Health Effects of Short-Term Exposures to Air Pollution with Particular Reference to the Concentration Range on High and Very High Days

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Summary

Introduction

This report summarises the health effects of short-term exposure to air pollution with particular reference to the concentration ranges relevant to high and very high days and to shorter term intervention studies to reduce higher levels of air pollution. Four areas are considered:

- the upper end of the range of concentrations in routine time-series studies the shape of the concentration-response function at higher concentrations in time-series studies
- health effects in episode studies
- health benefits in intervention studies.

Methods and results

The concentration ranges were considered for a selection of time-series: those in London for the relevant location; multi-city studies in Europe for powerful evidence and similar types of location and studies with tight confidence intervals used in the meta-analyses used to define the concentration-response function. These were identified with a combination of a PubMed literature search and references held by the authors.

High and very high days are relatively rare occurrences in London and thus provide very few (or even no) data points in recent time-series studies in London. This was also true for many European multi-city studies, although a study in Southern Europe had a few cities with a reasonable number of days with $PM_{2.5}$ in the higher range. Some studies from earlier years or other parts of the world that had tight confidence intervals and were included within the concentration-response function meta-analyses, also had a reasonable number of days with $PM_{2.5}$ or ozone in the higher range.

A PubMed search for the shape of concentration-response functions for $PM_{2.5}$, NO_2 and O_3 and all-cause mortality; respiratory, asthma, COPD (chronic obstructive pulmonary disease), cardiovascular, cardiac and stroke hospital admissions (the pollutants and outcomes used in the health impacts of episodes report) identified 15 studies plus one additional recent large global study.

The shape of the concentration-response relationship varied from flatter, to maintained, to steeper slopes at higher concentrations of $PM_{2.5}$ in the few studies to examine this directly. Fewer studies for NO_2 and O_3 also showed mixed results. Interpretation is complex due to issues such as correlations with confounding pollutants. It was considered reasonable to continue to assume the standard log-linear relationship in health impact calculations in the absence of firm evidence to the contrary.

A PubMed search for episode studies on $PM_{2.5}$, nitrogen dioxide or ozone identified nine studies. For at least some episodes, including in the UK, health effects are observed when pollutant concentrations (including nitrogen dioxide) are equivalent to those seen in high or very high days in the Defra Daily Air Quality Index for all pollutants. Some episode studies do not find effects – whether this is due to a lack of statistical power (episodes are only a few days long) is unclear. Most studies (with or without an association) were on particulate matter, with only a few on NO_2 or O_3.

A targeted approach to identifying intervention studies examining health endpoints was used. 30 studies were identified from considering the review of schemes report (part of this project); identifying previous reviews, accountability research funded by the Health Effects Institute and a literature search over the last three years.

Only two studies have looked at tailored or designed emergency measures and their associated public health benefits based on forecasting air quality. Both found improvements in health outcomes (statistically significant in one case). Both studies were small and lacked a control group in the wider region to control for unrelated time trends in health outcomes.

Some studies assessing the effects on health from planned short-term interventions during specific high-profile event lasting up to a few weeks, showed health benefits. The studies of the Beijing Olympic Games (where the emergency measures taken were particularly widespread) were consistent in showing improvements in health outcomes.

Studies of permanent interventions where health impacts were assessed in the first few months generally showed that the health burden from air pollution can be lessened by reducing concentrations, although the results were not always statistically significant and, for some examples, more complex follow-up studies did not confirm the earlier results.

Conclusions

Overall, while effects are likely to be increased at concentrations equivalent to those seen in high or very high days in the Defra Daily Air Quality Index, there is some increased uncertainty over the exact size of the effect at these concentrations. (Note that only epidemiology studies were considered here – there is also evidence from human volunteer studies).

At the current time, it is reasonable to use concentration-response functions derived from the full range of concentrations in time-series studies to calculate health impacts of high and very high days, while noting the mixed results on effect size at these concentrations, and the fact that composition of pollution may vary in location with higher compared with lower concentrations.

Research continues on the shape of the concentration-response functions at higher concentrations, particularly as more studies are done in countries with higher concentrations. Future work on health impacts should consider the latest evidence on this aspect when deciding on appropriate concentration-response functions.

While there are studies showing public health benefits from short-term interventions to reduce air pollution, the number of studies is small, particularly for emergency measure interventions lasting days rather than weeks or months. The health benefits of emergency measure interventions are difficult to demonstrate due to lack of statistical power but seeking opportunities to study this further (perhaps by clustering multiple implementations) would still be worthwhile.

1 Introduction

This report is part of a wider set of work packages that gather evidence on the health impacts of emergency / short-term action plans to control air pollution episodes in London. Combined, they explore the information that might be needed if the Mayor wanted to consider introducing a scheme of emergency measures. The work packages a to e:

a) Summarised the health effects of short-term exposure to high levels of air pollution
b) Estimated the magnitude of the health impact of high air pollution episodes in London.
c) Reviewed the evidence on the effectiveness of emergency measures (e.g. Madrid, Paris, Beijing).
d) Assess the accuracy of existing air quality forecasting for use in triggering emergency air quality measures.
e) Convened an expert workshop that considered the work packages A to D and the conclusions that could be drawn from them.

This report covers work package a and summarises the health effects of short-term exposure to air pollution with particular reference to the concentration ranges relevant to high and very high days. It is not intended to review the entire literature on the health effects of short-term exposure which would be a vast project by itself but to highlight particular aspects of relevance to considering the health impacts of episode days, such as episode studies and studies on the shape of the concentration-response function.

1.1 General information on health effects of air pollution

In these series of reports, we have concentrated on the health effects of short-term not long-term exposures. Within the health effects of short-term exposure, we have chosen to look in more detail at time-series studies of deaths brought forward and hospital admissions, as these types of outcomes are more routinely quantified and there are many more studies of these outcomes. This is described in the health impacts of episodes report. We checked for good quality meta-analyses to define concentration-response functions to use in calculations of health impacts of episode days. We selected concentration-response functions for deaths brought forward, all respiratory hospital admissions all ages, all cardiovascular admissions all ages, COPD admissions all ages, asthma admissions in children, asthma admissions in adults, cardiac admissions in the elderly and stroke admissions all ages. There is other evidence of short-term exposure and health outcomes including asthmatic symptoms in asthmatic children (WHO,2013a) GP consultations (Hajat et al, 1999), A&E visits (Atkinson et al, 1999a), and ambulance calls (Smith et al 2015). In addition, there is an extensive literature from the US on air pollution and emergency room visits (e.g. Strosnider et al, 2018). While this does not have a health service equivalent in the UK (being a combination of GP consultations, A&E visits and hospital admissions), it does provide broad support for health effects of short-term exposure.

1.2 Structure of the report

The details of the assessment of which concentration-response function to use is given in the health impacts of episodes report (reproduced in Appendix 1 for convenience). These concentration-response functions are well-established and assumed to be linear between the concentrations and the log of the relative risk across the full range of concentrations. The next two sections (sections 2 and 3) of the report investigate whether this assumption is reasonable by considering (i) whether the concentration-ranges in the time-series studies cover the range of concentrations found on high and very high days and (ii) whether the shape of the concentration-response relationship is indeed log-linear, or whether it flattens off at higher concentrations.

Section 4 considers studies that have investigated whether there is evidence for health effects on specific episode days and section 5 covers intervention studies that have sought to reduce air pollution and see if health benefits have results in the short-term.

2 Do concentration ranges in time-series studies cover the concentrations found on high and very high days?

2.1 Methods for concentration ranges in time-series studies

2.1.1 Definition of concentration range of particular interest

As the project is focussed on health impacts of high and very high days, we defined the concentration range of particular interest as the concentrations at the border between the moderate and high bands in the Daily Air Quality Index (Table 1) (COMEAP, 2011; DEFRA, 2013). This was concentrations of daily maximum 8-hour average ozone above 160 µg m^{-3}, of 1-hour average nitrogen dioxide above 400 µg m^{-3} and of 24-hour average $PM_{2.5}$ above 54 µg m^{-3}.

Band	Index	Ozone	Nitrogen Dioxide	Sulphur Dioxide	$PM_{2.5}$ Particles (EU Reference Equivalent)	PM_{10} Particles (EU Reference Equivalent)
		Running 8 hourly mean	hourly mean	15 minute mean	24 hour mean	24 hour mean
		μgm^{-3}	μgm^{-3}	μgm^{-3}	μgm^{-3}	μgm^{-3}
Low	1	0-33	0-67	0-88	0-11	0-16
	2	34-66	68-134	89-177	12-23	17-33
	3	67-100	135-200	178-266	24-35	34-50
Moderate	4	101-120	201-267	267-354	36-41	51-58
	5	121-140	268-334	355-443	42-47	59-66
	6	141-160	335-400	444-532	48-53	67-75
High	7	161-187	401-467	533-710	54-58	76-83
	8	188-213	468-534	711-887	59-64	84-91
	9	214-240	535-600	888-1064	65-70	92-100
Very High	10	241 or more	601 or more	1065 or more	71 or more	101 or more

Table 1 Daily Air Quality Index as defined in the update of 2013. The 24-hour mean used for PM2.5 is specified as a fixed midnight to midnight daily average. Defra (2013)

2.1.2 Concentration ranges of influential time-series studies

The purpose of this section is to check whether the evidence for associations between daily variations in air pollution concentrations and health outcomes, such as hospital admissions, applies in the concentration ranges relevant to high and very high days. There are a very large number of time-series studies. Checking all of them was considered impractical in the time available. The following groups of studies were considered:

(i) All time-series studies performed in London (as the episode calculations are in London)

(ii) Major multi-city studies in Europe (a good way to assess the range of concentrations in Europe in studies showing associations with health outcomes)

(iii) Studies having a key influence on the concentration-response functions used in calculating the health impacts of episodes, if not already covered by (i) or (ii).

For (i) a broad search on 'time-series AND air pollution AND London' was performed on PubMed. Studies were further sifted to ensure that they covered the health outcomes relevant to the episode calculations. For (i) and (ii) above we included studies on related pollutants (e.g. PM_{10}) and averaging times (e.g. 1-hour maximum or 24-hour average ozone) as these could be used to loosely infer the likely concentration ranges for 24-hour average $PM_{2.5}$, 24-hour average NO_2 and daily maximum 8-hour average ozone. For (iii), only the latter averaging time/pollutant combinations were used as the specific concentration-response functions used in the health impacts of episodes report related to these combinations. We did not include black smoke for (i) and (ii) as it is more difficult to relate it to levels of $PM_{2.5}$. For PM_{10}, we did not need to convert it $PM_{2.5}$, because the daily air quality index concentrations for $PM_{2.5}$ have been converted from PM_{10} in any case i.e. PM_{10} concentrations can be compared directly with the PM_{10} index bands.

Conversion factors used to convert ppb (parts per billion) to µg/m^3 were

NO_2: 1.9125

O_3: 1.9956

2.2 Results for concentration ranges in time-series studies

2.2.1 Time-series studies in London

The literature search picked up 85 studies. 61 studies were screened out for being about heatwaves, pollen or fungi, from London (Ontario, Canada), had London as an author surname, air pollution only not health, reviews or meta-analyses not original studies, and health studies referring to the London 1952 episodes but not being based in London.

A further 16 studies were ruled out because they addressed GP consultations (3), COPD exacerbations (2), sickle cell disease (1), ischaemic heart disease admissions (1), infant mortality (1), cause-specific mortality (2) or other pollutants (2) not covered in the health impact assessment of episodes. A letter with no original analysis, reviews/meta-analyses (2) and a study giving results by country rather than city were also excluded. This left eight studies for further analysis, supplemented by seven studies already held by the authors. The results from these 15 studies are reported in the following paragraphs and in Tables 2-4.

High and very high days are fortunately relatively rare in London in more recent years. Recent time-series studies in London therefore do not include many days at the concentrations that define high or very high days (Table 2). Older time-series studies in London pre-date $PM_{2.5}$ measurements – none of the $PM_{2.5}$ or earlier PM_{10} studies had a reasonable proportion of days above moderate. Studies using data going back before the early 1990s probably did but the PM metric used was black smoke, which is not easily converted to $PM_{2.5}$ measurements.

Reference	Pollutant	Time-period	Concentration Data µg/m^3	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Atkinson et al 2010	$PM_{2.5}$	2000-2005	Median 12.7 75th %ile 17.1 Max 60.6	Probably not, although maximum is higher	No association (all-cause mortality) marginally significant association cardiovascular mortality	

Reference	**Pollutant**	**Time-period**	**Concentration Data μg/m³**	**Reasonable proportion of data above moderate/ high switch**	**Associations shown or not for each outcome?**	**Comment**
Samoli et al 2016a	$PM_{2.5}$	2011-2012	Mean 12.2 Median 9.0 90th %ile 25.0	No (but max not given)	No association (cardiovascular and respiratory admissions; weekly exposure and respiratory admissions age 0-14 approached statistical significance)	2 years of data is relatively short
Atkinson et al 1999b	PM_{10}	1992-1994	Median 24.8 90th%ile 46.5 Max 99.8	Probably not, maximum is above but 90th percentile is lower.	Yes (all respiratory all ages; COPD/asthma 65+; lower respiratory admissions 65+; all cardio-vascular admissions) No (asthma admissions all ages).	2 years of data is relatively short
Atkinson et al 2001	PM_{10}	1992-1994	Median 24.9 Maximum 80.4	Unclear, maximum is above	No clear association asthma 0-14; COPD 65+; all respiratory 65+, almost statistically significant for asthma 15-64 (Europe wide summary estimates showed associations)	2 years of data is relatively short
Samoli et al 2016b	PM_{10}	2011-2012	Median 15.0 90th %ile 32.5	No (but max not given)	No association (all cause, respiratory and cardiovascular mortality; cardiovascular and respiratory admissions; except significant negative association respiratory admissions 65+)	2 years of data is relatively short

Table 2 Concentration ranges in London time-series studies of particulate matter and health Ave = average; max = maximum; %ile = percentile. COPD chronic obstructive pulmonary disease. 65+ = aged over 65 years.

The studies of nitrogen dioxide are shown in Table 3. The nitrogen dioxide bandings are defined based on chamber study evidence – background concentrations were typically not as high as the concentration switching from moderate to high days even in the early 1990s. An exception was the 1991 nitrogen dioxide episode (reviewed separately under episode studies) but that contributed very few days to the overall total for the relevant studies.

Reference	**Pollutant**	**Time-period**	**Concentration Data µg/m³**	**Reasonable proportion of data above moderate/ high switch**	**Associations shown or not for each outcome?**	**Comment**
Ponce de Leon et al 1996	NO_2 1-hour max	1987-1992	Median 98 95th %ile 195	No	Yes (all respiratory admissions, 24-hour mean)	Includes 1991 NO_2 episode
Sunyer et al 1997	NO_2 24-hour ave	1987-1991	Median 69 Max 347	Unclear, probably not given overlap of date range with Anderson et al 1998	Yes (asthma admissions 0-14); No (asthma admissions 15-64)	Includes 1991 NO_2 episode
Anderson et al 1997	NO_2 24-hour ave	1987-1991	Median 67	Unclear, probably not given date overlap with Poloniecki et al 1997	Yes (COPD admissions all ages)	Includes 1991 NO_2 episode
Anderson et al 1998	Nitrogen dioxide (1-hour max)	1987-92	Mean 112 90th %ile 158 95th %ile 192, Max 725	No	Yes (asthma admissions)	Includes 1991 NO_2 episode
Anderson et al 1996	Nitrogen dioxide (1-hour max)	1987-92	Mean 112 90th %ile 158 95th %ile 192, Max 725	No	Positive but just ns (24-hour ave) (all-cause mortality)	Includes 1991 NO_2 episode
Poloniecki et al 1997	NO_2 24-hour mean	1987-1994	Median 67 90th %ile 101 Max 379	No	Yes (all cardiovascular admissions) No (stroke admissions)	Includes 1991 NO_2 episode

Reference	Pollutant	Time-period	Concentration Data μg/m^3	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Atkinson et al 1999b	Nitrogen dioxide (1-hour max)	1992-1994	Median 97 90th%ile 135 Max 429	Probably not; maximum is above but not 90th percentile	Yes (all respiratory, all ages; asthma admissions 15-64; COPD/asthma 65+; lower respiratory admissions 65+; all cardiovascular admissions). No asthma admissions all ages; 0-14)	2 years of data is relatively short; Using ppb to μg/m^3 conversion factor of 1.91
Williams et al 2014	Nitrogen dioxide (1-hour max)	2000-2005	Median 65.3 75th%ile 77.4 Max 155.3	No	No single pollutant model, yes multi-pollutant model (all-cause mortality)	Using ppb to μg/m^3 conversion factor of 1.91
Williams et al 2014	Nitrogen dioxide (24-hour ave)	2000-2005	Median 39 75th%ile 48.3 Max 99.3	No	No single pollutant model, yes multi-pollutant model (all-cause mortality)	Using ppb to μg/m^3 conversion factor of 1.91

Table 3 Concentration ranges in London time-series studies of nitrogen dioxide and health. Ave = average; max = maximum; %ile = percentile; ns = non-significant. Ppb = parts per billion. COPD = chronic obstructive pulmonary disease.

The results of ozone studies are shown in Table 4. Ozone concentrations were actually lower in London in the past due to greater amounts of scavenging by higher concentrations of NO. Again, high and very high days are not sufficiently common to contribute much to the overall evidence in these time-series studies.

Reference	**Pollutant**	**Time-period**	**Concentration Data μg/m³**	**Reasonable proportion of data above moderate/ high switch**	**Associations shown or not for each outcome?**	**Comment**
Ponce de Leon et al 1996	O_3 8-hour 9-5pm	1987-1992	Median 28 95th%ile 74	No	Yes (all respiratory admissions)	Using ppb to μg/m³ conversion factor of 1.9956
Anderson et al 1998	Ozone (8-hour max)	1987-92	Mean 31 90th %ile 56 95th %ile 72, Max 148	No	Yes (asthma admissions)	
Anderson et al 1997	Ozone (9-5pm 8-hour mean)	1987-1991	Median 28	Unclear, probably not	Yes (COPD admissions)	
Anderson et al 1996	Ozone (8-hour max)	1987-92	Mean 31 90th %ile 56 95th %ile 72, Max 148	No	Yes (all- cause mortality)	
Poloniecki et al 1997	Ozone 9-5pm 8-hour mean	1987-1994	Median 26 90th %ile 57 Max 188	Probably not, although maximum is above	No (all cardiovascular admissions and stroke admissions)	Using ppb to μg/m³ conversion factor of 1.9956
Atkinson et al 1999b	Ozone 8-hour mean	1992-1994	Median 32 90th%ile 60 Max 160	No	Yes (lower respiratory admissions 65+, all cardiovascular admissions) No (all respiratory, all ages; asthma admissions; COPD/asthma 65+)	Using ppb to μg/m³ conversion factor of 1.9956
Sunyer et al 1997	Ozone daily 1-hour max	1987-1991	Median 46 Maximum 188	No*	Almost significant for 1-hour max ozone, not for 8-hour max ozone	
Williams et al 2014	Ozone (1-hour max)	2000-2005	Median 59.8 75th%ile 73.2 Max 207.8	No*	Yes (all-cause mortality)	Using ppb to μg/m³ conversion factor of 1.9956
Williams et al 2014	Ozone (24-hour ave)	2000-2005	Median 33 75th%ile 43.8 Max 110.4	Probably not; maximum just over*	Yes (all-cause mortality)	Using ppb to μg/m³ conversion factor of 1.9956

Reference	Pollutant	Time-period	Concentration Data µg/m³	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Atkinson et al 2012	Ozone (daily 8-hour max)	1993-2006	Median 49 95th%ile 90 Max 178	Probably not; max is over, 95th percentile is not.	Yes (all-cause mortality)	
Bhaskaharan et al 2013/ Armstrong et al 2014	Ozone (24-hour ave)	2002-2006	Median 35** 90th %ile 58 95th %ile 65 Max 119	Probably not; max is over, 95th percentile is not.	Yes (all-cause mortality)	

Table 4 Concentration ranges in London time-series studies of ozone and health, Ave = average; max = maximum; %ile = percentile. Ppb = parts per billion. COPD = chronic obstructive pulmonary disease.

*Using approximate ratio max 1-hour to max 8-hour of 1.14 and max 8-hour to 24-hour average of 1.53 (Anderson and Bell, 2010)

** Calculated from raw data in Supplementary material of Bhaskharan et al 2013. (Armstrong et al 2014 uses same dataset).

2.2.2 Multi-city time-series studies in Europe

As in London, high and very high days may be relatively rare too in other cities of Europe in more recent years. In APHEA 1, the median or 90% percentile levels of PM_{10} for some cities were higher than 75 µg/m³, while in APHEA 2, though 90% percentile levels of PM_{10} for some cities were higher than 75 µg/m³, the median levels were lower than 75 µg/m³ for all 21 cities studied. Recent time-series studies in other cities of Europe therefore may not include many days at the concentrations that define high or very high days (probably for all pollutants of interest) (Table 5). As $PM_{2.5}$ only started to be measured more recently, and the most significant multi-city time-series studies were performed some time ago, the evidence is mainly on PM_{10}. A more recent study did look at $PM_{2.5}$ and concentrated on southern Europe where concentrations are higher (Karanisou et al 2014) (Figure 1).

Reference, project name	Pollutant	Time-period	Concentration Data µg/m³	Reasonable proportion of data above moderate/high switch	Associations shown or not for each outcome?	Comment
Anderson et al 1997 (APHEA1)	Ozone (8-hour max)	Various dates for various cities 1977-1992	Medians range across 5 cities 40 – 138 µg/m³	Unclear. Medians are lower than 160 µg/m³ but upper percentiles not given.	Yes (COPD admissions)	Cities Amsterdam Barcelona, London, Paris, Rotterdam

Reference, project name	**Pollutant**	**Time-period**	**Concentration Data µg/m³**	**Reasonable proportion of data above moderate/high switch**	**Associations shown or not for each outcome?**	**Comment**
Anderson et al 1997 (APHEA 1)	Nitrogen dioxide (1-hour max)	Various dates for various cities 1977-1992	Medians range across 5 cities 125-192 µg/m³	Probably not. Medians are much lower than 400 µg/m³. Maximums could be that high but rare.	Yes (COPD admissions) (borderline significant)	Cities Amsterdam Barcelona, London, Paris, Rotterdam. Includes 1991 NO_2 episode in London
Katsouyanni et al. 1997 (APHEA2)	PM_{10}	Various dates for various cities 1975-1992	Medians range across 6 cities 33-85 µg/m³	Probably yes. Median for Barcelona (85) is higher than 75 µg/m³. 90th percentiles for Bratislava (95), Milan (137) and Paris (81) are also higher than µg/m³.	Yes (total mortality)	Cities Barcelona, Bratislava, Cologne, Lyons, Milan, Paris
Katsouyanni, et al. 1997 (APHEA2)	SO_2	Various dates for various cities 1975-1992	Medians range across 12 cities 13-74 µg/m³	Probably not. Medians are much lower than 532 µg/m³. Maximums could be that high but rare.	Yes (total mortality)	Cities Athens, Barcelona, Bratislava, Cracow, Cologne, Lodz, London, Lyons, Milan, Paris, Poznan, and Wroclaw.
Atkinson et al. 2001 (APHEA2)	PM_{10}	Various dates for various cities 1988-1997	Medians range across 5 cities for PM_{10} from 14-53 µg/m³, median daily TSP levels for two cities (Milan and Rome) of 61 and 69 µg/m³, and Paris reported median daily levels of PM_{13} of 20 µg/m³.	Unclear. Medians are lower than 75 µg/m³ but upper percentiles not given. Maximums (Maximum for Barcelona PM_{10} 131.7 µg/m³) provided are higher than 75 µg/m³.	Yes (admissions for respiratory diseases: asthma, COPD, all-respiratory diseases)	8 Cities: Barcelona, Birmingham, London, Milan, The Netherlands (considered as a city because of its relatively small size and dense population), Paris, Rome, and Stockholm.

Reference, project name	**Pollutant**	**Time-period**	**Concentration Data µg/m³**	**Reasonable proportion of data above moderate/high switch**	**Associations shown or not for each outcome?**	**Comment**
Katsouyanni et al. 2001 (APHEA2)	PM_{10} (24-hour)	Various dates for various cities 1990-1997	Medians range across 30 cities 14-66 µg/m³	Probably yes. Medians are lower than 75 µg/m³ for all 21 cities. 90th percentiles for Barcelona (95), Cracow (86), Erfurt (98), Milan (88), Prague (124), Rome (81), Teplice (83), and Torino (129) are higher than 75 µg/m³.	Yes (total mortality)	21 Cities: Athens Barcelona Basel Birmingham Budapest Cracow Erfurt Geneva Helsinki London Lyon Madrid Milan Paris Prague Rome Stockholm Tel Aviv Teplice Torino Zurich.
Samoli et al. 2006 (APHEA2)	NO_2 (1-hour max)	Various dates for various cities 1990-1997	Medians range across 30 cities 46.2-154.8 µg/m³	Probably not. Medians are much lower than 400 µg/m³. 90th percentiles (largest for Tel Aviv 254.9) are lower than 400 µg/m³. Maximums could be that high but very rare.	Yes (Total, cardio-vascular and respiratory mortality)	30 Cities: Athens Barcelona Basel Bilbao Birmingham Budapest Bucharest Cracow Erfurt Geneva Helsinki Ljubljana Lodz London Lyon Madrid Marseille Milan Netherlands Paris Poznan Prague Rome Stockholm Tel Aviv Teplice Torino Valencia Wroclaw Zurich.
Ballester et al. 2003*	NO_2 (24-hour average)	Various dates for various cities 1990-1996	Means ranges 32.9-71.0 (SD=20.0) µg/m³	Probably not. Means (<75 µg/m³) are much lower than 400 µg/m³ with small SDs (<30 µg/m³). Maximums could be that high but rare.	Yes (total, cardio-vascular and respiratory mortality).	8 Spanish cities including Barcelona, Madrid and Valencia etc.

Reference, project name	**Pollutant**	**Time-period**	**Concentration Data µg/m³**	**Reasonable proportion of data above moderate/high switch**	**Associations shown or not for each outcome?**	**Comment**
Ballester et al. 2006*	NO_2 (24-hour average)	Various dates for various cities 1995-1999	Means ranges 23.4-76.2 µg/m³ 90th %iles ranges 39.2-99.6 µg/m³ across all cities	Probably not. Means and 90th percentiles are much lower than 400 µg/m³. Maximums could be that high but rare.	Yes (all cardio-vascular hospital admissions)	14 Spanish cities including Barcelona, Madrid and Valencia etc.
Samoli et al. 2009	Ozone (8-hour max)	Various dates for various cities 1990-1997	Medians range across 21 cities 39.2 – 123.2 µg/m³	Unclear. Medians and 75th percentiles are lower than 160 µg/m³ but upper percentiles not given.	Yes (respiratory mortality, total and cardio-vascular mortality)	21 Cities Athens Barcelona Basel Birmingham Budapest Geneva Helsinki Ljubljana London Lyon Madrid Milan Netherlands Paris Prague Rome Stockholm Teplice Turin Valencia Zurich.
Larrieu et al. 2007*	O_3 (8-hour average)	Various dates for various cities 1998-2003	Means range across 8 cities 68.4-106.1 µg/m³	Unclear, means are lower than 160 µg/m³. The maximums and percentiles data are not available.	No (cardio-vascular hospital admissions)	8 French cities including Paris and Marseille.
Karanasiou et al. 2014 (MED-Particles)	$PM_{2.5}$ (24-hour average)	Various dates for various cities 2001-2010	Mean levels ranged from 17 to 37 µg/m³ at the traffic sites and from 12 to 37 µg/m³ at the urban background sites.	Probably yes. Means are lower than 53 µg/m³ for all traffic sites and urban background sites, but percentiles not given. By eye in Figure 1, 90th percentiles of traffic sites are over 53 µg/m³ in several cities and 90th percentiles of background sites are over 53 µg/m³ in Milan and Turin. Maximums provided for several cities (such as Athens traffic sites 70, Bologna traffic sites 81, Thessaloniki traffic sites 110, Milan urban background site 177, Turin urban background site 118) are higher than 53 µg/m³.	Yes (total, respiratory, and cardio-vascular mortality. In general, associations were stronger for cardio-vascular and respiratory mortality than all-cause mortality.)	13 cities Athens, Barcelona, Bologna, Huelva, Madrid, Marseille, Milan, Modena, Parma, Reggio-Emilia, Rome, Thessaloniki, Turin across Southern Europe

Reference, project name	**Pollutant**	**Time-period**	**Concentration Data μg/m³**	**Reasonable proportion of data above moderate/high switch**	**Associations shown or not for each outcome?**	**Comment**
Karanasiou et al. 2014 (MED-Particles)	PM_{10} (24-hour average)	Various dates for various cities 2001-2010	Mean levels ranged from 42–52 μg/m³ at the traffic sites and from 26-46 μg/m³ at the urban background sites.	Probably yes by analogy with $PM_{2.5}$ above. Means are lower than 75 μg/m³ for all traffic sites and urban background sites, but percentiles not given. By eye in the plot for PM_{10} published in the paper, 90th percentiles of traffic sites are over 75 μg/m³ in most cities and 90th percentiles of background sites are over 75 μg/m³ in Milan, Turin and Modena. Maximums daily means provided for several cities (such as traffic sites for Athens 123, for Bologna 103, for Milan 188, for Thessaloniki 211, urban background sites for Athens 158, for Milan 190, for Thessaloniki 202, for Turin 157) are higher than 75 μg/m³	Yes (total, respiratory, and cardio-vascular mortality.)	13 cities Athens, Barcelona, Bologna, Huelva, Madrid, Marseille, Milan, Modena, Parma, Reggio-Emilia, Rome, Thessaloniki, Turin across Southern Europe

Table 5 Concentration ranges in European multi-city studies Ave = average; max = maximum; %ile = percentile.

**Those studies were also listed in the meta-analysis table in section 2.2.3.*

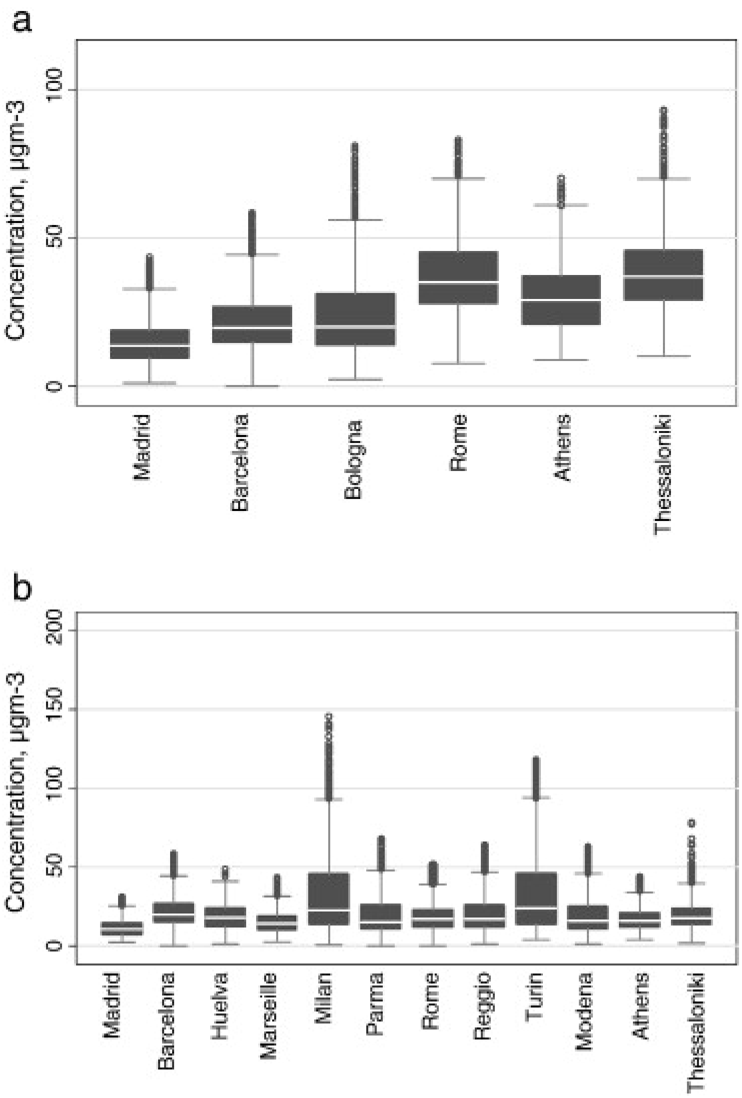

Figure 1 Distribution of $PM_{2.5}$ daily concentrations (μg m^{-3}) in a) traffic and b) urban background sites across Southern Europe. Median, 25th and 75th percentiles are shown in the box, whiskers indicate 10th and 90th percentiles and individual outliers are shown as points. Karanisiou et al (2014).

2.2.3 Influential time-series studies contributing to pooled concentration-response functions

Further investigation was carried out to pick up those time-series studies with most weights in the meta-analyses used to define the concentration-response functions used in the health impacts report (summarised in Appendix 1). Three meta-analyses (Atkinson et al, 2014; Mills et al 2015 and Walton et al 2014) for broader health outcomes such as deaths brought forward, all respiratory hospital admissions and all cardiovascular hospital admissions were checked for influential studies. Due to time constraints, studies from other parts of the world were only included if they were studies selected for the meta-analyses of the concentration-response functions used, i.e. only 24-hour average $PM_{2.5}$, 24-hour average NO_2 and maximum daily 8-hour average ozone. Further information about the concentration ranges was collected from these studies. Influential studies were selected based on the tightness of the confidence intervals (Table 6).

High and very high days may be relatively rare too in other cities of North America in more recent years. However, high and very high days especially for PM_{10} and $PM_{2.5}$ still happen often in Asian countries, such as China.

Reference	Pollutant	Time-period	Concentration Data μg/m³	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Zanobetti et al. 2009	$PM_{2.5}$, (24-hour average)	Various dates for various cities 1999-2005	Daily mean concentrations of $PM_{2.5}$ range across 112 cities 6.7-24.9 μg/m³.	Probably not. Medians are much lower than 53 μg/m³. Maximums could be higher (e.g., in California maximum>100 μg/m³) but rare.	Yes (total, cardio-vascular disease, myocardial infarction, stroke, and respiratory mortality)	112 cities including the biggest cities of Los Angeles, New York City, and Chicago in US.
Huang et al. 2009	$PM_{2.5}$, (24-hour average)	Mar. 4, 2004–Dec. 30, 2005	Median of $PM_{2.5}$ is 49.0 μg/m³.	Yes. Median of daily $PM_{2.5}$ concentrations (49.0) is lower than 53 μg/m³, but 75th percentile (72.4) is higher than 53 μg/m³.	Yes (total, cardio-vascular and respiratory mortality)	Shanghai city in China. A total of 79,530 deaths (41,857 males and 37,673 females) were recorded in this study population.
Burnett et al. 2004	$PM_{2.5}$ (24-hour average)	January 1, 1981 to Dec 31, 1999	Daily mean concentrations of $PM_{2.5}$ range across 12 cities 8.1-16.7 μg/m³.	Probably not. Daily means are much lower than 53 μg/m³ for all cities. Percentiles are not given. Maximums could be higher but rare.	Yes (total mortality).	12 Canada's largest cities: Halifax, Saint John, Quebec, Montreal, Ottawa, Toronto, Hamilton, Windsor, Winnipeg, Edmonton, Calgary, and Vancouver.
Host et al. 2008	$PM_{2.5}$ (24-hour average)	Various dates for various cities 2000-2003	Daily mean concentrations of $PM_{2.5}$ range across 6 cities 13.8-18.8 μg/m³.	No. Daily means and 95th percentiles (the highest: 33.0 μg/m³) are much lower than 53 μg/m³ for all cities.	Yes (hospital admissions for cardio-vascular diseases and respiratory infections); No (other respiratory diseases).	6 French cities including Paris and Marseille.
Jayaraman et al. 2008	$PM_{2.5}$ (24-hour average)	Jan 2004 to June 2005	Mean of respirable suspended particulate matter is 248.8 μg/m³	Probably yes, the daily mean (248.8) is not $PM_{2.5}$ but roughly is probably higher than 53 μg/m³. The minimum of daily average concentrations during the study period is 57 μg/m³.	Yes (respiratory hospital admissions)	A single city study in Delhi, India. Used respirable suspended particulate matter (RSPM) as $PM_{2.5}$ in the article.

Reference	Pollutant	Time-period	Concentration Data µg/m^3	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Ballester et al. 2003	NO_2 (24-hour average)	Various dates for various cities 1990-1996	Means ranges 32.9-71.0 (SD=20.0) µg/m^3	Probably not. Means (<75 µg/m^3) are much lower than 400 µg/m^3 with small SDs (<30 µg/m^3). Maximums could be that high but rare.	Yes (total, cardio-vascular and respiratory mortality).	8 Spanish cities including Barcelona, Madrid and Valencia etc.
Wong, Vichit-Vadakan et al. 2008	NO_2 (24-hour average)	Various dates for various cities 1996-2004	Medians range across 4 cities 39.7-62.5 µg/m^3	No, medians are much lower than 400 µg/m^3. Maximums are lower than 400 µg/m^3.	Yes (total, cardio-vascular and respiratory mortality)	4 cities in Asian areas: Bangkok, Hong Kong, Shanghai, and Wuhan.
Burnett et al. 2004	NO_2 (24-hour averages)	January 1, 1981 to Dec 31, 1999	Daily mean concentrations of NO_2 range across 12 cities 10.0-26.4 ppb (19.1-50.4 µg/m^3;1ppb = 1.91 µg/m^3).	Probably not. Daily means are much lower than 400 µg/m^3 for all cities. Percentiles are not given. Maximums could be higher but rare.	Yes (total and cardio-vascular mortality).	12 Canada's largest cities: Halifax, Saint John, Quebec, Montreal, Ottawa, Toronto, Hamilton, Windsor, Winnipeg, Edmonton, Calgary, and Vancouver.
Dominici et al 2003	NO_2 (24-hour average)	Various dates for various cities 1984-1993	Daily mean concentrations of NO_2 range across all cities 11.0-39.4 ppb (21.0-75.3 µg/m^3 ;1ppb = 1.91 µg/m^3). (Data from Californian Air Resources Board, 2007)	Probably not. Medians are much lower than 400 µg/m^3. Maximums could be that high but rare.	Yes (total mortality)	90 US Cities (NMMAPS). Main analyses were for PM and ozone. Size of NO_2 effect at lag 1 lost statistical significance after adjustment for PM_{10} and O_3.
Ballester et al. 2006	NO_2 (24-hour average)	Various dates for various cities 1995-1999	Means ranges 23.4-76.2 µg/m^3 90th %iles ranges 39.2-99.6 µg/m^3 across all cities	Probably not. Means and 90th percentiles are much lower than 400 µg/m^3. Maximums could be that high but rare.	Yes (all cardio-vascular hospital admissions)	14 Spanish cities including Barcelona, Madrid and Valencia etc.
Thach et al. 2010	NO_2 (24-hour average)	1996-2002	Mean 58.7 µg/m^3 Standard deviation 20.0 µg/m^3	Probably not. Mean is much lower than 400 µg/m^3. Percentiles were not available. Maximums could be that high but rare.	Yes (all cardio-vascular hospital admissions)	A single city study in Hong Kong, China.

Reference	Pollutant	Time-period	Concentration Data µg/m^3	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Gryparis et al. 2004	O_3 (8-hour average)	Various dates for various cities 1990-1997	Medians range across 21 cities 30 – 99 µg/m^3 during summer period, and 8 – 49 µg/m^3 during winter period	Unclear. Medians and 90th percentiles (100-154 µg/m^3 across 21 cities, the highest was in Torino during summer period) are lower than 160 µg/m^3.	No (all-cause mortality)	21 Cities Athens Barcelona Basel Birmingham Budapest Geneva Helsinki Ljubljana London Lyon Madrid Milan Netherlands Paris Prague Rome Stockholm Teplice Turin Valencia Zurich.
Wong, Vichit-Vadakan et al. 2008	O_3 (8-hour average)	Various dates for various cities 1996-2004	Medians range across 4 cities 31.5-81.8 µg/m^3	Unclear, medians are lower than 160 µg/m^3. Maximums are higher than 160 µg/m^3, but the percentiles data are not available.	Yes (total, cardio-vascular and respiratory mortality)	4 cities in Asian areas: Bangkok, Hong Kong, Shanghai, and Wuhan.
BorjaAburto et al. 1997	O_3 (8-hour moving average)	1990-1992	Median is 94 ppb (188 µg/ m^3; for O_3 1ppb = 2.0 µg/m^3)	Yes, median is higher than 160 µg/m^3. 75th percentile is 228 µg/m^3, which is nearly at very high level.	Yes, but lost significance if further adjusting for TSP (total and cardio-vascular mortality)	Mexico City in Mexico.
Lee et al. 2007a	O_3 (max daily 8-hour moving average)	Between January 1, 2000 and Dec 31, 2004.	Daily mean concentration of O_3 is 26.82 (SD=14.72) ppb (53.64 [SD=29.44] µg/m^3; for O_3 1ppb = 2.0 µg/m^3).	Probably not, daily mean is much lower than 160 µg/m^3 and SD is less than 30 µg/m^3. Percentiles data are not available.	Positive but not significant (total non-accidental mortality)	Seoul in South Korea.
Larrieu et al. 2007	O_3 (8-hour average)	Various dates for various cities 1998-2003	Means range across 8 cities 68.4-106.1 µg/m^3	Unclear, means are lower than 160 µg/m^3. The maximums and percentiles data are not available.	No (cardio-vascular hospital admissions)	8 French cities including Paris and Marseille.
Thach et al. 2010	O_3 (8-hour average)	1996-2002	Mean 36.9 µg/m^3 Standard deviation 23.0 µg/m^3	Probably not, mean is much lower than 160 µg/m^3 and SD is less than 30 µg/m^3. Percentiles data are not available.	No (cardio-vascular hospital admissions-stroke and IHD)	A single city study in Hong Kong, China.

Reference	Pollutant	Time-period	Concentration Data μg/m³	Reasonable proportion of data above moderate/ high switch	Associations shown or not for each outcome?	Comment
Chang et al. 2002	O_3 (8-hour average)	1997-1999	Mean 37.9 ppb (=75.8 μg/m³). Standard deviation 16.7 ppb (=33.4 μg/m³, for O_3 1ppb = 2.0 μg/m³)	Unclear, mean is lower than 160 μg/m³. The maximum (193.2 μg/m³) is higher than 160 μg/m³. Percentiles data are not available.	Yes (all respiratory hospital admissions)	Three cities in Taiwan.
Thach et al. 2010	O_3 (8-hour average)	1996-2002	Mean 36.9 μg/m³ Standard deviation 23.0 μg/m³	Probably not, mean is much lower than 160 μg/m³ and SD is less than 30 μg/m³. Percentiles data are not available.	Yes (all respiratory hospital admissions- acute respiratory disease and COPD)	A single city study in Hong Kong, China.

Table 6 Concentration ranges in studies that were influential in meta-analyses used to define concentration-response functions for deaths brought forward, all respiratory hospital admissions and all cardiovascular hospital admissions. Ave = average; max = maximum; %ile = percentile; SD = standard deviation, ppb =parts per billion. IHD = Ischaemic heart disease. COPD = Chronic obstructive pulmonary disease. TSP= Total suspended particulate matter.

2.3 Discussion for concentration ranges in time-series studies

Based on the time-series studies collected for this report, high and very high days for all three pollutants of interests are relatively rare in more recent years in London, in most other cities of Europe, and in developed areas and big cities of North America. Some studies still documented high and very high levels for PM very often in big cities in developing countries (e.g., China), which could be used to complete the full concentration ranges of PM for the concentration-response analysis. However, it is quite rare in recent years to capture high and very high daily mean concentrations for NO_2 and O_3 in cities all over the world, which makes it difficult to confirm the shape of the concentration-response relationship at higher concentrations. We are more interested in the upper end of the concentration ranges in this report, and the limited availability of those data in routine time-series studies that did not specifically examine the shape of the concentration-response relationship led us to consider studies that examined this directly and to episode studies that considered specific occasions with particularly high concentrations.

It should be noted that, due to time constraints, we only considered time-series in London (section 2.2.1), and multi-city studies in Europe (both for all averaging times, and for PM_{10} as well as $PM_{2.5}$, O_3 and NO_2) (section 2.2.2). Studies from other parts of the world were only included if they were studies selected for the meta-analyses of the concentration-response functions used, i.e. only 24-hour average $PM_{2.5}$, 24-hour average NO_2 and maximum daily 8-hour average ozone, and within those selected studies, only those with tight confidence intervals (section 2.2.3). This omitted some large studies e.g. the study of PM_{10} by Wong et al. 2008 in four cities (medians range across four cities 45.5-130.2 μg/m³) in Asian areas and the study by Katsouyanni et al. 2009 in 12 Canadian cities (medians range across 12 cities 11.4-27.5 µg/m^3) and 50 US cities (medians range across 50 cities 14-43.7 µg/m^3), and those data could be used to capture high and very high daily mean concentrations for PM_{10} in cities all over the world. And the study by Katsouyanni et al. 2009 in 12 Canadian cities and 50 US cities using O_3 (1-hour average), could enrich the concentration ranges of O_3 with different metrics of pollutants and explore the comprehensive associations between O_3 and health outcomes.

There may also be more studies than those reviewed and summarized here, for example, a recent published time-series study corroborated the robust relationship between $PM_{2.5}$ and mortality with data collected from 499 cities in 16 countries or regions (Liu et al. 2019). The strengths of this study include more complete concentration ranges at both higher and lower exposure levels and much greater statistical power with almost 60 million events. Details are given in section 3.3. Some studies may report time series studies with high and very high concentrations especially for NO_2 and O_3 in some specific settings too.

In general, it is plausible that effects shown in the range of concentrations that occur frequently would also occur at higher concentrations. It is more a case of increased uncertainty in the exact size of the effect at higher, less common concentrations. The concentration-response relationships between those pollutants and health are only likely to be better understood with wider ranges of concentrations and larger numbers of studies in different settings.

3 Shape of concentration-response functions

3.1 Introduction to shape of concentration-response function section

The health impacts of episodes report assumes that the concentration-response functions of the log of the relative risk against concentration are linear across concentrations. This is the standard form of analysis in the time-series studies from which the concentration-response functions are derived. Examining the results to see if the relationship is non-linear requires different types of analysis and is done in fewer studies. Usually, this is to examine the shape of the relationship at the bottom end of the concentration range. In this project, we are more interested in the upper end of the range since this is potentially the range of high and very high days. We therefore investigated studies examining the shape of concentration-response relationships for the shape at the upper end of the range.

3.2 Concentration-response relationship shape search

The following search was performed on PubMed:

> ((((((air pollution) OR particulate matter) OR nitrogen dioxide) OR ozone)) AND ((((shape) OR concentration-response curve) OR dose-response curve) OR exposure-response curve))) AND ((((((((mortality) OR deaths) OR hospital admissions) OR asthma) OR cardiovascular) OR stroke) OR cardiac) OR COPD) OR respiratory)

This was subsequently further limited to studies in humans and in the English language giving an initial group of 157 studies. 105 studies were sifted out by title for a variety of reasons, including being studies on other chemicals, shape not relating to the concentration-response curve e.g shape of nanoparticles, chamber studies, toxicology, occupational exposure, indoor exposure, smoking, temperature and health outcomes other than those specified. This left 52 studies.

It was subsequently noted that the PubMed filter for studies in humans had excluded some epidemiology studies, leading to sifting back in 19 studies and a further 23 studies were added from other sources e.g. Endnote libraries held by the authors. Added to the 52 studies previously identified, this led to a total of 94 studies for further detailed sifting.

More detailed sifting divided the 94 studies into 6 chamber studies, 30 long-term exposure studies and 58 short-term exposure studies. The latter were considered further with full screening of the articles. The inclusion criteria were the pollutants ($PM_{2.5}$, NO_2 and O_3) and health outcomes (all-cause mortality; respiratory, asthma, COPD, cardiovascular, cardiac and stroke hospital admissions) used in the health impacts report. 43 further articles were excluded at this point (17 other pollutants; 12 other health outcomes; 14 other reasons e.g. shape referring to distributed lag models rather than concentration-response curves.)

One further important study published after the original search was added (Liu *et al* 2019).

The remaining 16 studies are mentioned or tabulated in the section below.

3.3 Results for the shape of the concentration-response function

The results for $PM_{2.5}$ are shown in Table 7. There were six studies examining the shape of the relationship between $PM_{2.5}$ and all-cause mortality. One (Schwartz *et al*, 2002) did not extend upwards into the range of high or very high days. For the remainder of studies, one suggested a linear relationship, one a relationship that steepened at higher concentrations and three some flattening off (one only at much higher concentrations and with wide confidence intervals). One study of hospital admissions showed a reduction in steepness at higher concentrations. Not all studies did formal tests for compatibility with linearity. Overall, the evidence is mixed and not conclusive for whether the curve flattens off at higher concentrations or not. There is wider evidence on other particulate matter metrics than described here. This evidence was reviewed, along with $PM_{2.5}$, in WHO (2013b). This concluded that there was no evidence for a threshold at the lower end of the range of concentrations and that European studies of short-term exposure and $PM_{2.5}$ had not detected significant deviations from linearity.

Reference	**Mortality or hospital admissions**	**Diagnosis**	**Concentration range of $PM_{2.5}$**	**Results**
Schwartz et al (2002)	Mortality	All cause (non-accidental)	Means across 6 US cities 11.3 – 30.5 µg/m^3 Concentrations above 35 µg/m^3 were rare.	Showed a linear relationship in the range 1- 35 µg/m^3 (not analysed above that range).
Chen et al (2017)	Mortality	All cause (non-accidental)	Median 54 µg/m^3 Mean 56 µg/m^3 75th %ile 67 µg/m^3 Max 127 µg/m^3 (Annual means across 272 Chinese cities 2013-2015)	Slight flattening off above about 200 µg/m^3 24-hour average (but widening confidence intervals).
Cai et al (2019)	Mortality	All cause (non-accidental)	Median 30 µg/m^3 Mean 35 µg/m^3 75th %ile 47 µg/m^3 Max 137 µg/m^3 (Shenzen 2013-2015)	Linear across full range of concentrations
Yan et al (2019)	Mortality	All cause (non-accidental)	Mean 89.2 µg/m^3 Max 388 µg/m^3 (Beijing 2009-2012)	Steepens continuously as concentrations increase
Li et al (2019)	Mortality	All cause	Range of means 2013-2015 across 104 Chinese counties 23.2-106 µg/m^3 Means are of daily satellite modelled data by county. Max from graph 250 µg/m^3	Meta-regression slope approximately linear to about 60 µg/m^3, then decreases slowly using a model showing the least heterogeneity (22%) across locations. Test for linearity not reported but visually confidence intervals look incompatible with this. Confidence intervals potentially compatible to flattening off from about 60-150 rather than decreasing.

Reference	Mortality or hospital admissions	Diagnosis	Concentration range of $PM_{2.5}$	Results
Sun et al (2019)	Hospital admissions	COPD	Median 35.2 µg/m^3 Mean 45.2 µg/m^3 75th %ile 58.9 µg/m^3 Max 230.1 µg/m^3 (Yancheng, 2015-2017)	Flatter (but still increasing) slope above 40 µg/m^3
Liu et al (2019)	Mortality	All cause	Median 31.9 µg/m^3 Mean 35.6 µg/m^3 75th %ile 43.5 µg/m^3 Max 116.9 µg/m^3	Steeper below 20 µg/m^3. A continuous curve but approximately linear 20-75 µg/m^3. Flattens more markedly above about 100 µg/m^3. NB Very large study, 499 cities

Table 7 Time-series studies investigating shape of concentration-response relationship for $PM_{2.5}$, all ages. Max = maximum. %ile =percentile. COPD = chronic obstructive pulmonary disease.

The results for nitrogen dioxide are shown in Table 8. Suggestions of a flattening of the slope above 100 or 150 µg/m^3 are inconclusive.

Reference	Mortality or hospital admissions	Diagnosis	Concentration range of nitrogen dioxide	Results
Chen et al (2012)	Mortality	All cause (non-accidental)	Mean 26 – 67 µg/m^3 75th percentile 27 – 80 µg/m^3 Max 52 – 178 µg/m^3 Range across 17 Chinese cities, 24-hour average	Conclusion in paper: almost linear, no significant difference between spline and linear model. Other information: Slight flattening around 150 µg/m^3 but not conclusive as data points rare in this range
Moolgavkar et al (2013)	Mortality	All cause	Not given. From graph max around 150 µg/m^3 24-hour average.	Conclusion in paper: Suggestion of a threshold around 20ppb (approx. 40 µg/m^3) but confidence intervals too wide to exclude linearity. Other information: Appears to flatten off around 100 µg/m^3 but again confidence intervals too wide to exclude linearity.

Table 8 Time-series studies investigating shape of concentration-response relationship for nitrogen dioxide. Max = maximum, ppb = parts per billion.

There were seven studies on ozone but for a variety of averaging times. The averaging time used in the Daily Air Quality Index is maximum 8-hour average. The shape of the concentration-response relationship can vary with averaging time. Before explaining this point, some general points about the effects of correlations between pollutants on concentration-response relationships are described in the paragraph below.

The vast majority of studies for any of the pollutants examined the shape of the concentration-response relationship for single pollutant models; considering just one pollutant at a time. In fact, pollutants are correlated with each other. This means associations for one pollutant can be partially reflecting other pollutants as well. To add even more complexity, the way in which the associations for one pollutant also reflect others can change across the concentration range, affecting the shape of the concentration-response relationship. This is particularly apparent for ozone where correlations with PM tend to be negative in the winter and positive in the summer; and correlations with NO_2 are usually negative, particularly in the winter. As ozone is low in the winter, health effects can appear to be high at low ozone levels (because PM or NO_2 related health effects are higher). This can appear to indicate a threshold at lower concentrations that is not actually real. While this report is considering the upper rather than the lower end of the concentration range, higher ozone concentrations are also partially representing other pollutants but in a different way.

The points in the above paragraph are also relevant to averaging time. 24-hour average ozone concentrations include the night-time period when ozone concentrations are low but other pollutants are low as well. The nature of the correlations between pollutants are therefore different for 24-hour average ozone compared with daily maximum 8-hour average ozone, the latter normally reflecting the daytime pollutant correlations. This difference in correlation patterns will in turn be reflected in the shape of the concentration-response relationships. As the concentration-response relationships used for the calculations in the health impacts of episodes report were based on daily maximum 8-hour average ozone, we did excluded studies of the shape of concentration-response relationships for 24-hour average ozone concentrations (Bae et al, 2015; Bell et al, 2006; Collart et al, 2018; Jhun et al, 2014 and Moolgavkar et al, 2013).

Table 9 does not include studies published prior to 2014 because these have been reviewed by the Committee on the Medical Effects of Air Pollutants (COMEAP, 2015a). This excluded Atkinson et al (2012) and Gryparis et al (2004) both of which were covered in the COMEAP report. The COMEAP report concluded that at the lower end of the concentration range, it was reasonable to assume no threshold. It also discussed several points relating to correlation between pollutants, as explained above. It was also noted that towards the upper end of the concentration range, temperatures are higher. Consequently, people are more likely to open windows and to spend time outside, both of which increase personal exposure to ozone. Theoretically, this could steepen the slope of the concentration-response relationship, as health effects are expected to increase with increasing personal exposure. This was in fact what was seen in the one study (Zu et al 2017) on the shape of the concentration-response relationship for ozone after exclusion of 24-hour average studies and pre-2014 studies (Table 9).

Reference	Mortality or hospital admissions	Diagnosis	Concentration range of ozone	Results
Zu et al (2017)	Hospital admissions	Asthma	Median 61.9 μg/m^3 75th percentile 80.0 μg/m^3 90th percentile 97.0 μg/m^3 Maximum 165.2 μg/m^3 (converted from ppb)	For children, the concentration-response curve became steeper in the range 80 to 140 μg/m^3 i.e. above the 75th percentile; For adults, the curve was a little steeper over about 100 μg/m^3

Table 9 Time-series studies investigating shape of concentration-response relationship for maximum 8-hour average ozone, published since COMEAP (2015a). ppb = parts per billion.

3.4 Discussion

Based on the studies picked up from this specific literature search, there is no conclusive evidence suggesting that the assumption of linearity on the log scale used in the calculations in the health impacts of episodes report is unreasonable. There are some suggestions that flattening off may occur at higher concentrations of pollutants but also studies suggesting it remains linear or gets steeper. There may also be more studies than those reviewed here. (Work for the COMEAP ozone report (COMEAP, 2015a) found more evidence when hand searching all time-series studies on ozone.)

Interpretation of shapes of concentration-response relationships, particularly for single pollutant models, is complex and is only likely to be better understood with larger numbers of studies incorporating investigations of the influence of correlations between pollutants.

4 Review of episode studies

4.1 Introduction for review of episode studies

Some studies concentrate specifically on major air pollution episodes and examine their health effects. This section reviews these studies and compares them with the episodes in London from 2009-2017.

4.2 Methods for review of episode studies

A search was performed on PubMed of 'air pollution' and 'episode' and 'health' for all dates to October 2019. This was a relatively simple search, given the small scale of the project and some studies may have been missed. This search picked up 196 references. 162 were sifted out on titles and abstracts (53 general studies on air pollution and health; 47 general or episode studies on air quality only; 23 studies on smoking; seven indoor studies; four studies on temperature; three general air pollution and health reviews; three toxicity studies on episode pollution mixtures; five health impact assessments of episodes; one intervention study and 16 other). Further sifting after reading articles and selecting on papers containing measurements of ozone, nitrogen dioxide or $PM_{2.5}$, and epidemiological analysis of health outcomes (not health impact assessment) gave nine studies. The excluded studies were mainly for other PM metrics (18 studies); other pollutants (e.g. VOCs) (three studies); sulphur dioxide (one study); general discussion of episodes (one study) and two studies where the full text could not be obtained in the time available.

4.3 Results for review of episode studies

Most studies had pollutant concentrations above the switch from moderate to high in the Defra Air Quality Index, sometimes significantly higher.

In discussing the studies below, it should be borne in mind that, by their nature, air pollution episodes are usually only a few days long. This often means there is insufficient statistical power. Thus, increased risks which lack statistical significance does not necessarily mean that the increased risk is not real.

There was only one study with a **nitrogen dioxide** concentration above the border between moderate and high days (Anderson *et al* 1995 on the 1991 London nitrogen dioxide episode). In fact, using the conversion of 1ppb = 1.91 $\mu g/m^3$, the maximum of 423 ppb is well into the very high band (above 600 $\mu g/m^3$). This study found significantly increased risks for all-cause mortality and COPD admissions in comparison with the same week as the episode week in other years and increased risks that were not significant in comparison with control areas. There were also other increased risks (see table).

Nitrogen dioxide concentrations in the study of an agricultural burning episode in Winnipeg by Long et al (1998) did not reach the equivalent of the high band and $PM_{2.5}$ was not measured, although PM_{10} concentrations were above the borderline for the very high band. A small proportion of the COPD patients studied experienced breathing trouble and eye, nose and throat irritation.

Nitrogen dioxide concentrations were also measured in the study by Yamasaki et al (2014) (see below).

There was only one study that set out to examine an **ozone** episode (Cuijpers et al 1994) (but see also Yamasaki et al 2014 below). This 1991 study in Maastricht found small inconsistent changes in lung function and no increase of respiratory symptoms in primary school children.

There were several studies where **$PM_{2.5}$** was measured in a variety of types of episodes. The one most relevant to London is by Smith et al (2015) which examined two spring 2014 air pollution episodes in England, including the London area. $PM_{2,5}$ concentrations were high or very high; other pollutants were moderate or lower. The first episode had higher $PM_{2.5}$ concentrations (although there were very high days in both episodes); for the second the concentrations were not as high but the episode was more prolonged and covered a wider area. There were significantly increased calls to the NHS 111 service, GP consultations (in/out of hours) and A&E visits for at least one of difficulty breathing, asthma, wheeze or breathlessness for each service. The numbers of excess in hours GP consultations (compared with that normally expected for the time of year) was extrapolated for England from the data in the syndromic surveillance scheme (55% of the population). This gave estimates of 2300 excess GP consultations for wheeze and breathlessness and 400 for severe asthma for the second episode. The estimates for the first episode were lower (1200 and 100) and not statistically significant. It is not clear if this was due to less statistical power for a shorter episode across a narrower area or whether shorter exposures have no effect, even with higher concentrations. The former explanation seems more likely, given other evidence on increased health effects with increased concentrations.

Of the remaining studies measuring $PM_{2.5}$, two were close to fires (Rappold et al 2012 (peat fire in North Carolina) and Shao et al (2019) (coal mine fire in Australia). While heathland and moorland fires occur in the UK, they are unlikely on any large scale close to London. The results of these studies are in the table but will not be discussed in detail here. Transboundary episodes from a wildfire source do occasionally occur in London, notably when smoke from Russian wildfires reached the UK in 2002 and 2006 (Witham et al. 2007). The study by Hanninen et al 2009 of a transboundary episode in Finland, as a result of wildfires in Eastern Europe in 2002 is therefore of some interest. $PM_{2.5}$ concentrations were in the range that occurs on high and very high days in London. Increased daily all-cause mortality was found in the episode periods. These were not statistically significant, but the authors expected this due to low statistical power.

While not related to wildfires, the pollution mixture in China is quite different being more dominated by coal burning[1]. Air pollution concentrations can be very high. A study by Yamasaki et al (2014) in Japan looked at health effects of transboundary pollution from several air pollution episodes in China. The raised $PM_{2.5}$ concentrations were more in the range of pollution in London (equivalent to high days but not very high days) than levels in Beijing itself. This study did not find an association between $PM_{2.5}$ and asthma emergency room visits at night, but did with ozone. It was difficult to tell from the paper whether ozone concentrations were as high as those defined as high or very high days in the UK because results were given as monthly averages rather than maximum daily 8-hour averages. The monthly average ozone in the month with the most episodes (March 2013) had the second highest monthly average of the January, February and March of 2011, 2012 and 2013 (30.6 ppb). Nitrogen dioxide also had the second highest monthly average and had a significant association with asthma emergency room visits (not highlighted in the paper) but this was not maintained in multi-pollutant models. The ozone association was stable to adjustment for other pollutants.

Finally, Zhou et al (2015) examined a series of episodes in China throughout 2013. The episodes were defined as concentrations above 100 $\mu g/m^3$ for more than 3 consecutive days. While concentrations above 100 $\mu g/m^3$ have occurred in London, this has not happened since 2011 and was not for three consecutive days. In contrast, there were 20 such episodes in Beijing and the wider

[1] Episodes may be secondary particle dominated with more sulphate than would be expected in the UK.

region, of which nine had concentrations above 200 µg/m^3. Smog episodes were found to be significantly associated with all-cause mortality in 5 out of 7 districts. This association lost statistical significance after control for temperature in urban but not rural districts close to Beijing. Significant associations with cardio-respiratory mortality were also found in rural districts close to Beijing.

Measurement of $PM_{2.5}$ is relatively recent. There are therefore many historical episodes that have been studied for their health effects that are not included in **Error! Reference source not found.** because they used different PM metrics or measured other pollutants e.g. SO_2. Examples include the London 1952 episode linked to all-cause, respiratory and cardiovascular mortality and respiratory and cardiovascular morbidity indicators (Ministry of Health, Great Britain, 1954; Bell et al 2001,2004). There are also a series of papers summarised in Wichman (2004) on an episode in 1985 in Germany with elevated TSP and SO_2 concentrations. The studies found increased mortality and hospital admissions for respiratory and cardiovascular disease, increased ambulance calls and outpatient visits and increased chronic bronchitis exacerbations. Biomarkers of cardiovascular disease could also be examined as a result of an ongoing cohort study at that time. This showed increases in plasma viscosity (can be related to blood clotting); C-reactive protein (a marker of inflammation) and heart rate. There was some debate about the effect of the concurrent low temperatures on plasma viscosity but the results were controlled for meteorological variables (Peters et al 1997). Outside Europe there are also studies of dust storm events e.g. Tam et al (2012) in Hong Kong. A full list of references using PM metrics other than $PM_{2.5}$ is available on request.

Study	Episode date and location	Type of pollution episode	$PM_{2.5}$	NO_2	O_3	Effect on health outcomes in health impacts report	Effect on other health outcomes
Anderson et al 1995	London, winter 1991	Traffic related (NO_2 dominated)	n/a (148 µg/m³ 24-hour BS) ($PM_{2.5}$ not reported but probably would have been at least a moderate episode for $PM_{2.5}$)[2]	**423 ppb 1-hour max**	n/a	Significantly increased risk[a]: all-cause mortality, COPD admissions; Marginally non-significant increased risk: respiratory admissions; Non-significant increased risk: asthma admissions in children No increased risk: asthma admissions in adults	Significantly increased risk[a]: cardiovascular mortality; ischaemic heart disease mortality; respiratory hospital admissions in the elderly; Marginally non-significant increased risk: respiratory mortality, respiratory admissions all ages; Non-significant increased risk: respiratory infection mortality, obstructive lung disease mortality, ischaemic heart disease admissions.
Long 1998	Winnipeg 1992	Agricultural burning episode	n/a (80-110 µg/m³ 24-hour PM_{10})	110 ppb 1-hour max	n/a	n/a	Increased breathing trouble in about 5% and eye, nose and throat irritation in about 10% of COPD patients (derived from paper Table 3). Significance testing was only for differences between men and women.

[2] Difficult to translate into modern measurements. Judgement roughly based on conversion from Black Smoke as measured at the time to Black carbon (Heal and Quincey, 2012)

Study	Episode date and location	Type of pollution episode	$PM_{2.5}$	NO_2	O_3	Effect on health outcomes in health impacts report	Effect on other health outcomes
Cuijpers 1994	Maastricht summer 1991	Summer smog (ozone dominated)	n/a PM_{10} 54 µg/m³ 12-hour ave	51 µg/m³ 24-hour ave	Many days >120 µg/m³ daily 8-hour max; **max day 163 µg/m³**	n/a	Small inconsistent changes in lung function and no increase of respiratory symptoms in primary school children.
Smith et al (2015)	England, 2014	Transboundary, secondary PM episode	Two spring periods of high or very high days in English regions, **over 54 and over 71 µg/m³ $PM_{2.5}$** respectively	n/a	n/a	n/a	Significantly increased NHS111 calls, GP consultations and A&E visits for difficulty breathing, asthma/ wheeze or breathlessness
Hanninen et al (2009)	Finland, 2002	Transboundary from Eastern European wildfires	**Two peaks at 55 µg/m³ and one at 90 µg/m³ $PM_{2.5}$** in Helsinki	n/a	n/a	Increased daily mortality. Not statistically significant as expected due to low statistical power.	n/a
Yamasaki 2014	Himeji city, Japan, 2013	Transboundary pollution from spring 2013 Beijing episodes, PM dominated.	**Max 24-hour averages around 60 µg/m³ $PM_{2.5}$** in January and several times in March; March monthly average 37.2 µg/m³ (highest of all Jan, Feb or March averages in 2011, 2012 and 2013). PM_{10} and OC also highest that month.	Monthly ave for March 2013 14.5 ppb (2nd highest of all Jan, Feb or March aves in 2011, 2012 and 2013)	Monthly ave for March 2013 30.6 ppb (2nd highest of all Jan, Feb or March aves in 2011, 2012 and 2013)	n/a	Case-cross over study of cases of asthma emergency room visits at night for time period Jan-March 2013. No association found with $PM_{2.5}$. An association was found with ozone.

Study	Episode date and location	Type of pollution episode	$PM_{2.5}$	NO_2	O_3	Effect on health outcomes in health impacts report	Effect on other health outcomes
Zhou et al (2015)	China, 2013	Probably secondary aerosol dominated with high proportion of sulphate	**Max 24-hour mean $PM_{2.5}$ 211 µg/m^3** in Beijing; episodes (around 20 in 2013) were defined as more than 3 days above **100 µg/m^3 24-hour average $PM_{2.5}$.**	n/a	n/a	Smog episodes significantly associated with all-cause mortality in 5 out of 7 districts, lost statistical significance after control for temperature in urban but not rural districts.	Cardio-respiratory mortality also significantly associated with smog episodes in rural districts.
Rappold et al (2012)	North Carolina, 2008	Peat fire	**Max 24-hour average 129 µg/m^3 $PM_{2.5}$**	n/a	n/a	n/a	Significant increases in asthma and congestive heart failure emergency department visits.
Shao et al 2019	Hazelwood Australia	Coal mine fire	75th percentile of 24-hour averages 16.8 µg/m^3 $PM_{2.5}$; 75th percentile of peak 1-hour averages 150.7 µg/m^3	n/a	n/a	n/a	Small but significant reduction in area under the reactance curve (a measure of the elastic properties of the lung) in 3-5 year old children

Table 10 Studies of health effects of air pollution episodes where ozone, nitrogen dioxide or $PM_{2.5}$ concentrations were measured (figures in bold indicate concentrations above the concentration at which the Defra Air Quality Index switches from moderate to high (54 µg/m^3 $PM_{2.5}$; 400 µg/m^3 NO_2; 160 µg/m^3 O_3). Max = maximum, Ave = average, ppb parts per billion. COPD = chronic obstructive pulmonary disease. BS = Black smoke.

[a] Results are for comparison of episode week with the same week in control years; comparisons with control areas were generally raised but not statistically significant.

4.4 Discussion of review of episode studies

This overview of episode studies shows that, for at least some episodes, health effects are shown at pollutant concentrations equivalent to high or very high days in the Defra Daily Air Quality Index (statistically significant associations in Anderson et al 1995; Zhou et al, 2015 and Smith et al, 2015).

This includes some outcomes that are the same as those used in the health impacts of episodes report, although these were for episodes with higher pollutant concentrations (Anderson et al 1995; Zhou et al, 2015) than those found in London from 2009-2017 (the period used in the health impacts report). Other studies found increased risks that were not statistically significant (Hanninen et al 2009). Statistical power is a particular challenge for episode studies that are only a few days long. Other challenges are controlling for temperature. These challenges probably account for the fact that there were relatively few studies to review, at least with the literature search terms that we used. Two messages can be summarised (i) episode studies do show health effects, including some that were not quantified in our health impacts of episodes report e.g. GP consultations and (ii) episode studies may have insufficient statistical power to demonstrate effects, particularly in less dramatic episodes. The latter point justifies our approach to use general time-series studies of daily variations in air pollution concentrations across time periods of a year or more for quantification of health impacts, rather than episode studies.

5 Intervention studies

5.1 Intervention studies - methods

The number of intervention studies on air quality actions taken to reduce air pollution and associated health impacts is quite large and a formal systematic review of literature searching was considered not feasible within the available time. The following groups of studies were considered and further checked:

(i) Intervention studies included in a separate report of this series of reports to the GLA with respect to emergency measures effectiveness (the review of schemes report), especially studies of health impacts associated with those emergency measures.
(ii) Key reviews of experts and systematic reviews on similar topics, the studies and references included in those reviews, and the studies citing those originally identified reviews.
(iii) Accountability studies funded by the Health Effects Institute (HEI) (Wave 1 to 3) if not already covered by (i) or (ii).
(iv) All intervention studies and natural experiments performed in the last 3 years further searched for on online literature databases, if not already covered by (i) or (ii) or (iii).

For (ii), several reviews were identified (Rich 2017; Burns et al. 2019; Bell et al. 2011, Boogaard et al. 2017, Henneman et al. 2017) and those reviews and references should include most of relevant studies up to August 2016. For (iv), studies were further identified using PubMed, Google Scholar and Scopus with search terms such as natural experiment, quasi-experiment, intervention, regulation, air pollution, mortality, hospital admission and health, etc.

Interventions and measures were categorized in this report according to the target source of air pollution directly or indirectly affected by the interventions or measures. Estimations show that approximately 25% of ambient pollution from $PM_{2.5}$ in urban areas is contributed by traffic and vehicular sources, 20% by residential sources and 15% by industrial sources (Karagulian et al. 2015), and in line with this, the categories of interventions considered in this report are as follows: reduction of traffic and vehicular sources (e.g., diesel vehicle ban), residential sources (e.g., wood burning ban), industrial sources (e.g., factory closure during strike), and multiple sources (e.g., coordinated measures during the 2008 Beijing Olympic Games).

Most intervention studies are not specifically about emergency measures. A lot of interventions and environmental policies aimed to influence air quality over a long period of time, which might be less relevant to the current report. But if those studies reported short-term health effects associated with measures to reduce air pollution, they may be included in this report. Some studies are specifically on emergency measures with short-term goals, such as emergency measures to reduce air pollution during the Beijing Olympics.

Regarding outcome measures, primary health outcomes we considered for this report were the following: all-cause mortality, cardiovascular mortality, respiratory mortality, hospital admissions due to respiratory events or cardiovascular events and birth outcomes (e.g., birth weight). Secondary health outcomes included respiratory effects and events (including symptoms), lung function, cardiovascular effects and events (including symptoms), health related biomarkers, loss of employment or school absenteeism. Studies that measured any primary or secondary outcome were eligible for inclusion in this report.

At the beginning, we aimed to harmonise the effect sizes as mean differences or risk ratios between treatment and control groups for those interventional studies, but we found later that the reported effects by included studies were quite heterogeneous and quantitatively pooling analyses would not be feasible at this stage, hence we summarized and reported the results separately.

5.2 Intervention studies – results

The literature search picked up 158 studies, 102 studies were screened out for being air pollution studies without health impacts, toxicological studies, reviews or meta-analyses not original studies, episode studies, indoor only studies, interventional studies testing air purifiers and filters. A further 26 studies were ruled out because they only addressed long-term interventions without short-term assessment of health outcomes, or were forecast or modelled studies rather than real observations, or reported health outcomes not included in the primary and secondary health outcomes of interest for this report.

This left 30 studies for further analysis and summary, as reported in the following paragraphs by categories of targeting sources of interventions.

5.2.1 Reduction of traffic and vehicular pollution sources

Four studies addressed the short-term health impacts of reducing traffic and vehicular pollution sources, and they are summarized in detail in Table 11.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
1996 Atlanta Summer Olympics						
Friedman et al., 2001 Atlanta, Georgia, US	1996 Atlanta Olympics: policies to reduce vehicular traffic and congestion	Reduced peak daily O_3 concentrations (81.3 ppb before games to 58.6 ppb during games), and 22.5% reduction in morning traffic counts during Olympics compared to 4 weeks before and after games	Acute care and hospitalizations for asthma	41.6% reduction in acute care and hospitalizations for asthma during Olympic Games (4.23 to 2.47 daily events)	Use of existing hospital and emergency room data; Use of existing air pollution data; A-B-A study design to control for confounding by time trends.	Only 73 day study period and only 17 day period of Olympics gave limited statistical power; Potential for residual confounding by seasonal patterns in pollution and hospitalizations; Potential for residual confounding by Atlanta residents changing behaviours and personal activity levels during Games.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Peel et al., 2010 Atlanta, Georgia, US	1996 Atlanta Olympics: policies to reduce vehicular traffic and congestion	20%–30% reductions in ambient ozone concentrations in Atlanta, but similar declines in ozone concentration were observed throughout Georgia and the South Eastern United States during this time; 2% to 20% reductions in weekday peak morning traffic counts, consistent with, but smaller in magnitude than those of (Friedman et al. 2001).	Cardiovascular and respiratory ED visits.	No reduction in cardiovascular or respiratory ED visits during the Olympics, which was inconsistent with the earlier work by (Friedman et al. 2001).	Compared to (Friedman et al 2001): Longer time period with health and air pollution data allowed better control of season and long term time trends; Traffic data from 18 sites within the five counties better represented regional traffic patterns; More spatially diverse air pollution data; Overall: Large, well characterized ED database within a large urban area.	Air pollution reduction may have not been large enough to elicit a detectable health response; lack of a 'control' area/county/city with a similar population where such a traffic reduction system was not available, which may result in residual confounding by time trends.
2002 Busan Asian Games						
Lee et al., 2007b Busan, South Korea	14 days of traffic volume control in 2002 Asian Games.	1%–25% reductions in air pollutants in the Post-games period compared to the Pre- and During-Games period	Hospital admissions for asthma.	Reduced risk of asthma hospitalizations (RR = 0.73) in children in the "Post-Games" period compared to the "Pre- and During-Games" period. Interquartile range changes in concentrations of NO_2 (15.09 ppb), SO_2 (3.64 ppb), PM_{10} (28.82 µg/m^3) and O_3 (12.39 ppb) associated with 24% to 35% changes in the risk of hospital admissions for asthma in a mini time-series analysis across the whole pre-, during- and post-games period.	Complimentary analyses of: 1. Changes in a health outcome across 2 periods, 2. Change in a health outcome associated with increased air pollutant concentration. A-B-A design comparing year of Asian Games (2002) to years before and after to control for long term time trends.	Unclear why the effective period was chosen to be after the games with the actual games period being included in the baseline. 14 day period may not be long enough to compare "During-Games" period to "Pre-Games" period as in Beijing Olympic studies. No control population to know if similar patterns of hospitalization and air pollutant concentrations were observed elsewhere.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Lebanon Beirut Vehicle Ban Study						
El-Zein et al., 2007 Beirut, Lebanon	A ban on diesel-powered motor vehicles: ban on the import of all light- and medium duty diesel engines on July 2002.	No air monitoring data associated with the study.	Respiratory hospital admissions in children under the age of 17 years from October to February (5 months).	Observed an immediate and significant slight reduction in respiratory hospitalizations (asthma and URTI [upper respiratory tract infection]) in children under 17 years from 1 year-pre-ban versus 1 year post-ban. The effect of the ban was negligible in the second year.	Use of existing hospital and emergency room and multiple respiratory health data. Restricted to a well-defined age group with limited confounding exposures. Adjusted for temperature, humidity, and rainfall. Several sensitivity analyses were carried out, e.g., excluding the flu months of January and February.	No air pollution monitoring done to determine the change in air pollutant concentrations after the ban. No control group, thus cannot assess the influence of secular trend. Autoregressive effects not considered. Some covariates may be inappropriately selected and it could bias the results. Failed to adjust for some important confounders.

Table 11 Summary of the studies on reduction of traffic and vehicular pollution sources and associated health impacts. ED = Emergency department. URTI = Upper respiratory tract infection.

5.2.2 Reduction of residential pollution sources

Three studies addressed the short-term health impacts of reducing residential pollution sources, and they are summarized in detail in Table 12.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
San Joaquin Valley wood burning ban study						
Yap, 2015 San Joaquin Valley, California, US	Rule 4901: required mandatory ban of residential wood burning when air quality was forecast to be poor during the heating season.	$PM_{2.5}$ levels were reduced by 3.79 µg/m³ (12%), 3.23 µg/m³ (11%), and 5.65 µg/m³ (15%) and coarse particle levels were reduced by 1.61 µg/m³ (8%), 1.37 µg/m³ (7%), and 2.24 µg/m³ (11%) in the San Joaquin Valley Air Basin (SJVAB) as a whole, in rural regions, and in urban regions, respectively.	Hospital admission rates for CVD, IHD, and COPD	Among those aged 65 years and older, Rule 4901 was estimated to prevent 7%, 8%, and 5% of CVD cases, and 16%, 17%, and 13% of IHD cases, in the entire SJVAB and in rural and urban regions, respectively.	Extensive adjustments for potential confounding variables including day of the week, relevant meteorological variables, no-burn days, and percentage of poverty. Inclusion of year-dummy variables to assess influence of the underlying time trend.	No control group, and to what extent the underlying time trend and autoregressive effects were considered was not clear. Seasonality not considered, and only wintertime was analysed.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Ireland coal ban study						
Clancy et al, 2002 Dublin, Ireland	Ban on marketing, sale and distribution of coal used for heating in Dublin starting in September, 1990 (it was long-term/ permanent measure, but may have assessment of health outcomes in short-term after the intervention)	Black smoke was reduced from 50.2 to 14.6 μg/m³ (70%) in all seasons, and from 85.4 to 21.5 μg/m³ in winter. SO_2 was reduced from 33.4 to 22.1 μg/m³ in all seasons, and from 40.4 to 24.9 μg/m³ in winter.	All-cause mortality/ cardiovascular mortality/ respiratory mortality	Respiratory and cardiovascular standardised death rates fell coincident with the ban on coal sale immediately. Estimated mortality reductions: total non-trauma: -5.7%, respiratory: −15.5%, and cardiovascular: −10.3%.	Use of nationally-maintained mortality data. Use of already collected black smoke and SO_2 measurements. Adjustment for meteorological variables and influenza epidemics to control for other causes of respiratory mortality.	Adjustment for national cause-specific mortality rates, does not completely control for background mortality rate changes, resulting in residual confounding by time trends. Population size and age distribution changed substantially during study period. Could only estimate population size, potentially resulting in bias.
Dockery et al, 2013 1. Cork, Ireland. 2. Arklow, Drogheda, Dundalk, Limerick, & Wexford, Ireland. 3. Dublin, Ireland (reanalysis).	Ban on marketing, sale and distribution of coal used for heating in several cities of Ireland: 1. Cork (1995) 2. 5 cities (1998) 3. Dublin (1990, reanalysis) (it was long-term/ permanent measure, but may have assessment of health outcomes in short-term after the intervention)	Black smoke reductions (all seasons): 1. Cork: −49%, 33.7 to 17.2 μg/m³; 2. 5 Cities: −48% to −61%. No clear pattern in SO_2 measured as total gaseous acidity associated with the bans was observed.	All-cause mortality/ cardiovascular mortality/ respiratory mortality and hospital admissions.	The trends of change in deaths in the short-term associated with the coal ban were not consistent in different cities. In long-term analyses, no reductions in total and cardiovascular mortality in any city. Significant reductions in respiratory mortality in Dublin (−17%), and non-significant reductions in Cork (−9%) and 5 Cities (−3%). Dublin ban associated with non-significant small changes (−2% to −3%) in cause-specific mortality rates in 12 Midland counties. The changes in hospital admissions for respiratory and cardiovascular disease were supportive of these findings but cannot be considered to fully confirm them.	Use of nationally-maintained mortality data for 10 years rather than 6 years, resulting in better control for time trends. Use of already collected black smoke measurements. Adjustment for meteorological variables and influenza epidemics to control for other causes of respiratory mortality. Adjustment for mortality rates in coastal counties rather than entire country likely better control of confounding than Clancy et al (2002. Assessment of 12 Midland Counties as a comparison.	Population size and age distribution changed substantially during study period. Could only estimate population size, potentially resulting in bias. And the secular improvements in the same health indicators would make the assessment difficult.

Table 12 Summary of the studies on reduction of residential pollution sources and associated health impacts. COPD = chronic obstructive pulmonary disease. IHD = Ischaemic heart disease. CVD = Cardiovascular disease.

5.2.3 Reduction of industrial pollution sources

Seven studies addressed the short-term health impacts of reducing industrial pollution sources, and they are summarized in detail in Table 13. The study periods for all seven studies were during a factory closure or strike.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Studies of Utah Valley Steel Mill						
Pope, 1989 Utah Valley, Utah, US	Closure of a large steel mill from August 1986 to September 1987	Average PM_{10} concentration reduced from 90 µg/m^3 to 51 µg/m^3 (about 43% lower)	Hospital admissions in adults and children, and for bronchitis, asthma, pneumonia, pleurisy	Children's admissions were two to three times higher during the winters when the mill was open compared to when it was closed. Regression analysis also revealed that PM_{10} levels were strongly correlated with hospital admissions.	Use of already collected air pollution and hospital admissions data. A-B-A design to control for confounding by time trends in morbidity.	Did not have simultaneous temporal comparisons in other Utah counties (control counties) to provide additional control for confounding by time trends.
Pope, 1991 Utah Valley, Utah, US	Closure of a large steel mill from August 1986 to September 1987	Average PM_{10} concentration reduced from 90 µg/m^3 to 51 µg/m^3 (about 43% lower)	Bronchitis and asthma admissions for preschool-age children	Approximately twice as frequent in Utah Valley when the steel mill was operating versus when it was not. Regression analysis also demonstrated a statistical association between respiratory hospital admissions and PM_{10} pollution.	Use of already collected air pollution and hospital admissions and mortality data. A-B-A design to control for confounding by time trends in mortality/ morbidity	Did not have simultaneous temporal comparisons in other Utah counties (control counties) to provide additional control for confounding by time trends
Ransom and Pope, 1992 Utah Valley, Utah, US	Closure of a large steel mill from August 1986 to September 1987	Average PM_{10} concentration reduced from 90 µg/m^3 to 51 µg/m^3 (about 43% lower)	Childhood school absenteeism	An increase in 28-day moving average PM_{10} equal to 100 µg/m^{3}was associated with an increase in the absence rate equal to approximately two percentage points, or an increase in overall absences equal to approximately 40%	Use of already collected air pollution and school absenteeism data. A-B-A design to control for confounding by time trends in mortality/ morbidity	Did not have simultaneous temporal comparisons in other Utah counties (control counties) to provide additional control for confounding by time trends
Pope et al., 1992 Utah Valley, Utah, US	Closure of a large steel mill from August 1986 to September 1987	Average PM_{10} concentration reduced from 90 µg/m^3 to 51 µg/m^3 (about 43% lower)	Total non-accidental mortality, respiratory mortality, and cardiovascular mortality	An increase in 5-day moving average PM_{10} levels, equal to 100 µg/m^3, was associated with an estimated increase in deaths per day equal to 16%. The association with mortality and PM_{10} was largest for respiratory disease deaths, next largest for cardiovascular deaths.	Use of already collected air pollution and mortality data. A-B-A design to control for confounding by time trends in mortality.	Did not have simultaneous temporal comparisons in other Utah counties (control counties) to provide additional control for confounding by time trends

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Pope and Dockery, 1992 Utah Valley, Utah, US	Closure of a large steel mill from August 1986 to September 1987	Average PM_{10} concentration reduced from 90 µg/m³ to 51 µg/m³ (about 43% lower)	Respiratory symptoms and peak expiratory flow	Increased PM_{10} pollution was associated with higher incidence of respiratory symptoms, and less peak expiratory flow.	Use of already collected air pollution and respiratory symptoms and PEF data. A-B-A design to control for confounding by time trends in mortality/ morbidity	Did not have simultaneous temporal comparisons in other Utah counties (control counties) to provide additional control for confounding by time trends
Parker et al., 2008 Utah Valley and other counties in Utah, US	Closure of a large steel mill from August 1986 to September 1987	Average PM_{10} concentration reduced from 90 µg/m³ to 51 µg/m³ (about 43% lower)	Preterm birth rates	Utah Valley mothers who were already pregnant at the time of mill closure were less likely to deliver prematurely than mothers pregnant before or after the closure; no pattern in mothers from other Utah counties	Use of already collected birth data; A-B-A design to control for confounding by time trends; Simultaneous temporal comparison in other Utah counties (control counties) provides additional control for time trends.	13 month period too long to examine specific windows of pregnancy; No examination of air pollution changes in other counties; No complimentary analysis of air pollution and preterm birth to confirm that air pollution changes drove changes in Utah Valley preterm birth rate.
Study of nationwide copper smelter strike						
Pope et al., 2007 New Mexico, Arizona, Utah, and Nevada	Nationwide copper smelter strike from July 1967 to April 1968 (8.5 months)	Estimated 60% (~ 2.5 µg/m³) reduction of suspended sulphate particles	Monthly mortality rates during, before and after strike	1.5% - 4.0% decrease in mortality during strike compared with before and after strike.	Use of available mortality data; A-B-A design to control for confounding by time trends; Adjustment for regional and national mortality rates to control for confounding by background trends in cardiorespiratory mortality; Adjustment for nationwide influenza/ pneumonia rates to control for confounding by national or regional epidemics; Adjusted for monthly mortality counts in neighbouring states (control states) to account for confounding by time trends.	Only reported the results for suspended sulphate particles, but no complementary estimation of change in mortality associated with sulphate or other pollutant concentrations.

Table 13 Summary of the studies on reduction of industrial pollution sources and associated health impacts

5.2.4 Reduction of multiple pollution sources

Sixteen studies addressed the short-term health impacts of reducing multiple pollution sources, and they are summarized in detail in Table 14. Usually the emergency measures would be coordinated policies targeting multiple sources of air pollution.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Study of tailored measures on high-pollution days in Santiago, Chile						
Mullins, 2015 Santiago, Chile	Policy involves the announcement of “Environmental Episodes” on days forecast to have particularly poor air quality, and triggering a number of government protocols for coordinated measures including mandatory restrictions on driving, the shutdown of certain major stationary emitters, restriction on biomass burning for heating etc..	Reduced ambient concentrations of PM_{10} in the Santiago Metropolitan Region significantly by 16.9% (approximately 22.5 μg/m^3) on the day of implementation, with effects persisting into subsequent days.	All-cause and respiratory mortality (age>64 years)	Announcement of an episode reduced mortality among the elderly (over the age of 64) on the day-of and days-after Episode implementation, which represented a 5.6% decrease in cumulative deaths (not statistically significant).	Use of already collected mortality and PM_{10} and meteorological da ta. Results were robust to a broad range of specification and sensitivity checks. Adjusted for relevant meteorological variables.	Lack of power because of the lower numbers of deaths within cause-specific sub-samples and the shorter time period with death information; unable to test whether the program reduced overall mortality over the longer term. Cannot identify the effectiveness of each restriction. Lack of data on hospitalization.
2008 Beijing Summer Olympics						
Zhang et al., 2013; Rich et al., 2012; Huang et al., 2012 Beijing, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	18% to 60% reductions in all pollutants, but ozone had a 20% increase.	Cardio-metabolic and respiratory biomarkers.	Large reductions in most biomarkers, but not heart rate variability markers.	A-B-A design to control for time trends; Prospective measurement of all health and pollution data; Measurement of biomarkers allowing investigation of impacts of air pollution on physiologic mechanisms; Assessed numerous pollutants including ions and PM components.	All pollutants, but ozone, were reduced simultaneously making assessment of health responses associated with individual pollutants difficult; These are healthy young subjects, and thus not those where such biomarker changes would be indicative of actual clinical events (e.g. myocardial infarction, stroke).

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Mu et al., 2014 Beijing, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	All PM concentrations were 54%–60% lower during the games compared to before the games.	Peak expiratory flow as an indicator of lung function, breath rate, blood pressure.	Peak expiratory flow increased (improved) in 78% of study subjects from before to during the Olympic Games. Percent of subjects with a fast respiration rate (> 20 breaths/min) decreased during the games compared to before the games, and increased after the games compared to during the games. No clear pattern of blood pressure change across periods.	A-B-A design to control for time trends; Prospective measurement of all health and pollution data; Measurement of biomarkers allowing investigation of mechanism.	Potential for residual confounding by a change in personal activities by study subjects during the games, compared to before and after the games.
Su et al., 2015 Beijing, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	15.9% to 54.1% reductions in all air pollutant concentrations (PNC, PM and NO_2) during the games compared to before the games, with increases after the games	Cardiovascular mortality.	8.8% increase in cardiovascular mortality associated with interquartile range increases in 1 and 5-day average ultrafine particle counts.	Use of already collected mortality and NO_2 and PM_{10} data; A-B-A design to control for time trends; Coupled with other Beijing Olympic studies investigating mechanistic biomarkers, this study's assessment of cardiovascular mortality provides information on important clinical outcomes, thereby presenting a more complete assessment of health impacts of the air pollution reductions during the Beijing Olympics in adult Beijing residents.	Potential for bias in that Beijing residents may have left Beijing during the games, and thus not be included in a daily count of cardiovascular deaths used in the study. However, authors argue against this since there were no public holidays during the games, and thus little chance to leave the city during the games.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Li et al., 2010 Beijing, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	$PM_{2.5}$ substantially lower (35% to 41%) during the games (46.7 μg/m^3) compared to the baseline period (78.8 μg/m^3) and pre-Olympic period (72.3 μg/m^3)	Number of outpatient visits for asthma.	Number of outpatient visits for asthma were lower (7.3/day) during the games compared to the baseline period (June 2008; 12.5/day). Increases in $PM_{2.5}$ (10 μg/m^3) and O_3 (10 ppb) concentration associated with 2.0% to 4.4% increases in asthma visits.	Use of already collected pollutant and asthma outpatient visit data. Coupled with other Beijing Olympic studies investigating mechanistic biomarkers, this study's assessment of asthma visits provides an assessment of important clinical outcomes, thereby presenting a more complete assessment of health impacts of the air pollution reductions during the Beijing Olympics in adult Beijing residents.	A-B design may result in residual confounding by time trends and season; Potential for bias in that Beijing residents may have left Beijing during the games, and thus not be included in a daily count of asthma outpatient visits used in the study.
Lin et al., 2011 Beijing, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	BC and $PM_{2.5}$ concentrations substantially lower during games, compared to before the games.	Exhaled nitric oxide as an indicator of respiratory inflammation.	Increases in BC (4.0 μg/m^3) and $PM_{2.5}$ (149 μg/m^3) associated with 16.6% and 18.7% increases in exhaled nitric oxide, respectively	Prospective measurement of all health and pollution data. Measurement of biomarkers allowing investigation of mechanism.	Did not have A-B-A design to control for time trends. Potential for residual confounding by a change in personal activities by study subjects during the games, compared to before and after the games. Did not directly estimate change in exhaled nitric oxide levels during the Olympic Games (Visit 5 period) compared to the Pre-Olympic periods (Visits 1–4).

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
He et al., 2016 Beijing, Tianjin, and another 32 cities, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	The summer monthly PM_{10} concentrations decreased from 145 μg/m^3 in 2007 to 101 μg/m^3 in 2008 (30% reduction).	Monthly all-cause /cardiovascular /respiratory mortality.	Each 10 μg/m^3 reduction in monthly PM_{10} concentration associated with 8.36% to 9.61% reduction in monthly all-cause mortality, and a 8.78% reduction in monthly cardiovascular or respiratory mortality	Use of large, existing dataset of mortality in Beijing residents; Compared changes in monthly PM_{10} concentration and mortality rates between cities experiencing large reductions in PM_{10} (treated cities) and those with little to no reduction (control cities).	Although plots suggest there was a greater proportional reduction in PM_{10} concentrations and monthly mortality counts in the cities with large reductions in PM_{10} compared to cities with small concentration reductions, there was not a multivariable analysis to rule out confounding by other temporal and spatial characteristics
Rich et al., 2015 Beijing, China	A series of emergency control measures during 2008 Beijing Summer Olympics included driving restrictions, industry and construction shutdowns, drastic reductions in emissions from numerous sources.	Concentrations of several pollutants [$PM_{2.5}$, NO_2, CO, SO_2, sulphate, elemental carbon, organic carbon] monitored between June and October of 2008 decreased during this Olympics/Paralympics period by 18–59% from pre-Olympics levels	Birth weight.	Babies whose 8th month of pregnancy was during Olympics were 23 g heavier than babies with their 8th month of pregnancy during the same calendar dates in 2007 or 2009. No clear pattern for other months of pregnancy. Increases in concentrations of $PM_{2.5}$ (19.8 μg/m^3), NO_2 (13.6 ppb), SO_2 (1.8 ppb), and CO (0.3 ppm) during 8th month associated with 17-34 g decreases in birth weight	A-B-A design to control for confounding by time trends. Use of large birth registry to provide ample statistical power. Complimentary analyses of: 1. Changes in birth weight from before to during the games, 2. Change in birth weight associated with increased air pollutant concentration.	Potential for residual confounding by women's personal activities during Olympics. No complimentary measurement of biomarkers of potential mechanisms linking air pollution exposure to fetal growth restriction. No control population experiencing same trends in birth weight and fetal growth, but not the air pollution reductions during the Olympics.
2010 Guangzhou Asian Games						
Lin et al., 2014 Guangzhou China	During the 2010 Asian Games in Guangzhou, short-term measures mainly included transportation restrictions and emission control from industries were implemented for 51 days (November 1 to December 21, 2010).	9.22% decrease (from 88.64 to 80.61 μg/m^3) in PM_{10} concentrations during the Asian Games period compared with baseline period, decrease in other pollutants (SO_2 and NO_2) was not significant.	Daily mortality/ cardiovascular disease mortality/ respiratory disease mortality.	Significant decrease in total mortality with relative risk of 0.79 (95%CI: 0.73, 0.86) in comparison with the same period for four years before (2006–2009) and one year after (2011).	A-B-A design to control for confounding by time trends. Use of already collected pollutant, meteorological and mortality data. Extensive sensitivity analyses were done.	Relatively short intervention period and limited data for other pollutants such as ozone and $PM_{2.5}$. Some potential confounding factors associated with air pollution control measures may influence the findings.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Wu et al., 2019 Guangzhou China	During the 2010 Asian Games in Guangzhou (November 12 to December 18, 2010), enhanced air pollution control measures were implemented.	Reductions in 11.8% of PM_{10} (from 86.3 to 76.1 µg/m^3), 11.4% of $PM_{2.5}$ (from 59.9 to 53.1 µg/m^3) and 0.02% of NO_2 (from 44.9 to 44.8 µg/m^3) and increase in 5.2% of O_3 (from 114.6 to 120.6 µg/m^3) were observed during the game period.	Total mortality/ cardiovascular mortality/ respiratory mortality	Decrease in total mortality of 9.3% (95%CI: −15.0, −3.2) and in cardiovascular mortality of 16.0% (95%CI: −22.8, −8.6) during the game period in comparison with that observed in the baseline period after controlling for potential confounders.	A-B-A design to control for confounding by time trends. Use of already collected pollutant, meteorological and mortality data. Extensive sensitivity analyses were done.	Relatively short intervention period that might limit statistical power, as well as some confounding factors were not collected, such as smoking behaviour, activity pattern, dietary style and medical quality that might influence the findings.
Zhang et al., 2019 Guangzhou China	During the 2010 Asian Games in Guangzhou, short-term measures mainly included transportation restrictions and emission control from industries were implemented for 51 days (November 1 to December 21, 2010).	Daily PM_{10} decreased from 65.86 µg/m^3 to 62.63 µg/m^3 during the Asian Games period; the daily NO_2 level decreased from 51.33 µg/m^3 to 42.63 µg/m^3.	Daily hospital admissions from non-accidental diseases/ respiratory diseases/ cardiovascular diseases in general population of the Haizhu District, Guangzhou. Two biomarkers of CRP and fibrinogen among 36 COPD patients.	Daily hospital admissions: decreased from 116 to 93 for non-accidental diseases, from 20 to 17 for respiratory, and from 11 to 9 for cardiovascular diseases during the Asian Games period. Significant improvement in CRP and fibrinogen by -20.4% and -15.4% from a pre-Asian Game period to a during-Asian Game period among 36 COPD patients.	Use of already collected air pollution and mortality data. A-B-A design to control for confounding by time trends. Did analyses of biomarkers in a cohort of COPD patients. Had control city to compare during the Asian Games.	Relatively short intervention period that might limit statistical power, as well as some confounding factors that were not collected, such as cigarette smoking, unmeasured medical or environmental factors.
Study of restrictions on sulphur content of fuel in Hong Kong						
Hedley et al, 2002 Hong Kong	Reduction in sulphur content of fuel oil used in power plants and on-road vehicles from July 1990 (it was long-term/ permanent measure, but may have assessment of health outcomes in short-term after the intervention)	Reductions from before to after intervention in SO_2 (mean change = −45% over 5 years after intervention)	Total mortality/ cardiovascular mortality/ respiratory mortality	Seasonal reductions in respiratory, cardiovascular, and total mortality after the intervention in the first 12 months (immediate effects after the intervention- as short-term effects of measures). However, a peak in the cool-season death rate between 13-24 months, and returning to the expected pattern during years 3-5.	Use of already collected air pollution and mortality data in Hong Kong. Extensive adjustments for potential confounding variables including time trend, seasonality, meteorological variables etc..	Residual confounding by infectious disease mortality, e.g., influenza is possible. A-B design may result in residual confounding by time trends in mortality and air pollution. No control population/group could be used to determine if similar changes in seasonal patterns of mortality were observed elsewhere in Hong Kong.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Wong et al, 1999 Hong Kong	Reduction in sulphur content of fuel oil used in power plants and on-road vehicles from July 1990	Resulted in an immediate fall in levels of SO_2 in the most polluted areas in Hong Kong by up to 80% and an initial, smaller but unsustained reduction in total and respirable suspended particulates (<10 µm) of 23% and 18% respectively.	Respiratory symptoms using self-completed questionnaires in a cohort of 3,405 non-smoking women.	There was no significantly greater decline ($P > 0.241$) in the more polluted compared with the less polluted district for poor respiratory health between 1989 and 1990-1991. (i.e. an unexpected but non-significant improvement) Implementation of the measures appeared to have some impact on the respiratory health of women, but the effect was not statistically significant.	Use of already collected air pollution and health data from an existing cohort as a general health survey (avoid bias of overreporting) in Hong Kong. Response rates for questionnaires were very high (96%). Extensive adjustments for potential confounding variables.	A-B design may result in residual confounding by time trends in respiratory health and air pollution. The study was not able to take the autocorrelation within districts into account. Did not consider occupational exposures.
Wong et al, 1998 Hong Kong	Reduction in sulphur content of fuel oil used in power plants and on-road vehicles from July 1990	SO_2 levels fell rapidly by 84% in the Kwai Tsing district. Smaller reduction in total and respirable suspended particulates (<10 µm) of 23% and 18% respectively.	Bronchial hyperreactivity (BHR) and bronchial reactivity slope (BR slope).	Comparing measurements made before the intervention and one year afterwards, both BHR and BR slope declined from 29% to 16% ($p = 0.026$) and from 48 to 39 ($p = 0.075$) respectively in the polluted district; and from 21% to 10% ($p = 0.001$) and 42 to 36 ($p > 0.100$) in the less polluted district.	Use of already collected air pollution and health data from existing cohorts in Hong Kong. Extensive adjustments for potential confounding variables and repeated measurements.	A-B design may result in residual confounding by time trends in respiratory health and air pollution. The study was not able to take the autocorrelation within districts into account.
Peters et al, 1996 Hong Kong	Reduction in sulphur content of fuel oil used in power plants and on-road vehicles from July 1990	Resulted in an immediate fall in levels of SO_2 in the most polluted areas of the Territory by up to 80% and an initial, smaller but unsustained reduction in total and respirable suspended particulates (<10 µm) of 23% and 18% respectively.	Respiratory symptoms using self-completed questionnaires in a cohort of 3,521 children.	There was a greater decline in the polluted compared with the unpolluted district for reported symptoms of cough or sore throat, phlegm, and wheezing between 1989 and 1990-1991.	Use of already collected air pollution and health data from an existing cohort of children as a general health survey (avoid bias of overreporting) in Hong Kong. Response rates for questionnaires were very high. Extensive adjustments for potential confounding variables.	A-B design may result in residual confounding by time trends in respiratory health and air pollution. The study was not able to take the autocorrelation within districts into account.

Study, design and location	Description of the emergency measures and duration of emergency measures	Effects on improvement of air quality	Health outcomes selected (e.g., daily mortality, hospital admissions etc.)	Main findings of health effects and effect sizes	Major strengths	Major limitations
Wong et al, 2012 Hong Kong	The implementation of a regulation restricting sulphur to 0.5% by weight in fuel on July 1, 1990	The mean levels of SO_2, nickel (Ni), and vanadium (V) showed a statistically significant decline, particularly in industrial areas.	Mortality and life expectancy.	Ni and V showed the greatest impact on mortality, especially for respiratory diseases in the 5-year pre-intervention period for both the all-ages and 65+ groups among all chemical species. There were decreases in excess risks associated with Ni and V after the intervention, but they were nonsignificant. a 10 µg/m^3 increase in concentration of PM_{10} was associated with a change in life expectancy of -69 days (95% CI, -140 to 1) and a change of -133 days (95% CI, -172 to -94) for the same increase in SO_2.	Use of already collected air pollution and mortality data in Hong Kong. Poisson regression Core Models with natural spline smoothers to control for long-term and seasonal confounding variations in the mortality counts and with covariates to adjust for temperature (T) and relative humidity (RH) were developed. Did extensive sensitivity analyses.	The assumption of homogeneous survival is unrealistic and hard to verify. Have not taken co-pollutants into account. Did not consider the possibility of a distribution of risk relative to exposure within the population. Did not assess the relationship in specific age groups. Used monitored air pollution data as proxy measures for personal exposure.

Table 14 Summary of the studies on reduction of multiple pollution sources and associated health impacts. ppb = parts per billion. COPD = chronic obstructive pulmonary disease. BC = Black carbon. CRP = C-reactive protein.

5.3 Discussion of intervention studies

In the rapid review of available evidence, we found that most of the available data only described measures and their effects on emissions of air pollution, with limited data or little discussion on potential human exposure and/or health effects

It has been especially noted that studies on public health impacts of reducing traffic and vehicular pollution sources remain scarce. In a recently published systematic review and meta-analyses (Burns, Boogaard et al. 2019) of interventions to reduce ambient PM air pollution and their effect on health, 22 interventional studies aiming to reduce air pollution from vehicular sources (both short- and long-term effects) were included but only 5 of them did assessment of health effects. Another supporting example is that despite more than 200 low emission zones (LEZs) now in operation aiming to improve air quality all over the world, direct rather than evidence that LEZs improve public health in the short term or long term is still limited. Intervention studies are difficult to do in terms both of catching the timing of before and after a policy is implemented and also in terms of having sufficient statistical power.

Moreover, the reduction in emissions of a pollutant achieved by emergency measures does not always translate to an equivalent reduction in ambient concentrations or people's exposure/health benefits, as other potential confounding factors such as meteorology (especially temperature, relative humidity and wind speed), chemical transformation in the air, co-pollutants, and transport of pollutants may play roles in those pathways too. Hence, more studies of the measures targeting reduction of air pollution in the future should include an important component of assessment of public health impacts and benefits and potential confounding factors in more detail.

During special international athlete events, for example, in 2008 Beijing Olympic Games, measures aiming to reduce multiple sources of pollution were carried out, and several studies reported different estimates for the concentration changes that occurred during the Games and associated changes in health outcomes. Rich et al. (Rich et al. 2012) reported that 24-hour mean concentrations of $PM_{2.5}$ were reduced from 100.9 μg/m^3 before the Games (35 days) to 69.4 μg/m^3 during the Games (33 days), NO_2 were reduced from 26.0 ppb to 13.9 ppb, SO_2 were reduced from 7.6 ppb to 3.1 ppb, while O_3 were increased from 31.8 ppb to 39.5 ppb. Su et al. (Su et al. 2015) reported that 24-hour mean concentrations of $PM_{2.5}$ were reduced from 87.4 μg/m^3 before the Games (62 days) to 52.6 μg/m^3 during the Games (51 days), PM_{10} were reduced from 151.9 μg/m^3 to 69.7 μg/m^3, and NO_2 were reduced from 43.2 μg/m^3 to 28.3 μg/m^3. Lin et al. (Lin et al. 2011) found that 24-hour mean concentrations of $PM_{2.5}$ were reduced from 183.4 μg/m^3 before the Games (12 days) to 46.4 μg/m^3 during the Games (12 days), black carbon were reduced from 3.57 μg/m^3 to 1.80 μg/m^3, and NO_2 were reduced from 26.55 ppb to 25.85 ppb, and further comparisons of concentrations of pollutants during the Games (September 2008) and a year before the Games (September 2007) have also shown the much lower levels of $PM_{2.5}$, black carbon and NO_2. The concentration changes after the measures might be different in those studies, which could have resulted from the varied start time and duration of each observation period for calculations (before, during, after-Games), or different monitoring data sources, however, the consistent results of the improvement of air quality and health outcomes suggest the strength of evidence of effectiveness of those emergency measures during the 2008 Beijing Olympic Games was high.

Most of interventional studies included in this report found associated improved health outcomes with short-term measures/interventions, however, some studies did not find similar effectiveness or found smaller effect sizes in terms of health outcomes even for the same measures, such as the studies of 1996 Atlanta Summer Olympics (Friedman et al. 2001, Peel et al. 2010) and the Ireland coal ban studies (Clancy et al. 2002, Dockery et al. 2013). For these two examples, the effectiveness of measures had been demonstrated for short-term occasions, while the effectiveness lost significance for longer term assessment. This discrepancy may be due to the varied duration of the observation period for assessment of measures, or different scales of study and designs of study (e.g., having an adequate control population that experienced the similar secular trends in mortality). Those examples also suggest that the long-term effects of those short-term measures should be evaluated in more detail.

The common limitations for those studies summarised here include failure to take secular changes of health outcomes into account, and not setting a comparable control group as described above. We also found that some studies did not have any associated air monitoring data when they studied the health effects of those measures, and the strength of such evidence was weakened and the dose-response relationship between reduction of air pollution and improvement of public health could not be established. Better design and more comprehensive data collection are requested for future studies.

Only three studies (Giovanis 2014, Mullins et al. 2015, Yap et al. 2015) reported tailored or designed emergency measures and associated public health benefits on the basis of forecasting of air quality, which is quite relevant to the topic of our series of reports. Among the three studies, one of them in Chile (Mullins and Bharadwaj 2015) has been included in the category of reduction of multiple pollution sources, and one of them in San Joaquin Valley (Yap and Garcia 2015) in the reduction of residential pollution sources. The third one is a case study in North Carolina to evaluate ozone smog alerts and associated people's voluntary behaviour change after health education on air pollution and actual ozone concentrations (Giovanis 2014), but it was not included in this report as the health benefits were not very clearly reported.

However, measurable effects on ambient concentrations and associated public health benefits in the short term reported in those studies could be further tested in better designed (with comparable control groups) studies. Moreover, the effectiveness of those approaches in the longer term remains unknown. The importance of abatement interventions with better designs and better evaluations of those emergency measures in the longer term should be emphasized.

6 Discussion

This report overviews some key aspects of the evidence on air pollution and health as it relates to analysis of the health impacts of air pollution episodes. It is not a review of the overall evidence on air pollution and health, which is available elsewhere e.g. WHO (2013b) nor a review with a view to selecting concentration-response functions (discussed in the separate health impacts of episodes report and summarised in Appendix 1 to this report). Rather it focusses on the evidence on the effects of air pollution and health in the concentration range of high and very high days in London in routine time-series studies; studies of the shape of the concentration-response relationship; episode studies and intervention studies that aim to reduce higher concentrations over the short-term.

The Daily Air Quality Index takes into account both health evidence and the frequency of occurrence of the different concentrations in setting the levels of the index. Moderate days are reasonably frequent – these are considered in the health impacts of episodes report but not here because the concentration range for moderate days is much more obviously within the core range of routine health studies.

High and very high days are, in contrast, relatively rare occurrences in London. This means that they provide very few (or even no data points for some pollutants) in recent time-series studies in London. This was also true for many European multi-city studies, although a study in Southern Europe had a few cities with a reasonable number of days with $PM_{2.5}$ in the higher range, that also showed associations with health effects. Some studies from earlier years or other parts of the world that had tight confidence intervals and were included within the meta-analyses that provided the concentration-response functions used in the health impact calculations, also had a reasonable number of days with $PM_{2.5}$ or ozone in the higher range. This was not the case for nitrogen dioxide.

Time-series studies consider the full range of concentrations and have substantial statistical power. Thus, the associations are well founded in across the majority of the concentration-range. It is a reasonable first assumption that the associations continue through the higher concentrations, even if, strictly, there are insufficient days at these concentrations to influence the results. While the lower frequency of days with higher concentrations may still be an issue, it is also worth considering evidence on concentration-response relationships and episode studies.

Routine time-series studies assume a linear relationship between the log of the relative risk and concentrations in single pollutant models. Only a few studies specifically examine the shape of the concentration-response relationship. The findings are mixed from flatter, to maintained, to steeper slopes at higher concentrations of $PM_{2.5}$, with fewer but still mixed studies for NO_2 and O_3. Interpretation is complex due to issues such as correlations with confounding pollutants. It was therefore considered reasonable to continue to assume the standard log-linear relationship in health impact calculations.

For at least some episodes, including in the UK, health effects are observed when pollutant concentrations (including nitrogen dioxide) are equivalent to those seen in high or very high days in the Defra Daily Air Quality Index for all pollutants. Some episode studies do not find effects – whether this is due to a lack of statistical power (episodes are only a few days long) is unclear. Most studies (with or without an association) were on particulate matter, with only a few on NO_2 or O_3.

Only two studies have looked at tailored or designed emergency measures and their associated public health benefits based on forecasting air quality. One found statistically significant reductions in cardiovascular and IHD (ischaemic heart disease) hospital admissions and the other found a nonstatistically significant association between the use of the emergency measure and reductions in mortality in the elderly. Both studies were small in size and lacked a control group in the wider region to control for unrelated time trends in health outcomes.

Further studies have assessed the public health benefits arising from planned short-term interventions to control air pollution for a specific high-profile event, often lasting longer than a couple of days. The studies of the Beijing Olympic Games in particular (where the emergency measures taken were particularly widespread) were consistent in showing improvements in health outcomes.

Studies of interventions that sought to make a permanent improvement in air pollution concentrations but where short-term (a few months) health impacts were assessed were also examined. These generally showed that the health burden from air pollution can be lessened by reducing concentrations, although the results were not always statistically significant and for some examples, more complex follow-up studies did not confirm the earlier results.

The above discussion has assumed air pollution is similar in all locations but there is the issue that health effects of increased concentrations (or health benefits of reduced concentrations) at higher levels may also involve air pollution of a different composition. This can either be in the relative proportions of different pollutants (e.g Air pollution in developing countries can be much greater than in the UK, this is especially the case for PM, changing the PM to NO2 ratio); or in the composition of PM itself (as a mixture rather than a specific compound, as for gaseous pollutants). Studies on the health effects of PM of different composition have not been reviewed here but have elsewhere (WHO, 2013b; COMEAP 2015b). While there are some suggestions of specific components being more harmful than others (e.g. combustion particles may be of more concern than secondary ones), the results are not conclusive. Currently, different PM components are treated as if they have similar effects for the purposes of health impact assessments, while recognising that this is more for a lack of conclusive quantitative evidence as to what else to do (COMEAP, 2015b).

The report has only considered epidemiological studies (these are more relevant to health impact assessment, which needs evidence of effects in the wider population. For nitrogen dioxide and ozone, however, the daily air quality index is based on chamber study evidence (COMEAP, 2011). These studies on human volunteers have the advantage that they can be more obviously allocated to the specific pollutants and often use higher concentrations, more relevant to concentrations in episodes. On the other hand, the number of volunteers are small, and, for ethical reasons, people with anything other than mild disease are not studied. The effects of ozone in chamber studies are well established. The chamber study evidence on health effects for nitrogen dioxide, while weaker than for ozone (as expected for a weaker oxidant) has strengthened to some extent since the Daily Air Quality Index values were set (re-analysis of pooled data from past chamber studies (Brown, 2015) and coherence with epidemiological studies of effects on asthma (US EPA, 2016). Historically, there were no chamber studies of particulate matter, as it required technological advances to distribute the concentrations evenly through the chamber. A few such studies do now exist and find evidence of health effects (strongest for effects on endothelial function, limited for respiratory effects in healthy populations and minimal for effects in asthma and COPD patients (US EPA 2019).

7 Conclusions and recommendations

Overall, while health effects are likely to be increased at concentrations equivalent to those seen in high or very high days in the Defra Daily Air Quality Index, there is some uncertainty over the exact size of the effect at these concentrations.

At the current time, it is reasonable to use concentration-response functions derived from the full range of concentrations in time-series studies to calculate health impacts of high and very high days, while noting the mixed results on effect size at these concentrations.

Research continues on the shape of the concentration-response functions at higher concentrations, particularly as more studies are done in countries with higher concentrations. Future work on health impacts should consider the latest evidence on this aspect when deciding on appropriate concentration-response functions.

While there are studies showing public health benefits from short-term interventions to reduce air pollution, the number of studies is small, particularly for emergency measure interventions lasting days rather than weeks or months. The health benefits of emergency measure interventions are difficult to demonstrate due to a lack of statistical power but seeking opportunities to study this further (perhaps by clustering multiple implementations) would still be worthwhile.

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10 Appendix 1

The starting point for the selection of concentration-response functions was a Department of Health systematic review and meta-analysis project funded for the purpose of developing concentration-response functions from time-series studies published up to 2011 (Atkinson *et al* (2014); Mills *et al* (2015) and Walton *et al* (2014)). An ongoing literature search on 'systematic reviews and air pollution' was checked for more recent reviews and meta-analyses, in addition to use of reviews identified or performed as work on other projects. COMEAP reports were also used.

The results used for the broad categories of deaths brought forward; respiratory hospital admissions and cardiovascular admissions are given in Table A1. Positive associations were also found between one or more air pollutants and specific types of hospital admissions within these broad categories: COPD admissions, all ages; asthma admissions in children; asthma admissions in adults; cardiac admissions, age 65+ and stroke admissions, all ages. Details are given in the Health Impacts of Air Pollution Episodes in London 2009-2017 report.

Pollutant	**Deaths brought forward**	**Respiratory hospital admissions**	**Cardiovascular admissions**
	% increase in mortality per 10 µg m^{-3}	% increase in hospital admissions per 10 µg m^{-3}	% increase in hospital admissions per 10 µg m^{-3}
	All ages	All ages	All ages
	All cause	All respiratory	All cardiovascular
$PM_{2.5}$ (24- hour average)	1.04 % increase (0.52 % – 1.56%)[a]	1.90% (-0.18, 4.02)[a]	0.90 % increase (0.26 % to 1.53%)[a]
NO_2 (24- hour average)	0.71% (0.43% to 1.00%)[b]	0.52% (0.09-0.95%) [b]	0.66 (0.32, 1.01)%[b]
O_3 (max 8-hour average)	0.34% (0.12, 0.56%)[c]	0.75% (0.30, 1.20%)[c]	0.11% (–0.06, 0.27%)[c]

Table A1 Concentration response functions for all-cause mortality, all ages; all respiratory admissions, all ages and all cardiovascular admissions, all ages

[a] Atkinson et al (2014); [b] Mills et al (2015); [c] COMEAP (2015a). Max = maximum.