *Building and Environment* 194: 107718.

Zhang Y, Liu X, Fang Y, Liu D, Tang A, Collett Jr JL (2020) Atmospheric ammonia in Beijing during the COVID-19 outbreak: Concentrations, sources, and implications. *Environmental Science & Technology Letters* 8(1): 32-38.