Health costs of air pollution in European cities and the linkage with transport

CE Delft

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Delft, CE Delft, October 2020

Publication code: 20.190272.134

Air Polution / Cities / Transport / Health / Costs / Analysis

Client: A consortium of public interest NGOs in ten European countries (ES, FR, DE, PL, SI, HU, RO, BG, NL, IT) led by the umbrella organisation European Public Health Alliance (EPHA) commissioned this report

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Content

Acronyms

Acronym	*Explanation*
AF	Attributable Fraction
AGF	Age group fraction
CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
CRF	Concentration Response Function
CVD	Cardiovasculair disease
DALY	Disability-adjusted life year
EEA	European Environmental Agency
EPHA	European Public Health Alliance
GDP	Gross Domestic Product
HEI	Health Effects Institute
ICCT	The International Council on Clean Transportation
MRAD	Minor restricted activity days
NEEDS	New Energy Externalities Development for Sustainability, a European funded research program
netRADs	netto Restricted activity days
NH^3	Ammonia
NMVOC	Non-methane volatile Organic Compounds
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
OECD	Organisation for Economic Co-operation and Development
PPP	Purchasting Power Parities
QALY	Qualtiy-adjusted life year
RGF	Risk Group Fraction
RR	Relative Risk
SO_2	Sulphur Dioxide
SOMO35	Sum of Ozone Means Over 35 ppb, an indicator of 8-h ozone concentrations exceeding 35 parts per billion
UBA	German Federal Environmental Agency
VOC	Volatile Organic Compounds
VOLY	Value of Life Years
VSL	Value of Statistical Life
WHO	World Health Organisation
WLD	Work loss days
WTP	Willingness to Pay
YOLL	Years of Life Lost

Executive Summary

This study investigates the health-related social costs of air pollution in 432 European cities in 30 countries (the EU27 plus the UK, Norway and Switzerland). Social costs are costs affecting welfare and comprise both direct health care expenditures (e.g. for hospital admissions) and indirect health impacts (e.g. diseases such as COPD, or reduced life expectancy due to air pollution). These impacts affect welfare because people have a clear preference for healthy life years in a good and clean environment. As a clean environment is not something that can be bought in the marketplace, however, a robust methodology is required to monetize them in order to quantify the wider public health impacts.

Environmental economists have performed numerous studies to quantify the impacts of air pollution on health and monetize these as social costs. These studies were used to develop the methodological framework adopted in the present study, which encompasses sixteen health impacts attributable to air pollution by fine particulate matter, ozone and nitrogen oxides (Table 2, Page 15). Using data on reported air quality in the Urban Audit statistics and the EEA Air Quality network, the physical impacts on human health were quantified using concentration-response functions based on the recommendations of the World Health Organization (WHO). The physical impacts were subsequently monetized using a valuation framework developed in the peer-reviewed Handbook of External Costs published by the European Commission's Directorate General for Mobility and Transport, DG MOVE. The resulting social costs incurred in a specific city were then determined from the air pollution levels reported there and the size, age structure and living standards of the population in that particular city.

For all 432 cities in our sample (total population: 130 million inhabitants), the social costs quantified were over € 166 billion in 2018. In absolute terms, London is the city with the highest social costs. In 2018, the loss in welfare for its 8.8 million inhabitants totalled € 11.38 billion. London is followed by Bucharest, with an annual loss in welfare of € 6.35 billion and Berlin, with an annual loss of € 5.24 billion. City size is a key factor contributing to total social costs: all cities with a population over 1 million feature in the Top 25 cities with the highest social costs due to air pollution (see Table 1).

In 2018, on average every inhabitant of a European city suffered a welfare loss of over € 1,250 a year owing to direct and indirect health losses associated with poor air quality. This is equivalent to 3.9% of income earned in cities. It should be noted that there is a substantial spread in these figures among cities: in the Romanian capital Bucharest total welfare loss amounts to over € 3,000 per capita/year, while in Santa Cruz de Tenerife in Spain it is under € 400/cap/yr. In many cities in Bulgaria, Romania and Poland the health-related social costs are between 8-10% of income earned. Most of these costs relate to premature mortality: for the 432 cities investigated, the average contribution of mortality to total social costs is 76.1%. Conversely, the average contribution of morbidity (diseases) is 23.9%.

Table 1 - Top 24 cities with the highest total damage costs of air pollution in 2018

No.	City/urban area	Country	Social costs € mln	No.	City/urban area	Country	Social costs € mln
1	London (greater city)	UK	11,381	13	Sofia	Bulgaria	2,575
2	Bucuresti	Romania	6,345	14	Wien	Austria	2,567
3	Berlin	Germany	5,237	15	Greater Manchester	UK	2,409
4	Warszawa	Poland	4,223	16	Praha	Czechia	2,253
5	Roma	Italy	4,144	17	Barcelona	Spain	2,020
6	Metropolia Silesia	Poland	3,596	18	Torino	Italy	1,815
7	Paris	France	3,505	19	West Midlands urban area	UK	1,807
8	Milano	Italy	3,499	20	Köln	Germany	1,787
9	Madrid	Spain	3,383	21	Bruxelles/Brussel	Belgium	1,586
10	Budapest	Hungary	3,272	22	Kraków	Poland	1,490
11	Hamburg	Germany	2,936	23	Frankfurt am Main	Germany	1,345
12	München	Germany	2,878	24	Zagreb	Croatia	1,312

City air pollution stems from many sources: transport activities, household heating and a range of other activities including agriculture and industry. Without further analysis, the relative share of each source cannot be assessed with any certainty. In this study we did investigate the role of city transport in explaining these social costs using econometric methods. Although there is a severe lack of data at the level of individual cities, we do find evidence that transport policies impact the social costs of air pollution, using several proxy indicators that are available for many cities, including commuting times and car ownership. Our results show that a 1% increase in the average journey time to work increases the social costs of PM_{10} emissions by 0.29% and those of NO_2 emissions even by 0.54%. A 1% increase in the number of cars in a city increases overall social costs by almost 0.5%. This confirms that reduced commuting and car ownership has a positive impact on air quality, thus reducing the social costs of poor city air quality.

Comparison of our study's findings regarding welfare losses with those from other research shows that our results are sometimes higher than previously found. To a large extent this can be explained by the more recent figures used here for valuing the adverse impacts of air pollution. Our findings provide additional evidence that reducing air pollution in European cities should be among the top priorities in any attempt to improve the welfare of city populations in Europe. The present COVID-19 pandemic has only underscored this. Comorbidities feature prominently in the mortality of COVID-19 patients and among the most important of these are those associated with air pollution.

The figures reported here are cited without uncertainty ranges. In this kind of study, uncertainty bounds are typically around 30-40%, implying that the figures reported here could be a factor 1/3 lower or 1/3 higher. Finally, it should be stressed that our study is based on reported levels of air quality, which may diverge from the actual situation, given that air quality is still relatively sparsely monitored across Europe. As a result, the social costs reported are likely to be an underestimate in some cities. If air pollution levels are in fact higher than the figures reported in official statistics, the social costs will increase accordingly.

1 Introduction

1.1 Introduction

In many European cities, air pollution poses a significant threat to human health. For Europe, the WHO estimate for the number of premature deaths attributed to air pollution is over 500,000 (WHO Europe, 2018), with 400,000 early deaths in the EU28. Other studies conclude that the WHO figures represent an underestimation and conclude that the factual number of excess mortality is even higher (Lelieveld et al., 2019). Globally, air pollution is considered as the 4th highest cause of death among all health risks, exceeded only by high blood pressure, diet and smoking (HEI, 2018).

Outdoor air quality exceeds the WHO Air Quality Guidelines in many European cities and public health and environmental action groups, citizens and politicians have called for stricter air quality standards and policies to reduce emissions, especially from traffic. An earlier study by CE Delft (CE Delft, 2018a) estimated that the total social costs of road traffic related air pollution in the EU28 in 2016 was equivalent to € 67- 80 billion depending on the emissions factors that were used. The share of diesel vehicles in these costs amounts to 83% (CE Delft, 2018a). However, an integral calculation of the social costs of air pollution in specific European cities so far has been lacking. This research aims to fill the gap by calculating the social costs of air pollution at the level of individual cities through a common methodology.

Cities are especially interesting from the policy perspective of improving the air quality. Through planning, organizing and regulating various modes of transport, city governments can have decisive influence on the air quality. While the study by CE Delft (CE Delft, 2018a) primarily investigated social costs and policies at the national scale, the present study aims to investigate this from the perspective of individual cities.

Text box 1 - Air pollution and the COVID-19 crisis

Recently, air quality has gained interest during the COVID-19 pandemic. Some initial research (see e.g. (Cole, 2020 #7993) has suggested that air pollution is a relevant contributor to COVID-19 mortality as it (i) may increase the risk of infection, and (ii) result in a higher mortality from the disease. The first impact relates to the fact that aerosols containing the virus may be more easily spread in areas where there are more aerosols from air pollution. The second impact relates to the fact that air pollution can cause hypertension, diabetes and respiratory diseases: conditions that doctors are linking to higher mortality rates for COVID-19. The correlation between air pollution and COVID-19 mortality could also be explained with reference to the negative impact air pollution has on the immune system. More fundamental research on the relationship between COVID-19 mortality and air pollution is, however, beyond the scope of the present study.

1.2 Project aims

The present project has the following aim:
To estimate for European cities, provided data availability, the social costs of outdoor air pollution and to assess the impact of the design of transport in those cities on air quality.

The project thus tackles two different questions:
1. What are the health related damage costs from air pollution in European Cities?
2. What is the contribution of transport to these health costs?

1.3 Delineation and caveats

There are a number of limitations in our methodology that should be well understood:

- The study focusses **only on outdoor pollution**. Indoor pollution, such as in houses or metro's, is not considered in this study.
- The project focuses **only on three causes of air pollution**: (i) PM_{10} and $PM_{2.5}$ concentrations; (ii) Ozone formation above the 35ppb; (iii) NO_2 concentrations. There are many other pollutants that have adverse impacts on human health, such as polycyclic aromatic hydrocarbons, or trace heavy metals: these have not been included in the research. There are also other classifications of particulate matter concentrations that may have a more direct link with damage from air pollution, such as ultrafines or black carbon. However, these have not been included in this research either for reasons of lack of data. Therefore our study typically presents a lower estimate of the social costs of air pollution.
- The research estimates **social costs from *reported* air quality**. Therefore, our research uses data from Eurostat, Urban Audit, to estimate the social costs of air pollution. The Urban Audit data are basically reported by the cities themselves. We did not check in this research if the reported data of air quality was correct, or representing the true situation of pollution in a particular city. Therefore our results are entirely contingent on the quality of the data and our procedures to update the data of Eurostat's Urban Audit to more recent years. In Paragraph 2.4 and Annex A we describe our data procedure in more detail.
- The use of data from the Urban Audit also implied **that *cities* in this research should be read as 'urban areas'** as in some cases areas are input in the calculations rather than administrative cities. We did not take a decision here but took the administrative unit that was reported in the Urban Audit statistics as our point of entry in this research. If not a city but an area was reported, we use the prefix *Greater* to the city name unless the administrative unit has its own name, such as the Górnośląsko-Zagłębiowska Metropolia in Poland that was named by us with its popular name 'Metropolia Silesia'.
- In this research we use **concentration response functions that have been recommended by the WHO**. The WHO recommended values (WHO, 2013) are based on studies that are now slightly outdated. Recent research has indicated convincing evidence for a variety of other adverse health impacts of air pollution. However, our research does not address any impacts beyond those recommended by the WHO. Paragraph 2.2. identifies which impacts have been considered in this study and which impacts have not been quantified.
- In this research we **only focus on health related costs**. There may be other costs from air pollution, such as ecosystems degradation or adverse impacts on buildings and materials that have to be maintained more often (e.g. the loss of the quality of paint due to ambient ozone or soiling of building stones). Such impacts have not been included in this study.
- In this research we **do not differentiate between anthropogenic and natural PM emission**s. The European Commission (EC, 2011) recommended that natural fractions, such as sea salt and desert dust fractions, should be subtracted from the annual mean of concentration. However, this proved not to be possible in this research as this would imply that we would have to determine the natural contribution to every measuring station used in this research.
- There have been many research papers quantifying the social costs at the level of individual cities including spatial modelling of emission and dispersion. We immediately recognize that such approach is superior over our method based on reported values of air quality. Therefore, **our results should not be seen as an update or improvement over more detailed studies** (see Paragraph 1.4). Such studies also tend to take other

subtleties into account, such as the various components in PM concentrations and these have not been incorporated here as well due to lack of data. The advantage of our study, however, is the sheer size of cities to be included, as this study provides a monetary estimate of the social costs of air pollution in 432 cities through a harmonized methodology. However, the results from this study should always be regarded as indicative and detailed future research on the individual city level is to be preferred from a scientific perspective.

1.4 Relation to other research in this area

Adverse impacts of air pollution on health in European cities has been the subject of a growing number of studies. These studies often show the incidence of air pollution on mortality and morbidity endpoints for single cities or a group of cities in one country. Examples are, for example, Garrett and Casimiro (2011) for Lisboa, Bañeras et al. (2018) for Barcelona, Badyda et al. (2017) for 11 Polish cities and Fang et al. (2016) for 74 cities in China.

A few studies have done this in particular for transport related emissions, such as ICCT (2019) that has estimated the global burden of disease from transport related emissions and developed specific factsheets for e.g. Paris, London and Germany. Sometimes these studies also offer monetization of the impacts on air quality. E.g. Kings College (King's College, 2015) has quantified in-depth the costs of air pollution in London while other studies have conducted such research for Thessaloniki (Vlachokostas et al., 2012) or Skopje (Martinez et al., 2018). Although the literature on this topic is thus relatively abundant, they can be poorly compared to each other due to differences in methods, coverage (i.e. the impacts taken into account) and data.

Our study is different in this respect in the sense that it provides an overview of social costs of air pollution in 432 cities using a comprehensive common methodology that has been developed in peer-reviewed work for the European Commission (CE Delft and INFRAS, 2019).[1] In this way cities can be compared with each other and conclusions can be drawn on the question in which cities air pollution has the most adverse impacts. Moreover, we aim to connect this information with the structure of transport and other activities in a city to investigate to what extent air pollution can be reduced by transport related policies.

1.5 Reading guide

Chapter 2 describes concepts used in this study. Chapter 3 contains the results of the estimation of the social costs of air pollution in 432 cities. Chapter 4 contains the results of the estimation of the impact of transport to these costs. Chapter 5 concludes.

1 We applied some adaptations to this methodology to be able to apply it at the city level. See also Chapter 2.

2 Concepts and methods

2.1 Introduction

In this chapter we introduce the concept of social costs that is central in this research and outline the methodology that we have been using for estimating the health costs from air pollution in European cities. First in Paragraph 2.2 we present an overview of known health impacts from air pollution and discuss health impacts that have been included in our research. Then, in Paragraph 2.3, we introduce the concept of social costs as a way to monetize these health impacts. Subsequently, in Paragraph 2.4, we will outline the methodology followed in this research to estimate damage costs to human health from air pollution.

2.2 Health impacts from air pollution[2]

Since a long time air pollution is known to have adverse impacts on human health. In the 1950s many cities were heated with coal fired stoves. For example, in London, the great smog of December 1952, killed 3-4,000 citizens according to official statistics — a figure that in later research has been upscaled to over 12'000 when comorbidity impacts were properly taken into account (Bell et al., 2004). The WHO published in 1958 their first monograph on adverse health impacts from pollution and since then evidence of air pollution on a variety of health related endpoints has been growing.

In general four major impacts can be considered stemming from air pollution:
1. Concentration of primary and secondary aerosols ($PM_{2.5}$/PM_{10}).
2. Concentration of ozone ambient levels (O_3).
3. NO_2 concentrations.
4. Other toxic substances.

Below we will elaborate on these impacts in more detail.

2.2.1 Concentration of particulate matter

Particulate matter is a collective term for liquid and solid particles in the air (also known as aerosols). Different particulates are commonly classified by their size: PM_{10}, $PM_{2.5}$ and PM0.1 (the latter called ultrafine particles). The numeric number means the maximum diameter size of these particles. $PM_{2.5}$ relate thus to all particles with an aerodynamic diameter of 2.5µm and smaller. $PM_{2.5}$ is sometimes called "fine particulates" and $PM_{0.1}$ 'ultrafine particulates'.

All three size groups of PM are associated with transport emissions. All three categories of particulate matter contain exhaust emissions from transport. PM_{10} also includes the wear of brakes, tires and roads; $PM_{2.5}$ and $PM_{0.1}$ are primarily related to the exhaust emissions from the tailpipe of diesel vehicles and other modes of transport. Aviation can also be an important emitter of $PM_{0.1}$.

Next to primary PM directly emitted by diesel vehicles, secondary PM is mainly formed through chemical reactions between SO_2, NH^3, NO_x and VOCs. Such particles are being

2 This chapter is partly based and recycled from CE Delft (2018).

formed under influence of sunlight, weather conditions and general atmospheric conditions. WHO (2013) has concluded that secondary particles are just as harming as primary particles so the distinction only refers to the different origin, not to the relative harm caused by the aerosols.[3]

Ambient particulate matter (PM) is ranked as the 6th risk factor for total deaths globally, through cancer, lower- and chronic respiratory diseases and cardiovascular diseases (HEI, 2018). This makes it the most harmful element of diesel exhaust to the human health. The reason for this is that the most dominant way the human body takes up air pollutants is by breathing. The severance of the harm caused is largely determined by how far a certain pollutant can penetrate into the human body through inhalation. The smaller a pollutant is, the further into the tissue of the lungs it can get. That's the reason why the particulate matter from diesel exhaust is so harmful: it mainly consists of fine and ultrafine particulate matter.

Diseases which have been proven to be causally relatable to $PM_{2.5}$ are ischemic heart disease, stroke, lung cancer, lower respiratory infections, and chronic obstructive pulmonary disease (COPD) (HEI, 2018). Both long- and short-term exposure to $PM_{2.5}$ has negative respiratory and cardiovascular effects, including acute (out of hospital cardiac arrests) and chronic cardiovascular mortality. Other impacts include neurological disorders and diabetes, out of hospital cardiac arrests and birth defects. However, these latter diseases have not yet been recommended by the WHO to be included in cost-benefit analysis as more research would be required to quantify their precise impact.

There is some evidence that smaller particles, such as $PM_{0.1}$ (ultrafine particles), contain the most dangerous fractions that cause most of the adverse health impacts. However, ultrafine particles are presently not frequently measured in monitoring stations. To some extent, $PM_{2.5}$ can serve as a proxy for the impacts of ultrafine particles (see also Text box 2).

Text box 2 - Health effects of ultrafine particles

In general, the smaller the particles the larger the health impacts. However, the question whether ultrafine particles (UFP) have an additional health damage to other pollutants such as $PM_{2.5}$ is still subject to scientific debate. Theoretically, UFP have the potential to cause more harm than bigger particles, since it can penetrate deeper into the body. Potential conditions that are linked with UFP are i.a. systemic inflammation, endothelial dysfunction, cardiovascular disease, diabetes, cancer, and cerebral and autonomic dysfunction. Therefore the potential health cost of UFP is therefore substantial. However, the precise role of UFP in such illnesses is still unknown(Schraufnagel, 2020).

There are some recent studies that demonstrate the effects of ultrafine particles on aspects of health, independent of other sizes of particles. For instance, (Lavigne et al., 2019) find that the onset of asthma in children can be linked to exposure to UFP during a critical period of lung development. These results are found independent of the influence of $PM_{2.5}$ and NO_2. Furthermore, short term exposure to UFP is associated with an increased heart rate during various physical activities (Rizza et al., 2019). Short term exposure to UFP has also been found to be associated with decreased lung function and a prolonged QTc interval in healty adults (Lammers et al., 2020) Moreover, a recent study shows that exposure to UFP is associated with increased risk of brain tumors in adults, whereas this cannot be said for $PM_{2.5}$ and NO_2 (Weichenthal et al., 2020).
However, there are also studies that cannot conclude that particle size matters for certain health effects, i.e. that different particle sizes have an independent effect on health. For instance, (Ohlwein et al., 2019) find some short-term associations of UFP with inflammatory and cardiovascular changes. However, these effects are

[3] Currently the WHO is in the process of updating the 2013 recommended values, which may also include a reassessment of the relative harm of various origins of $PM_{2.5}$.

only partly independent, and for other health outcomes the results are inconclusive. In a study on the effects of UFP on respiratory health in adults, (Donaire-Gonzalez et al., 2019) do not find evidence of the relevance of particle size for the potential to cause respiratory disease.

Overall, although not all effects are proven, the health impacts of ultrafine particles (UFP) could be larger than the impacts of fine particles ($PM_{2.5}$). It is also possible that a large part of the health effects of $PM_{2.5}$ is in fact caused by the UFP part in $PM_{2.5}$. However, UFP are not usually monitored in the monitoring stations. Therefore, $PM_{2.5}$ is the closest alternative. Moreover, the health effects included in this study are proven to be associated with exposure to $PM_{2.5}$. The extent to which $PM_{2.5}$ and UFP are representative of each other, is, however, debatable. For instance, (De Jesus and al., 2019) show that measurements of UFP and $PM_{2.5}$ are not representative of each other. Consequently, $PM_{2.5}$ measurements may be somewhat inaccurate when calculating the cost of health effects.

A relatively large share of transport related emissions contain black carbon (also known as soot particles or elementary carbon). The health effects associated with them do not only lie in their small size, but as well in the fact that they can carry traces of heavy metals or PAHs and NMVOCs on their surface: these enter your body when soot does. Soot has been characterized as being a carcinogen by the International Cancer Research Organization. Although there is growing evidence that black carbon is much more dangerous than other types of particles (WHO, 2012) and that the concentration of these particulates in the air is a 100% higher in streets with a high amount of traffic than in a street with little traffic (RIVM, 2013) a separate valuation has not been included in the WHO (2013) guidelines.

2.2.2 Concentration of ozone

Tropospheric (also known as ground-level) ozone (O_3) is a secondary air pollutant. It is formed via multiple reactions between NO_x, CO and volatile organic compounds (VOCs), in the presence of light (e.g. photo-chemically). Under certain weather conditions, a high concentration of ozone in the air can lead to smog which is especially a problem in warm urban areas. In some places the occurrence of smog is highly related to the season.

Short-term exposure to ozone has proven to be causally related to respiratory effects such as inflammation, aggravation of asthmatic symptoms, increase in hospital admissions and respiratory related acute mortality. Additionally, it is a cause of chronic obstructive pulmonary disease (COPD) and is probably related to cardiovascular effects and acute all-cause mortality. In warm weather, acute impacts of elevated ground-level ozone levels can be experienced by both healthy people and people with already reduced lung function. Long-term exposure may cause an increase of incidence of asthma amongst children. Globally, ozone is ranked as the 33th risk factor for total deaths, due to its severe causal relation to chronic respiratory diseases (HEI, 2018).

2.2.3 Concentration of NO_2

Primary nitrogen oxides (NO_x) from combustion of fuels is mainly composed of NO which can be oxidized to secondary NO_2 in the presence of oxygen (from air). However, it should be noted that the share of primary NO_2 in diesel vehicle exhaust is higher than in petrol vehicle exhaust, as NO is already oxidized in the diesel vehicle's exhaust treatment system. NO_x is part of the gas phase emissions of diesel engines. In a study by Jonson et al. (2017) it is estimated that 10,000 premature deaths of adults over 30 in 2013 in the EU28 and Switzerland, can be attributed to NO_x emissions from diesel cars and light commercial vehicles. Of these, 50% could have been avoided if the cars had the same on-the-road NO_x emissions as reported in the laboratory tests.

NO_x enters the body by inhalation and is adsorbed through the respiratory system tissue into the circulation (Finnish Institute for Occupational Health, 2016). The evidence of adverse health impacts of NO_x have long not been attributed to the compounds itself (mainly NO_2), but rather to $PM_{2.5}$ and ozone as these are formed by NO_x. Double-counting of health effects has to be avoided. However, in recent years experts have stated that substantial evidence has become available for health effects of both short-term and long-term exposure directly attributional to NO_2 (COMEAP, 2015, EPA, 2016) Now a relation between short-term NO_2 exposure and respiratory symptoms such as inflammation, aggravation of symptoms in asthma patients and aggravation of allergic reactions in the respiratory tract have been proven. Additionally, the incidence of asthma in children due to long-term exposure to NO_2 is probable. WHO (2013) therefore state that NO_2 can be included as all-cause mortality but that double counting with the all-cause mortality of $PM_{2.5}$ should be avoided. Experts acknowledge that the discussion about whether or not NO_2 is directly accountable for negative health effects caused by air pollution, is still open. This is illustrated by the recently published statement of COMEAP on NO_2 mortality effects: experts of the COMEAP group state that they were not able to reach consensus about all the outcomes in the report (COMEAP, 2018).

2.2.4 Other substances

There is ample evidence that other substances as PAHs (polycyclic aromatic hydrocarbons) and some NMVOCs are carcinogenic in nature. In addition, non-cancer health effects have been reported for PAHs. Although important, such elements have not been included in the WHO (2013) recommendations on including health impacts from air pollution in cost-benefit analysis. In addition, monitoring stations in Europe for PAHs are still largely absent. Therefore, such substances have not been included in our study.

2.2.5 Quantification of physical endpoints

The present study uses the WHO (2013) guidelines on including the impacts from air pollution as a starting point. The WHO WHO (2013) reports the relative risks of various endpoints. Relative risk is a measure of the impact of a disease measured as the ratio of the incidence observed at two different exposure levels. The RR thus can be interpreted as the increase in percentages in the relative risk in the reported impact due to an increase in exposure levels of 10µg/m^3. Both in the handbook on Environmental Prices (CE Delft, 2018b) as the Handbook of External Costs of Transport (CE Delft et al., 2019) and (CE Delft, 2018a), these relative risks have been translated to concentration response function.[4]

In this study we have used a hybrid approach between (i) directly using the RR from the WHO (2013)with country specific information on incidence rates to calculate the attributable risks, and (ii) using concentration response functions that provide a direct translation between concentration of pollution and the impacts that these pollution cause:
1. For **mortality from $PM_{2.5}$, O_3 and NO_2** we have used the relative risks from WHO (2013) and applied country specific incidence rates to determine the additional mortality in a

[4] A concentration response function TNO, FACIT, VTT, GRAZ, T., PTV, DAI, CLU, VCC, SAFER, UNIS, et al. 2014. Impact assessment and user perception of cooperative systems : D11.4 of the Drive C2X project. Delft: TNO. is a function that describes the chance of getting a disease from a certain level of air pollution. To quantify damages one needs to translate the relative risk (RR) in terms of an concentration response function, also called exposure response function (Rabl et al., 2014). For this one needs to know the existing risk on these incidents. So for an RR of 1.046 per 10/µg/m^3 for Working Days Loss due to $PM_{2.5}$ lung diseases, one needs to understand how often the population already is losing working days from lung diseases. Then the CRF can then be regarded as the product of the baseline incidence and the Delta RR.

specific city from a certain level of air pollution. These mortality endpoints together constitute around 70% of total damage because of air pollution.
2. For **morbidity impacts plus infant mortality** we use concentration response functions as developed in CE Delft (2019). In the calculation of these concentration response functions, European average incidence rates have been used (which are thus not differentiated between countries).[5] The morbitidy endpoints cause, in general, around 30% of damage from air pollution. Annex B.1 provides more information on the provided methods, relevant risks and concentration response functions that have been used.

Table 2 below provides an overview of the impacts have been included in this research. Here all the potential impacts from air pollution are listed. The table shows that on average we have covered most proven impacts. However, various probable impacts that have been reported in the literature but have yet not been considered as proven by the WHO (see also the discussion in CE Delft (2018a)) and that provides the reason why they have not been included.

Table 2 - Included health effects of exposure to NO_2, $PM_{2.5}$ and ozone

	Effects proven and included	Effects proven but not included	Effects probable but not included
PM_{10}/$PM_{2.5}$	– All cause mortality (chronic)* – Acute mortality* – Infant mortality^ – Work days loss^ – Restricted activity days (minor and net)^ – Chronic bronchitis (COPD)^ – Respiratory hospital admissions^ – Cardiovascular hospital admissions^		Medication use Lower respiratory symptoms Diabetes
Ozone	– Acute mortality* – Respiratory hospital admissions^ – Cardiac hospital admissions^ – Restricted activity days (minor)^	– COPD	– Chronic mortality – Work days loss
NO_2	– Increased mortality risk (long-term)* – Bronchitis in asthmatic children^ – Respiratory hospital admissions^		– Cardiovascular effects – Acute mortality
PAHs		– Cancer	– Cardiovascular effects

Source: CE Delft assessment based on (WHO, 2013), Dutch Health Council, 2018, (HEI, 2018), (EPA, 2016), (COMEAP, 2015)

* Impacts calculated using Relative Risks (WHO, 2013) and country-specific incidence rates;

^ Impacts calculated using Concentration Response Functions (CE Delft et al., 2019) using European incidence rates.

Table 3 provides an overview of the sixteen endpoints that have been quantified in this research with their Relative Risks and Concentration Response Functions per μg/m^3 pollution and respective age groups. This table forms the core of our calculations.

[5] This hybrid approach has been selected to provide the best possible quality against the time of research. An improvement would be to also calculate the morbidity impacts using country specific information on incidence rates. However, as such information was not readily available, calculation of these impacts would imply a substantial amount of time not available in the present research. Sensitivity analysis revealed that this approach may introduce a margin of error of up to 5% in our final estimates of the total social costs. For the majority of cities the differences would be below the 2%.

Table 3 – Overview of endpoints included in this study

Endpoint	Substance	Age groups	RR or CRF	Value^	Source
Life expectancy reduction - chronic	$PM_{2.5}$	Adults 30+	RR (Beták et al.)	6.20E-03	WHO (2013)
Life expectancy reduction - acute	$PM_{2.5}$	Adults 30+	RR (Beták et al.)	1.23E-03	WHO (2013)
netto Restricted activity days (netRADs)	$PM_{2.5}$	All	CRF	9.59E-03	NEEDS (2008)*
Work loss days (WLD)	$PM_{2.5}$	Labour Force	CRF	2.07E-02	NEEDS (2008)*
Minor restricted activity days (MRAD)	$PM_{2.5}$	Adults_18_to_64	CRF	5.77E-02	NEEDS (2008)*
Increased mortality risk (infants)	PM_{10}	All	CRF	4.00E-03	NEEDS (2008)*
New cases of chronic bronchitis	PM_{10}	Adults_18 and Aboves	CRF	4.51E-05	CE Delft (2019)*
Respiratory hospital admissions	PM_{10}	All	CRF	7.03E-06	NEEDS (2008)*
Cardiac hospital admissions	PM_{10}	All	CRF	4.34E-06	NEEDS (2008)*
Medication use/bronchodilator use	PM_{10}	Children_5_to_14	CRF	4.76E-03	CE Delft (2019)*
Increased mortality risk	SOMO35	All	RR (Beták et al.)	2.90E-04	WHO (2013)
CVD and respiratory hospital admissions	SOMO35	Elderly_65+	CRF	3.43E-05	CE Delft (2019)*
MRAD	SOMO35	Adults_18_to_64	CRF	1.15E-02	NEEDS (2008)*
Increased mortality risk	NO_2	Adults 30+	RR (Beták et al.)	7.60E-04	CE Delft (2020)*
Prevalence of bronchitis in asthmatich children	NO_2	Children_5_to_14	CRF	5.25E-03	CE Delft (2019)*
Hospital admissions due to respiratory diseases	NO_2	All	CRF	1.11E-05	CE Delft (2019)*

* These values are consistent with WHO (WHO, 2013)The consistency has been checked and described in CE Delft (2019).

2.3 The concept of social costs

2.3.1 Purpose and definition

The concentration response functions (TNO et al.) provide the relationship between a given concentration of pollution and the impacts this has on human health. These impacts can be valued. Valuation, also called monetization, has two advantages in analysing the impacts of air pollution:

1. Various endpoints, as identified in Table 1, can be added to each other. One should notice that each of these endpoints is in different units: mortality is reported in deaths, working days loss in days, and hospital admissions in cases. By monetizing each endpoint one can obtain insight in the combined effect of air pollution on all of these endpoints. Therefore monetization can help in developing an overall point of view on the impacts of air pollution.
2. Valuation expresses a total number in Euros, and this number can be compared with other indicators that are being expressed in Euros, such as GDP per capita. Moreover,

most people immediately have an idea how serious the impact is if the effects of air pollution are being monetized. If these impacts would mount to € 10 per capita per year, one would know that this is probably relatively small. However, if these impacts would mount to thousand Euro per capita per year, one can imagine that these impacts are actually reducing a substantial amount of our welfare.

The value of the impacts of air pollution could be described as 'social costs'. In economic terms, social costs are private costs borne by individuals directly involved in a transaction together with the external costs borne by third parties not directly involved in the transaction. Social costs imply that total welfare is lower in a market economy because various market failures exists. Air pollution is a traditional example of such a market failures when the polluter does not take into account the costs his pollution causes upon the society. Another typical cause of a market failure is that certain goods, such as a good health or freedom cannot be bought on a market and that property rights are not well defined.

Social costs consist of market costs and non-market costs. Market costs are equivalent to expenditures, non-market costs are impacts on welfare that do not lead to expenses. While a few impacts of air pollution result in expenditures, such as hospital admissions, most of the impacts do not result in expenditures but yet deeply impact on welfare. Consider for example child mortality. While it is clear that a child dying is a nightmare of all parents that would have to be circumvented against any costs, parents cannot "buy" the health of their children on a market. Nor can the costs of funerals be representative of the feelings of grief and loss from the death of a child. Clearly, child mortality deeply impacts on the happiness and live conditions of their parents. The same applies to sickness of your own body: while it is clear that your life conditions are much better without COPD, we cannot buy this in a supermarket and the costs of medication and medical treatment are by no means indicative of the loss of welfare that someone with an uncurable disease like COPD experiences.

Therefore, economists have tried to investigate ways to monetize this loss of welfare so that it can be used in economic tools like cost-benefit analysis. The 'willingness to pay' or 'willingness to accept' are tools in economics that can determine the value to society of preventing the impacts on their health from air pollution, or the sum of money they are wanting to compensate for these impacts.

2.3.2 Social cost estimates of health effects

Monetization of social costs is equivalent to determine the Willingness to Pay (WTP) for avoiding the impacts of air pollution. In general four methods have been considered in the economic literature to estimate the WTP for damage avoidance (CE Delft, 2018b)
1. Damage valuation via revealed preferences.
2. Damage valuation via stated preferences.
3. Damage valuation based on restoration costs.
4. Damage valuation based on abatement costs.

In economics there is an order of preference for their application in social cost calculations: direct damage valuation via revealed or stated preferences is the most accurate method and valuation based on abatement costs the least preferred.[6]

[6] There may be exceptions to this general rule, though. For example, in the case of climate change, the damage costs — referred to as the 'social cost of carbon' — are so uncertain that the abatement-cost method may sometimes provide a better price indication.

Valuation through revealed preferences may be based on the salary premiums that are being paid for jobs that are more risky. In this way we can observe through actual market behaviour what the implicit price premium is for a higher chance of accidents. Alternatively, revealed preferences may be obtained through investigation of what people are willing to pay for houses that have cleaner air. One drawback of this method is that people have to be informed very well about the risks of living in more polluted areas if this method is to provide a reliable estimator of the damage costs.[7] Therefore, stated preferences, where people can assign values through questionnaires (contingent valuation method) or choice experiments, are believed to provide a more true picture of the value people would attach to attain a higher life expectancy (at the end of their lives). If respondents are honest, well-informed and rational, stated-preference research is in principle the most reliable source of information on people's preferences for environmental quality (Hoevenagel, 1994). However, this theoretical, ideal situation does not usually hold in practice. In practice, values are obtained through hypothetical questions and economic literature shows that people may overestimate their willingness to pay for a certain good if they do not have to pay for that directly. Moreover, strategic or socially desirable answers may further diverge the outcomes of stated preference research from the 'true' value.

Nowadays, most estimates of the valuation of the impacts of air pollution have been obtained through meta-analysis of various studies taken together. Valuation of mortality is nowadays largely based on the overview of the OECD (2012) that has suggested a value of statistical life (VSL) for air pollution related diseases of around € 2.5 million. As argued in the NEEDS project (NEEDS, 2008), a valuation of life years lost (VOLY) is probably a better estimate for air pollution as most impacts occur for elderly people. In CE Delft (2018b and 2019) and UBA (2019)an average value of the VOLY of € 70,000 (in prices 2015/2016) is suggested as average in the literature. This is considerably higher than the NEEDS (2008) estimate of € 40,000 (albeit in prices 2005), but still below the annuity of the OECD value of statistical life of 2.5 million.

For most morbidity impacts, valuation is obtained through analysis of productivity losses and the DALY/QALY framework ranking annoyances to various illnesses.[8] In Table 4 an overview of valuation of endpoints is given that has been constructed for the European Handbook of External Costs (CE Delft et al., 2019).

Table 4 - Valuation in € (2015) prices) of various included health effects of exposure to NO_2, $PM_{2.5}$ and ozone for average incomes in the EU28

Core Endpoints	Pollutant	Unit	Monet. Val. Per case or per YOLL [Euro]
Increased mortality risks (YOLL)*	$PM_{2.5}$, SOMO35, NO_2	YOLL*	70,000
netto Restricted activity days (netRADs)	$PM_{2.5}$	Days	157
Work loss days (WLD)	$PM_{2.5}$	Days	94
Minor restricted activity days (MRAD)	$PM_{2.5}$, SOMO35	Days	52
Increased mortality risk (infants)	PM_{10}	Cases	3,600,000^
New cases of chronic bronchitis	PM_{10}	Cases	240,000^
hospital admissions (CVD, respiratory)	PM_{10}, SOMO35, NO_2	Cases	2,850^

7 In addition, there may be econometric issues that would plague a true estimate of the revealed preferences. See also CE Delft (2018b) for a discussion in Chapter 5.

8 In CE Delft (2018b) it has been argued that in most cases the value of a DALY would be equivalent to that of a VOLY. Therefore, a DALY of € 70,000 seems to be the best guess of valuation of each of the impacts.

Core Endpoints	Pollutant	Unit	Monet. Val. Per case or per YOLL [Euro]
medication use/bronchodilator use	PM_{10}, NO_2	Cases	2

* YOLL = Years Of Life Lost.

^ Rounded figures.

The values in Table 4 are average values for the EU28. However, such average values may not be relevant when it comes to valuation of impacts for individual cities. This is due to differences in prices and differences in income. For example, hospital admissions may have lower costs in countries with lower incomes. And also annoyances, such as a restricted day of activity, may be valued relative to the income that could have been earned. For this reason it is common to correct the values for Table 2 based on the relative income. In this there are two corrections considered:

1. *Differences in prices*. Controlling for differences in prices is crucial to minimise errors when transferring values across locations. The recommended approach is to use *PPP (Purchasting Power Parities)-corrected exchange rates* to take into account the cost of living. If appropriate, adjustments can also be made in line with differences in living costs between regions within the same country.

2. *Differences in income*. A central issue when converting values between countries is to consider differences in income. Valuation of a certain social costs is dependent on the level of income. The common approach consists of multiplying the unit values by the ratio of income in the policy country to income in the study country as such:
   $WTP_{PS} = WTP_{SS} \left(\frac{I_{OS}}{I_{SS}}\right)^{\varepsilon}$,
   Where WTP_{PS} is the WTP transferred to the study site, WTP_{SS} is the WTP at the study site, I_{OS} and I_{SS} are income at the other and study sites, and ε is income elasticity of WTP. For the income elasticity, CE Delft *et al*. (2019) used a value of 0.8. This value is based on an extensive meta-analysis of the OECD, which concludes that the income elasticity for the WTP of environmental and health related goods falls between 0.7 and 0.9.[9]

We take both differences into account by using the PPP adjusted income levels at the city level and applying an income elasticity of 0.8 to these. This implies that if a city's average income (expressed in purchasing power parities) is half of that of the EU average, the valuation of a YOLL is being reduced from € 70,000 in the EU28 to € 40.204 in this particular city (e.g. 70,000 * $(0.5)^{0.8}$).

The practice to use income elasticities in social cost estimates is not without discussion. Sometimes, it is superficially interpreted as a moral judgement discriminating against the poor as in poorer cities human life seems to be valued lower. This view is erroneous because of two aspects:
1. We do not value human life in social cost estimates, but rather the risk of living a shorter life. This is something fundamentally different.
2. If we would not use an income elasticity, people in poorer cities would have to work much longer to compensate for the adverse impacts of air pollution. The city in our

[9] It should be noted though that there is a very substantial divergence in the literature with respect to the height of the values of income elasticities. E.g.

example above, would have to work twice as hard to compensate for the negative impacts from air pollution than the richer city. This may sound unfair as well.

Therefore, we use in this research a modest elasticity of 0.8 at the level of city's income.

2.4 Calculation of social costs in this research

2.4.1 General calculation

The method to estimate the total health related damage costs (social costs) consists of three steps:

1. Determine the **concentration of air pollutants** in an individual city.
2. Calculate **unit specific damage costs** for this city by applying the CRFs from Paragraph 2.2(and Annex B.3), life cohorts of the city (some endpoints are dependent on the age structure) and apply the valuation framework as given in Paragraph 2.3 at the level of individual cities using an income elasticity of 0.8.
3. Obtain a **total damage cost** figure by multiplying the concentration of pollutants by the unit specific damage costs and the inhabitants of a city.

Below these are described in more detail.

2.4.2 Step 1: Estimate the reported air quality

The average concentration of pollutants in a city was obtained by combining two datasets:

1. Eurostat, Urban Audit database, for reported concentration of PM_{10}; NO_2 and O_3. These provide information for 392 cities for average concentration of pollution of PM_{10}, O_3 and NO_2 for the year 2013. More recent years are not available.
2. EEA Air Quality Statistics that provide for over 500 cities information from their monitoring stations.

Starting point of our analysis has been the Eurostat Urban Audit database with information from the year 2013. In order to obtain a more recent dataset we have updated the 2013 information from the Urban Audit by calculating for both 2013 and 2018 the average concentration level of the monitoring stations in a city and using this as a factor to update the 2013 data from the Urban Audit. The final level of concentration was determined by using the following formula:

$$Conc_{i,j,2018} = Conc(UA)_{i,j,2013} * \frac{\sum_n Conc(EEA)_{i,j,2018} / n_{2018}}{\sum_n Conc(EEA)_{i,j,2013} / n_{2013}}$$

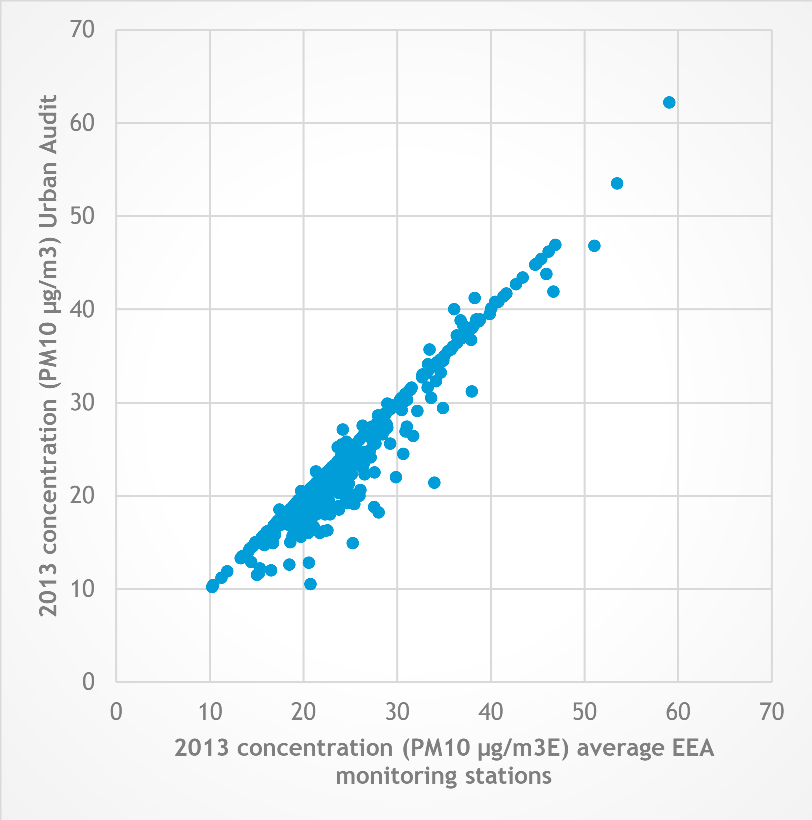
Where i = pollutant (PM_{10},O_3, NO_2), j = city, UA = data from Urban Audit, EEA = data from monitoring stations in an individual city.

This approach can provide a reliable result update of the reported level of concentration in the Urban Audit if the reported average concentration level to the Urban Audit matches the average level of concentration from the monitoring stations.[10] We have tested this. Figure 1 presents the correlation between the reported value in the Urban Audit for the city concentration and the average of the available monitoring stations in a city where each dots represents a city. This graph shows that there is a high degree of correlation (R2=0.964) between the reported value in the Urban Audit and the average concentration

[10] With average we mean here an arithmetic average where the summed concentration of all monitoring stations is.

from the monitoring stations. The 45 degree line where the values reported in the Urban Audit Database were similar to the average of monitoring stations in a city is visible in the graph so many cities indeed reported an average of all their monitoring stations.

Figure 1 – Relationship between Urban Audit data and average of monitoringsstations



Data: Eurostat (Urban Audit) and EEA (Air Quality Database).

One can also observe that the cities tend to report to the Urban Audit *lower* values than the average of their monitoring stations. The reasons for this can be multiple: cities may primarily have monitoring stations in more polluting areas as public awareness in these areas forces local governors to monitor air pollution more closely. Another explanation could be that cities tend to report more optimistic figures to Eurostat. Without further research going beyond the present study we cannot state which figure is more accurate.

It is in this light also important that various commentators have pointed us at the fact that an average of monitoring stations in reality may already underrepresent pollution in a city as local governors may also have an impetus to limit the measurement of air pollution to allow for greenwashing the city pollution. The actual level of pollution should therefore be subject of more study in the future.

The combination of the Urban Audit database and the EEA Air Quality database gives a representation of the reported air quality in a city. In Annex A.1 we report more precisely the two data sources that have been used to come at a value of reported air quality at the city level for 432 cities. In general, there are substantial differences in reported air quality between the various cities in Europe. Table 5 provides an overview of the cleanest and most dirtiest cities in our sample for the various indicators of air quality.

Table 5 - Overview of cleanest and dirtiest cities for concentrations (annual averages in µg/m³) for the year 2018

	Top 5 highest				Top 5 lowest		
	Country	City	PM_{10}		Country	City	PM_{10}
1	PL	Rybnik	50.65	1	NO	Bergen	9.96
2	BG	Plovdiv	46.54	2	UK	Edinburgh	10.66
3	CY	Lefkosia	44.80	3	SE	Stockholm	11.07
4	MT	Valletta	43.08	4	IE	Dublin	11.33
5	PL	Pabianice	42.45	5	FI	Oulu	11.53
	Country	City	NO_2		Country	City	NO_2
1	EL	Athina	61.34	1	EE	Narva	4.40
2	PT	Porto	56.15	2	EE	Tallinn	5.29
3	RO	Bucuresti	49.95	3	ES	Zamora	5.81
4	RO	Cluj-Napoca	47.23	4	EE	Tartu	5.85
5	RO	Brasov	45.58	5	ES	Palencia	6.03
	Country	City	O_3		Country	City	O_3
1	IT	Brescia	7.02	1	EE	Narva	0.00
2	IT	Lecco	6.15	2	EE	Tallinn	0.00
3	IT	Bergamo	6.03	3	EE	Tartu	0.00
4	IT	Milano	5.80	4	RO	Cluj-Napoca	0.00
5	IT	Piacenza	5.70	5	RO	Bistrita	0.01
	Country	City	$PM_{2.5}$		Country	City	$PM_{2.5}$
1	PL	Bielsko-Biala	32.39	1	FI	Kuopio	3.53
2	PL	Metropolia Silesia	32.10	2	ES	Arrecife	4.64
3	PL	Kraków	31.58	3	PT	Funchal	4.75
4	PL	Rybnik	31.54	4	ES	Santa Cruz de Tenerife	4.83
5	CZ	Karviná	30.09	5	FI	Lahti	5.19

2.4.3 Step 2: Calculate specific unit damage costs

Unit damage costs are the costs per unit of concentration (µg/m³/cap/yr). Specific unit damage costs are obtained:

- For mortality endpoints by multiplying the Relative Risk (expressed as the so-called attributable fraction) with the relative age groups and the incidence of mortality within this age group in each country and the value per life year lost.
- For morbidity (plus child mortality) by multiplying the Concentration Response Functions for each endpoint with the age group that applies to these CRFs with the valuation per endpoint.

The unit damage costs are expressed in (€/µg/m³/cap/yr). In order to obtain a city estimate of the level of pollution these unit damage costs are multiplied by the actual concentration of pollution and the number of people living in a city in Step 3. In Annex B the whole methodology is explained in much more detail.

Age groups and valuation are in this method city specific. In general the unit damage costs tend to increase if:

- The city has a larger share of adults (18+) and in particular a higher share of adults (30+);
- The city has a larger working population compared to total population. Working population has been defined by us as adults between 20 and 65 years old that are employed, or are actively looking for employment.

— The incomes earned in a city are higher as every 10% increase in income results in a 8% higher valuation of the impacts of air pollution due to the chosen income elasticity of 0.8 (see Paragraph 2.3.2).

2.4.4 Step 3: Calculate total damage costs

In a third step total damage costs are calculated by multiplying the reported concentration with the unit damage costs and the total population affected. This gives a figure of the total damage costs for air pollution in a given year. The larger the city, the greater the social costs all else equal. Therefore we will also present the social costs per capita in Chapter 3.

The method we employ use information at the level of cities, nations and Europe.
City specific information is used with respect to:
— the level of pollution in a city (see Step 1 above);
— the inhabitants of a city;
— the age cohorts living in a city;
— the average income earned in a city.

Nation specific information has been used with respect to:
— the incidence rates from mortality of different age groups.

European specific information has been used with respect to:
— the recommended relative risks from the WHO (2013),
— concentration response functions that combine relative risks and incidence rates for morbidity in Europe.

3 Results

3.1 Introduction

This chapter presents the calculated social costs associated with the impact of air pollution on human health in European cities using the methodological framework identified in Paragraph 2.4. The results will be presented in two different formats:

1. Absolute number of social costs of all cities (Paragraph 3.2).
2. Relative social costs per capita or per unit of GDP (Paragraph 3.3).

3.2 Total social costs

3.2.1 Total social costs

We have estimated the total social costs for 432 cities in 30 countries (EU28 plus Norway and Switzerland). In total, over 130 million people live in these cities, with an average of 301,754 inhabitants per city. In 2018, total social costs for all 432 cities trespassed € 166 billion. The average cost per city is over € 385 million.

Table 6 gives the 25 most important cities with respect to costs of air pollution. We see here that London has the highest costs of € 11.4 billion followed by Bucharest and Berlin. Overall, Europe's biggest cities are all included in the Top 25. Of course, population size is an important determinant of these damage costs and all of the cities in the EU28 with a population size larger than 1 million inhabitants (2018) are included in Table 6. The first city on the list with a population of under 1 million is Torino on place #18. Cities like the Greater city of Glasgow, Napoli and Stockholm are cities with a total population of just under 1 million that are not on the list of the most polluted cities.

Table 6 - Top 25 cities with the highest total damage costs of air pollution

No.	Country	City	Total damage costs
1	United Kingdom	London (greater city)	€ 11,380,722,416
2	Romania	Bucuresti	€ 6,345,139,087
3	Germany	Berlin	€ 5,237,257,544
4	Poland	Warszawa	€ 4,222,682,712
5	Italy	Roma	€ 4,144,344,954
6	Poland	Metropolia Silesia	€ 3,596,193,823
7	France	Paris	€ 3,505,259,275
8	Italy	Milano	€ 3,498,940,399
9	Spain	Madrid	€ 3,383,362,222
10	Hungary	Budapest	€ 3,272,079,833
11	Germany	Hamburg	€ 2,936,377,930
12	Germany	München	€ 2,877,847,412
13	Bulgaria	Sofia	€ 2,575,337,596
14	Austria	Wien	€ 2,567,485,526
15	United Kingdom	Greater Manchester	€ 2,409,496,795
16	Czech Republic	Praha	€ 2,253,053,555
17	Spain	Barcelona	€ 2,020,417,033
18	Italy	Torino	€ 1,815,447,357

No.	Country	City	Total damage costs
19	United Kingdom	West Midlands urban area	€ 1,806,623,126
20	Germany	Köln	€ 1,786,891,554
21	Belgium	Bruxelles / Brussel	€ 1,585,778,013
22	Poland	Kraków	€ 1,490,117,352
23	Germany	Frankfurt am Main	€ 1,344,636,105
24	Croatia	Zagreb	€ 1,312,028,080
25	Poland	Wroclaw	€ 1,239,522,247

Table 7 below presents for every country the Top 3 cities listed on their territory. The reader should notice that not all countries have three cities in the Urban Audit database with reported levels of air quality: some countries, like Norway, Malta, Luxembourg and Cyprus, have just one city listed here, while other countries, as Greece, have only two cities listed. More detailed information per country and the damage costs per city can be found in Annex C.

Table 7 - Top 3 cities with highest total damage cost, per country

	City	Total damage costs		City	Total damage costs		City	Total damage costs
Austria			**Germany**			**Norway**		
1	Wien	€ 2,567,485,526	1	Berlin	€ 5,237,257,544	1	Bergen	€ 156,113,675
2	Graz	€ 431,963,160	2	Hamburg	€ 2,936,377,930	2		
3	Linz	€ 286,076,935	3	München	€ 2,877,847,412	3		
Belgium			**Greece**			**Poland**		
1	Bruxelles	€ 1,585,778,013	1	Athina	€ 1,126,581,958	1	Warszawa	€ 4,222,682,712
2	Antwerpen	€ 744,293,817	2	Pátra	€ 200,144,612	2	Metropolia Silesia	€ 3,596,193,823
3	Gent	€ 386,424,103	3			3	Kraków	€ 1,490,117,352
Bulgaria			**Hungary**			**Portugal**		
1	Sofia	€ 2,575,337,596	1	Budapest	€ 3,272,079,833	1	Lisboa	€ 635,590,170
2	Plovdiv	€ 354,839,429	2	Debrecen	€ 165,282,269	2	Sintra	€ 236,064,011
3	Varna	€ 330,601,003	3	Győr	€ 153,362,078	3	Porto	€ 226,074,858
Croatia			**Ireland**			**Romania**		
1	Zagreb	€ 1,312,028,080	1	Dublin	€ 431,454,062	1	Bucuresti	€ 6,345,139,087
2	Osijek	€ 135,545,965	2	Cork	€ 89,735,878	2	Timisoara	€ 542,215,309
3			3			3	Brasov	€ 495,557,564
Cyprus			**Italy**			**Slovakia**		
1	Lefkosia	€ 222,378,715	1	Roma	€ 4,144,344,954	1	Bratislava	€ 891,503,030
2			2	Milano	€ 3,498,940,399	2	Kosice	€ 221,574,435
3			3	Torino	€ 1,815,447,357	3	Zilina	€ 106,162,266
Czech Republic			**Latvia**			**Slovenia**		
1	Praha	€ 2,253,053,555	1	Riga	€ 895,589,858	1	Ljubljana	€ 433,967,793
2	Brno	€ 485,338,520	2	Liepaja	€ 80,761,084	2	Maribor	€ 107,177,360
3	Ostrava	€ 420,868,108	3			3		
Denmark			**Lithuania**			**Spain**		
1	København	€ 785,432,237	1	Vilnius	€ 753,022,734	1	Madrid	€ 3,383,362,222
2	Århus	€ 306,769,731	2	Kaunas	€ 318,561,060	2	Barcelona	€ 2,020,417,033
3	Odense	€ 187,988,303	3	Klaipeda	€ 232,231,276	3	Valencia	€ 670,821,188

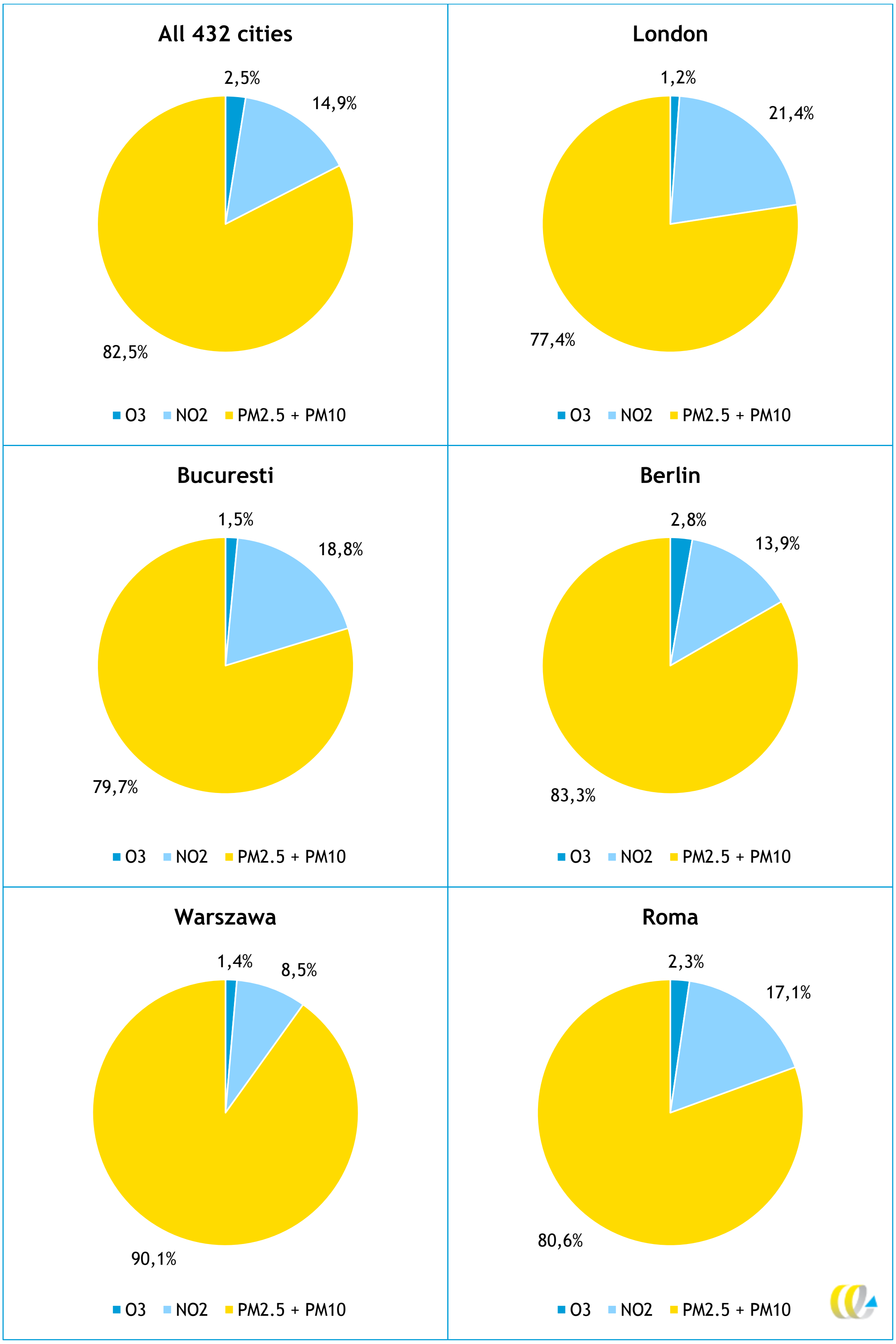
	City	Total damage costs		City	Total damage costs		City	Total damage costs
Estonia			**Luxembourg**			**Sweden**		
1	Tallinn	€ 249,194,994	1	Luxembourg	€ 166,146,874	1	Stockholm	€ 682,917,334
2	Tartu	€ 44,821,408	2			2	Göteborg	€ 418,060,115
3	Narva	€ 23,138,028	3			3	Malmö	€ 262,753,522
Finland			**Malta**			**Switzerland**		
1	Helsinki	€ 493,726,101	1	Valletta	€ 279,577,806	1	Zürich	€ 432,517,555
2	Tampere	€ 117,318,500	2			2	Basel	€ 182,369,253
3	Oulu	€ 105,873,953	3			3	Bern	€ 160,822,740
France			**Netherlands**			**United Kingdom**		
1	Paris	€ 3,505,259,275	1	Amsterdam	€ 1,054,817,803	1	London	€ 11,380,722,416
2	Marseille	€ 774,108,756	2	Rotterdam	€ 750,342,591	2	Greater Manchester	€ 2,409,496,795
3	Lyon	€ 585,267,499	3	's-Gravenhage	€ 521,202,760	3	West Midlands urban area	€ 1,806,623,126

3.2.2 Decomposition of social costs

Social costs are being caused by emissions of air pollutants leading to concentrations of $PM_{2.5}/PM_{10}$, O_3 and NO_2 in urban environments. In the combined Figure 2, the contribution of $PM_{2.5}/PM_{10}$, O_3 and NO_2 to total damage cost are illustrated in percentages. The chart in the left upper corner concerns the average contributions of each of the three main pollutants over all 432 cities. The other five charts represent the five cities with the highest total damage cost, as is shown in Table 7.

It is evident that particulate matter (measured by $PM_{2.5}$ and PM_{10}) causes the vast majority of total damage costs. On average, over all 432 cities, $PM_{2.5}/PM_{10}$ contributes to 82.5% of the total damage costs. NO_2 emissions result, on average, in a share of 15% while O_3 contributes, on average, to only 2.5% of the total damage costs. However, one should notice that these are average numbers that differ considerably between cities.
The contribution of $PM_{2.5}/PM_{10}$, for example, to total damage costs varies from 60.1% in Funchal, Portugal, to 94.0% in Narva, Estonia. The contribution of O_3 is in general very small and varies from 0% in the Estonian cities Tallinn, Tartu and Narva, to 7.6% in Cáceres in Spain. The contribution of NO_2 varies from 4.8% in Palencia, Spain to 34.4% in Funchal, Portugal.

Figure 2 - Contribution of each pollutant to total damage cost



High concentrations of particulate matter, O_3 and NO_2 result in premature mortality and morbidity (illness). On average, the contribution of morbidity in total social cost for all 432 cities is 23.9%. Conversely, the average contribution of mortality is 76.1%. However, this contribution differs between cities. In Table 8 an overview is given of the cities in which the contribution of morbidity risks from air pollution is highest, and in which the contribution of mortality risks is highest. In general, cities in central and eastern Europe tends to have higher mortality, while cities in Southern Europe tend to have higher morbidity. In general, morbidity impacts tend to be higher if:

- The NO_2 emissions are relatively small compared to the other impacts. NO_2 most predominantly gives impacts on premature mortality in the calculations using the method described in Paragraph 2.4 and Annex B. For a given concentration of NO_2, the morbidity impacts are small compared to the mortality impacts.
- If a smaller share of PM_{10} is belonging to $PM_{2.5}$. In the methodology used, PM_{10} predominantly is associated with morbidity while $PM_{2.5}$ is predominantly associated with mortality. Substantial PM_{10} emissions with relatively low $PM_{2.5}$ emissions would explain this difference. However, this may also be a matter of measurement. The measurement of Lefkosia is, for example, based on one single station. In general we would recommend more accurate measurement of air quality over more stations (see also Chapter 5).

Table 8 - Cities with highest contribution of mortality and morbidity

	Country	City	Contribution of mortality		Country	City	Contribution of morbidity
1	BG	Stara Zagora	85.3%	1	CY	Lefkosia	45.2%
2	LV	Riga	84.6%	2	ES	Arrecife	44.0%
3	RO	Oradea	84.1%	3	ES	Telde	40.3%
4	DE	Leverkusen	83.8%	4	MT	Valletta	37.0%
5	DE	Reutlingen	83.3%	5	IT	Sassari	35.4%

3.2.3 Comparison of results

There are other studies that have also calculated the social costs of air pollution in a more sophisticated way. One example is the study that soon will be published for Brussels (Vito, forthcoming). Another example is the study for London by King's College (2015). This study estimated the annual social costs of air pollution in London equivalent to € 1.38-3.65 billion. One should notice that this figure is a Factor 4.5 lower than our estimated annual costs of € 11.38 billion.

In contrast to our study, the study by King's College has applied sophisticated city modelling of the spread of air pollution. However the difference between their and our results is not the reason of their more sophisticated approach, but rather due to our broader scope of impacts with respect to pollutants and endpoints considered. While King's college (2015) only investigates $PM_{2.5}$ and NO_2 impacts for six endpoints, our analysis includes O_3, PM_{10} plus a larger range of sixteen endpoint impacts.

Table 9 provides more information on the differences in the cost calculations, where we have averaged the economic costs in the King's College study as the average between the minimum and maximum estimates for reasons of comparison. The second column in this table shows the total outcome of estimated costs of both studies, that evidence that our results are a Factor 4.5 higher. However, an important factor related to this is our inclusion of more morbidity endpoints (in particular COPD) and more pollutants. If we only look at the mortality endpoints of $PM_{2.5}$ and NO_2, our results are still a Factor 3.5 higher. However, most of this difference can be explained by the fact that we use a much higher figure for valuation in London. The King's College study uses a recommended value for England from DEFRA, while we use a specific value for London which is higher than the EU28 average value from the DG Move Handbook (CE Delft et al., 2019) because inhabitants of London earn in general a higher income than the average. In addition, population growth between 2012 and 2018 has also resulted in higher social costs.

Table 9 - Comparison of the present results with King's College (2015)

Study	Year of data	Economic costs € billion	ow mortality $PM_{2.5}/NO_2$	Pop	€/YOLL
Kings College (2015)	2012	2.52*	2.50*	8.003	45474^
Our study (2020)	2018	11.38	8.69	8.797	104448
Difference		452%	348%	110%	230%

* Calculated central value from averaging the low and upper range of estimated.

^ Taking the central value from Appendix 7 in King's College.

If we would correct for the impact of population growth and valuation, the results in our study are only 138% higher than in the study by King's College.[11] The most important factor of the remaining difference is probably related to the correction of $PM_{2.5}$ emissions for sea salt fractions, although other differences (with respect to spatial modelling or age groups) should not be singled out.

3.3 Social costs in perspective (relative numbers)

The total social costs are primarily influenced by population size and the size and type of economic activities that impact the air quality of a city. It is therefore interesting to investigate relative measures, such as the social costs per capita, or the social costs per unit of GDP.

3.3.1 Social costs per capita

Table 10 shows the social costs per capita and presents the cities that have the Top 10 highest and Top 10 lowest damage costs per capita. We see here that Bucharest in Romania has the highest damage cost per capita of € 3,004 in 2018. The city with the lowest damage cost per capita is Santa Cruz de Tenerife, Spain, with € 382 per capita in 2018. The average damage cost per capita over all 432 cities in the sample is € 1,095 in 2018. This implies that every citizen loses over € 1,000 in welfare over a year due to poor air quality.

Table 10 - Top 10 cities with highest and lowest damage costs per capita in 2018

Top 10 highest damage cost per capita				Top 10 lowest damage cost per capita			
	Country	City	Damage cost per capita		Country	City	Damage cost per capita
1	RO	Bucuresti	€ 3,004	1	ES	Santa Cruz de Tenerife	€ 382
2	IT	Milano	€ 2,843	2	EE	Narva	€ 405
3	IT	Padova	€ 2,455	3	FI	Kuopio	€ 428

[11] On the other hand, the city of London was more polluted in 2012 than in 2018. Therefore the 'real' difference between both studies when corrected for population growth and valuation is larger than 138%.

Top 10 highest damage cost per capita				Top 10 lowest damage cost per capita			
	Country	City	Damage cost per capita		Country	City	Damage cost per capita
4	PL	Warszawa	€ 2,433	4	ES	Arrecife	€ 448
5	SK	Bratislava	€ 2,168	5	FR	Pau	€ 467
6	IT	Venezia	€ 2,106	6	FR	Perpignan	€ 474
7	IT	Brescia	€ 2,106	7	EE	Tartu	€ 481
8	BG	Sofia	€ 2,084	8	FR	Brest	€ 501
9	IT	Torino	€ 2,076	9	CH	Genève	€ 510
10	DE	München	€ 1,984	10	FI	Tampere/ Tammerfors	€ 514

As stated above, population size is the most important variable explaining the total damage costs. Table 11 investigates the Top 3 cities with the highest damage per capita and presents this for each country. It is interesting to notice that in many countries, the capital city has the highest damage costs, while in Austria, Czech Republic, Germany, Italy, Lithuania, Spain, Sweden and Switzerland other cities in the country have higher per capita damage costs. More detailed information per country and the damage costs per city can be found in Annex C.

Table 11 - Top 3 cities with the highest damage cost per capita

	City	Damage cost per capita		City	Damage cost per capita		City	Damage cost per capita
Austria			**Germany**			**Norway**		
1	Graz	€ 1,600	1	München	€ 1,984	1	Bergen	€ 583
2	Salzburg	€ 1,544	2	Düsseldorf	€ 1,925	2		
3	Linz	€ 1,476	3	Heilbronn	€ 1,914	3		
Belgium			**Greece**			**Poland**		
1	Gent	€ 1,556	1	Athina	€ 1,697	1	Warszawa	€ 2,433
2	Antwerpen	€ 1,493	2	Pátra	€ 1,171	2	Kraków	€ 1,956
3	Bruxelles	€ 1,395	3			3	Wroclaw	€ 1,954
Bulgaria			**Hungary**			**Portugal**		
1	Sofia	€ 2,084	1	Budapest	€ 1,860	1	Lisboa	€ 1,159
2	Ruse	€ 1,379	2	Győr	€ 1,184	2	Setúbal	€ 954
3	Shumen	€ 1,208	3	Pécs	€ 909	3	Porto	€ 950
Croatia			**Ireland**			**Romania**		
1	Zagreb	€ 1,635	1	Dublin	€ 836	1	Bucuresti	€ 3,004
2	Osijek	€ 1,288	2	Cork	€ 756	2	Brasov	€ 1,710
3			3			3	Timisoara	€ 1,643
Cyprus			**Italy**			**Slovakia**		
1	Lefkosia	€ 929	1	Milano	€ 2,843	1	Bratislava	€ 2,168
2			2	Padova	€ 2,455	2	Zilina	€ 1,303
3			3	Venezia	€ 2,106	3	Nitra	€ 1,132
Czech Republic			**Latvia**			**Slovenia**		
1	Karviná	€ 1,927	1	Riga	€ 1,401	1	Ljubljana	€ 1,502
2	Praha	€ 1,815	2	Liepaja	€ 1,144	2	Maribor	€ 965
3	Most	€ 1,460	3			3		
Denmark			**Lithuania**			**Spain**		
1	København	€ 1,431	1	Klaipeda	€ 1,535	1	Barcelona	€ 1,256

	City	Damage cost per capita		City	Damage cost per capita		City	Damage cost per capita
2	Odense	€ 981	2	Siauliai	€ 1,486	2	Guadalajara	€ 1,183
3	Århus	€ 975	3	Vilnius	€ 1,381	3	Madrid	€ 1,069
Estonia			**Luxembourg**			**Sweden**		
1	Tallinn	€ 584	1	Luxembourg	€ 1,748	1	Malmö	€ 800
2	Tartu	€ 481	2			2	Lund	€ 785
3	Narva	€ 405	3			3	Göteborg	€ 751
Finland			**Malta**			**Switzerland**		
1	Helsinki/ Helsingfors	€ 777	1	Valletta	€ 1,246	1	Lugano	€ 1,314
2	Lahti/Lahtis	€ 577	2			2	Bern	€ 1,280
3	Oulu	€ 528	3			3	Zürich	€ 1,147
France			**Netherlands**			**United Kingdom**		
1	Paris	€ 1,602	1	Amsterdam	€ 1,301	1	London	€ 1,294
2	Lyon	€ 1,134	2	Eindhoven	€ 1,276	2	Bristol	€ 1,055
3	Nice	€ 1,128	3	Rotterdam	€ 1,213	3	Aberdeen City	€ 944

3.3.2 Social costs per unit of GDP

Next to population size, the size and type of economic activities in a city and its surroundings may impact on the costs of air pollution. Table 12 shows the cities that have the Top 10 highest and Top 10 lowest damage costs per unit GDP. This represents the percentage of the total damage costs in the total GDP of the relevant city and is thus a relative measure of the percentage of welfare loss due to air pollution. In this case, Ruse in Bulgaria displays the highest share of the total damage costs in GDP, with the total damage costs corresponding to almost 10% of total GDP in the city in 2018. In many cities in Bulgaria, Romania and Poland the contribution of social costs from polluted air is relatively high, trespassing the 8%. Especially the position of the Metropolia Silesia is of concern here, as this is also a very large urban area with a population area of almost 1.9 million in 2018.

The city where the damage costs are the lowest relatively to GDP, is Kuopio in Finland, with the total damage costs corresponding to 1.3% of GDP. Also interesting is the low share of air pollution costs in capital cities like Dublin, Stockholm and Talinn: part of this could be explained by reference to their location near the sea, but also other factors may contribute to the better air quality situation in those cities. On average over the 432 cities, the total damage costs of air pollution in a city is equal to 3.9% of GDP.

Table 12 - Top 10 cities with highest and lowest damage cost as a share of GDP in 2018

Top 10 highest				Top 10 lowest			
	Country	City	Share of damage costs in GDP		Country	City	Share of damage costs in GDP
1	BG	Ruse	9.9%	1	FI	Kuopio	1.3%
2	RO	Iasi	9.4%	2	IE	Dublin	1.4%
3	PL	Metropolia Silesia	8.6%	3	IE	Cork	1.5%
4	BG	Shumen	8.6%	4	SE	Stockholm	1.5%
5	PL	Bielsko-Biala	8.6%	5	NO	Bergen	1.5%
6	BG	Plovdiv	8.6%	6	FI	Oulu	1.6%

Top 10 highest				Top 10 lowest			
	Country	City	Share of damage costs in GDP		Country	City	Share of damage costs in GDP
7	PL	Rybnik	8.5%	7	ES	Arrecife	1.7%
8	BG	Burgas	8.2%	8	FR	Pau	1.7%
9	PL	Kraków	8.1%	9	ES	Santa Cruz de Tenerife	1.7%
10	RO	Brasov	8.1%	10	EE	Tallinn	1.8%

4 Estimating the impact of transport on social costs

4.1 Introduction

Air quality in cities is dependent on the pollution stemming from economic activities, both in the city, as in the surrounding areas. The amount of emissions in a certain area is therefore an important variable to explain urban air quality. The relation from emissions to concentrations, however, is not straightforward. The increase in concentrations of a given pollutant is, among others, dependent on the type of pollutant, the height of release of the pollutant, atmospheric conditions and geomorphological conditions.

Source contributions to urban $PM_{2.5}$ levels in the EU Member States have for example been modelled in the GAINS modelling suite (Kiesewetter and Amann, 2014). These reports show a precise estimation of the contribution to $PM_{2.5}$ air pollution at the city level. In this chapter we apply a different method: we try to estimate the impact of the type and organisation of transport in a city on the air quality in a city through econometric analysis.

First in Paragraph 4.2 we describe the methods that have been employed in this research. Then in Paragraph 4.3 we estimate the impact of transport related variables on the air quality in a city.

4.2 Description of the method

4.2.1 General description and data

To estimate the impact of city transport on air pollution, we have conducted an ordinary least squares (OLS) linear regression where the concentration of pollution is regressed on variables describing the situation with respect to transport in these cities. We estimated the model for PM_{10} concentrations, $PM_{2.5}$ concentrations and NO_2 concentrations as dependent variables. O_3 concentrations were omitted from the analysis as these were shown to provide only a small contribution to total social costs in Chapter 3.

The transport variables used in this exercise originate from the Urban Audit Statistics from Eurostat. This dataset covers over 1,000 cities in Europe and monitors a wide range of indicators, among which various indicators about transport within cities. There are sixteen variables available in the Urban Audit database on transport indicators. However, many of these were only included for a limited number of cities. In the end we decided to include the following data on transport indicators in our analysis for a reasonable number of cities:
- Share of journeys to work by car (%). This indicator tells us which percentage of all journeys to work within a city are done by car. As use of a car is more polluting than use of bicycle, public transport or walking, we would expect that the higher this share of journeys to work by car, the higher the concentration of pollutants in the city becomes.
- Number of cars registered per 1,000 population. This indicator represents relative car possession; for every 1,000 inhabitants in a city, this variable indicates how many of them own a car. As a higher number of cars per 1,000 people may imply a higher amount of car use in the city, we would expect pollution to go up as this indicator rises.

- Average time of journey to work (minutes). This indicator tells us how long it takes on average to arrive from home to work within a city, in minutes. The higher this indicator, the longer people are travelling within a city to arrive at their place of employment. As a longer travelling time would provide longer times to pollute, we expect pollution to rise as this variable increases.

It should be noted that these variables are not present for each city in the Urban Audit and the years for which data are available differ with considerable gaps in between years. After inspection of the data it was concluded that the data quality was too poor to estimate development over time. So we rather stick to cross-section analysis to investigate if the differences in reported air quality between cities can be explained with reference to the underlying transport variables.

For data collection, the year 2013 showed the highest frequency in data availability. However, to obtain a sufficient sample, we have complemented the 2013 sample with cities that had data in different years. These alternative years of data range from 2010 to 2016, with priority given to 2011, 2014 or 2012 if one of these were available. This method has been used due to the expected lack of variation over time in the variables included in the regression. As a result, a sample of over 230 cities is available for each estimated model.

The total dataset consists of a cross-sectional sample, and thus includes multiple cities with data for each variable for one point in time. The sample consists of 259 cities for the estimation with PM_{10} as a dependent variable, 257 cities for the estimation with $PM_{2.5}$ as a dependent variable, and 239 cities for the estimation with NO_2 as a dependent variable. Data for PM_{10}, $PM_{2.5}$ and NO_2 is taken from the European Environment Agency and Urban Audit, for the year 2013[12]. Each pollutant is measured as the annual mean concentration in µg per m^3.

4.2.2 Model formulation

In order to isolate the effect of the transport variables, other factors that impact air pollution in a city must be included in the model. Firstly, population density is included as an independent variable. The more people live on a square kilometre, the more average pollution per m^3 these people would probably cause. Secondly, GDP per capita (purchasing power parity) is included. It would be expected that a higher level of GDP per capita is associated with a higher level of economic activity, which in turn causes higher levels of pollution. On the other hand, higher income cities may be able to undertake more effort to improve air quality, for example, by installing environmental zones or subsidizing public transport. Concern for air quality may be growing when incomes grows. This would result in a negative relationship between air pollution and income. [13]

Although in many Eastern European cities the contribution to air pollution primarily comes from traffic, the suburbs or cities surrounding the cities are sometimes using coal or biomass fired stoves for household heating, especially in Central and Eastern Europe. Therefore, the link with traffic can be relatively weak or absent. For that reason, we have added a variable in the regression that covers this source of pollution in a country: the share of solid fossil fuels in total energy consumption by households. This includes the use of solid fossil fuels by households, as a percentage of total energy consumption by

[12] PM_{10} and NO_2 are taken from Urban Audit, consistent with the transportation variables. $PM_{2.5}$ is not available in the Urban Audit, therefore this is taken from the EEA.

[13] Both population density and GDP per capita are taken from Eurostat. For cities that did not have information about GDP per capita, we inserted the national average GDP per capita (see also Annex A).

households. This variable comes from Eurostat and is at the country level since it is not available at the city level. Therefore we assigned the national average to each city in the sample. We also tested models in which we included consumption of primary solid biofuels by households in the regressions as well, but this did not result in a significant improvement of the estimation. Therefore we present here the model with consumption of solid fossil fuels by households.

All data has been transformed into logarithmic values by taking the natural log of each variable. This implies that all coefficients can be regarded as elasticities showing the impact of a x% increase in the variable on ambient air quality.

4.3 Results

4.3.1 Results for PM_{10} and $PM_{2.5}$

The results for the estimations of the model with PM_{10} and $PM_{2.5}$ concentrations as dependent variable, are presented in Table 13. Considering the outcome for the model with PM_{10} concentrations as a dependent variable, the overall explanatory power of the model is 0.476, as seen by the adjusted R squared. This means that approximately 47.6% of the variation in PM_{10} concentrations is explained by the variation of the independent variables included in the model. All coefficients for the independent variables are statistically significant at the 1% significance level, except share of journeys by car, which does not show a significant coefficient. The explanatory power of the model where $PM_{2.5}$ is the dependent variable is 32.3%, given by the adjusted R squared of 0.322. In this model, all coefficients are statistically significant at, at least, the 5% significance level, except for GDP per capita and share of journeys by car.

Table 13 - Regression results for PM_{10} and $PM_{2.5}$

Dependent variable:	**PM_{10} (log)**	**$PM_{2.5}$ (log)**
GDP PPP per capita (log)	-0.261*** [0.060]	-0.044 [0.071]
Population density (log)	0.067*** [0.012]	0.106*** [0.015]
Share of solid fossil fuels in total energy consumption by households (log)	0.253*** [0.044]	0.261*** [0.052]
Share of journeys by car - % (log)	0.091 [0.068]	0.066 [0.081]
Average time of journey to work – minutes (log)	0.290*** [0.075]	0.185** [0.092]
Number of registered cars per 1,000 population (log)	0.490*** [0.063]	0.487*** [0.076]
Constant	0.941 [0.854]	-1.529 [1.025]
No. of observations	259	257
Adjusted R squared	0.476	0.322

Note: the table displays the coefficient with standard error in brackets.
*Significance levels: *p<0.10 **p<0.05 ***p<0.01.*

GDP PPP per capita shows a negative coefficient of -0.261 at the 1% statistical significance level in the model with PM_{10} as independent variable. The implication is that when GDP PPP per capita increases by 1%, PM_{10} concentration decrease, on average, by 0.26%, all else equal. In general, one would expect that a higher GDP, implying more economic activities, would result in a higher concentration of pollutants. That this is not the case could be indicative of the fact that most of the cities in this sample would lay on the right side of the Environmental Kuznets Curve that depicts that air quality may improve after certain income levels have been reached (De Bruyn, 2000). In practice, this could be due to the fact that the vehicle fleet in richer cities tend to be more clean or that these cities have better public transport networks. For $PM_{2.5}$, the coefficient for GDP PPP per capita is also negative, but not significantly different from zero. Income there does not seem to influence the concentration of $PM_{2.5}$ in our sample.

Population density shows a positive coefficient of 0.067 at the 1% statistical significance level for PM_{10}. This implies that a 1% increase in population density corresponds to a small (0.067%) increase in PM_{10} concentrations, all else equal. In the model for $PM_{2.5}$, the coefficient of 0.106 for population density is also positive and statistically significant at the 1% significance level. This implies that for every 1% increase in population density, $PM_{2.5}$ concentrations rise, on average, by 0.1%. Both results support a-priori expectations, namely that a higher number of people per square kilometre in a city corresponds to a higher concentration of air pollution.

The share of solid fossil fuels in total energy consumption by households shows a positive coefficient of 0.253 and 0.261 for PM_{10} and $PM_{2.5}$ respectively, being both significant at the 1% level. The values of the coefficients imply that a 1% increase in the share of solid fossil fuels in total energy consumption by households corresponds, on average, to a 0.25% and 0.26% increase in PM_{10} and $PM_{2.5}$ concentrations respectively. Compared to other sources of energy, solid fossil fuels are more polluting, and thus this result supports the theory that the more solid fossil fuels are consumed, the worse air quality in cities will be. While we have included and tested other variables here, such as the share of biomass use by households, these proved to be not significant and impoverished the overall model estimation, that's why they were left out.

Turning to the transport variables in the model for PM_{10}, average time of journey to work shows a positive coefficient at the 1% statistical significance level. This implies that, on average, when the average time of journey to work rises by 1%, the annual average concentration rises by 0.29%, all else equal. Moreover, the number of registered cars per 1,000 population also shows a positive coefficient of 0.490 at the 1% statistical significance level. This implies that PM_{10} concentrations increase, on average, by 0.49% for every 1% increase in the number of registered cars per 1,000 population, all else equal.
The coefficient for share of journeys by car is positive, but is not statistically significant. Therefore this variable cannot reliably be interpreted as having an impact on PM_{10} concentrations in cities. Although one would expect that this variable would have a positive sign on overall air quality as well, the reason why this is not the case may be related to difficulties in measuring this variable. While most of the variables can be obtained by standard statistical sources (e.g. number of registered cars), variables like the share of journeys by cars or the average length of commuting to the work have to be obtained through questionnaires. If questionnaires differ between cities in set-up, variables may show up not being significant in our regression analysis.

For the model with $PM_{2.5}$, the behaviour of the transport variables shows a similar pattern, although the impact of the chosen transport variables is slightly lower. Average time of journey to work displays a positive coefficient of 0.185 at the 5% statistical significance level. This implies that a 1% increase in the average time of journey to work corresponds to an average increase of 0.185% in annual mean $PM_{2.5}$ concentrations, all else equal. Additionally, the number of registered cars per 1,000 population also shows a positive coefficient of 0.487, at the 1% statistical significance level. This implies that on average, if the number of registered cars per 1,000 population increase by 1%, annual mean $PM_{2.5}$ concentrations increase by 0.487%. Similar to the coefficients for PM_{10}, these results support the theory that a higher volume of cars and a longer travelling time correspond to higher air pollution, and thus poorer air quality. The share of journeys by car is not statistically significantly different from zero.

4.3.2 Results for NO_2

Table 14 shows the regression results for the estimation with annual mean NO_2 concentrations as the dependent variable. The overall explanatory power of this model is 26.6%, as concluded from the adjusted R squared of 0.266. This means that approximately 26.6% of the variation in NO_2 concentrations is explained by the variation in the independent variables included in the estimation. In this model, all estimated coefficients are statistically significant, at least at the 5% statistical significance level.

Table 14 - Regression results for NO_2

Dependent variable:	NO_2 (log)
GDP PPP per capita (log)	0.453*** [0.098]
Population density (log)	0.086*** [0.020]
Share of solid fossil fuels in total energy consumption by households (log)	0.318*** [0.068]
Share of journeys by car - % (log)	0.281** [0.112]
Average time of journey to work - minutes (log)	0.547*** [0.129]
Number of registered cars per 1000 population (log)	0.494*** [0.104]
Constant	-8.153*** [1.375]
No. of observations	239
Adjusted R squared	0.266

Note: the table displays the coefficient with standard error in brackets.
*Significance levels: *p<0.10 **p<0.05 ***p<0.01.*

First, contrary to the model with PM_{10}, GDP per capita shows a positive coefficient of 0.453 at the 1% statistical significance level. This implies that for every increase of 1% in GDP per capita, average NO_2 concentrations increase by 0.453%, on average and all else equal. This result can be supported by the theory that a higher GDP per capita represents a larger amount of (potentially polluting) economic activity and that NO_2 emissions on average have not yet peaked in the Environmental Kuznets Curve in Europe.

Population density shows a positive coefficient of 0.086 at the 1% statistical significance level. This implies that a 10% increase in population density corresponds, on average, to a 0.86% increase in NO_2 concentrations, all else equal. This result can again be supported by the theory that a higher number of people per square kilometre inevitably together cause more pollution.

Also in this model, the share of solid fossil fuels in energy consumption by households has a positive coefficient of 0.318 at the 1% statistical significance level, implying an average 0.28% increase in NO_2 concentrations for every 1% increase in relative solid fossil fuel consumption by households, all else equal. This again supports the theory that the higher the share of solid fossil fuel is in the fuel mix in household energy consumption, the more polluting this energy consumption is, and the poorer the air quality in terms of NO_2.

In this model, all three transportation variables are positive and statistically significant. The coefficient of share of journeys by car is 0.281 at the 5% statistical significance level. This implies an average 0.281% increase in NO_2 concentrations for every 1% increase in share of journeys by car, all else equal. Contrary to the models with PM_{10} and $PM_{2.5}$, this result supports the theory that a higher share of journeys by car corresponds to a higher level of pollution, on average.

Average time of journey to work displays a positive coefficient of 0.547 at the 1% statistical significance level. For every 1% increase in the average time of journey to work, this result can be interpreted as an average corresponding increase in NO_2 concentrations of 0.547%, all else equal. This, similar to the models with PM_{10} and $PM_{2.5}$ supports the theory that longer journeys to work provide more opportunity to pollute, and therefore aggravates air quality.

Lastly, the number of registered cars per 1,000 population shows a positive coefficient of 0.494 at the 1% statistical significance level. This implies that when the number of registered cars per 1,000 population increases by 1%, NO_2 concentrations increase, on average, by 0.494%, all else equal. Again, this supports the theory that the more cars people own, relatively, the more these cars pollute, and the worse the air quality.

5 Conclusions

5.1 General findings

This study investigates the health-related social costs of air pollution in 432 European cities in 30 countries (the EU27 plus the UK, Norway and Switzerland). Social costs are costs affecting welfare and comprise both direct health care expenditures (e.g. for hospital admissions) and indirect health impacts (e.g. diseases such as COPD, or reduced life expectancy due to air pollution). These impacts affect welfare because people have a clear preference for healthy life years in a good and clean environment. Those impacts have been monetized in economics so that they can be added to actual expenditures to derive a measure of 'social costs'.

Environmental economists have performed numerous studies to quantify the impacts of air pollution on health and monetize these as social costs. These studies were used to develop the methodological framework adopted in the present study, which encompasses sixteen health impacts attributable to air pollution by fine particulate matter, ozone and nitrogen oxides (Table 2, Page 14). Using data on reported air quality in the Urban Audit statistics and the EEA Air Quality network, the physical impacts on human health were quantified using concentration-response functions based on the recommendations of the World Health Organization (WHO). The physical impacts were subsequently monetized using a valuation framework developed in the peer-reviewed Handbook of External Costs published by the European Commission's Directorate General for Mobility and Transport, DG MOVE. The resulting social costs incurred in a specific city were then determined from the air pollution levels reported there and the size, age structure and living standards of the population in that particular city.

For all 432 cities in our sample (total population: 130 million inhabitants), the social costs quantified were over € 166 billion in 2018. In absolute terms, London is the city with the highest social costs. In 2018, the loss in welfare for its 8.8 million inhabitants totalled € 11.38 billion. London is followed by Bucharest, with an annual loss in welfare of € 6.35 billion, Berlin (€ 5.24 billion), Warsaw (€ 4.22 billion) and Rome (€4.11 billion). City size is a key factor contributing to total social costs: all cities in Europe with a population over 1 million feature in the Top 25 cities with the highest social costs due to air pollution (see Table 6, Page 23).

In 2018, on average every inhabitant of a European city suffered a welfare loss of over € 1,250 a year owing to direct and indirect health losses associated with poor air quality. This is equivalent to 3.9% of income earned in cities. It should be noted that there is a substantial spread in these figures among cities: in the Romanian capital Bucharest total welfare loss amounts to over € 3,000 per capita/year, while in Santa Cruz de Tenerife in Spain it is under € 400/cap/yr. In many cities in Bulgaria, Romania and Poland the health-related social costs are between 8-10% of income earned.

Premature mortality is the largest component in social costs. For the 432 cities investigated, the average contribution of mortality to total social costs is 76.1%. The largest share of this is related to pollution of $PM_{2.5}$. Conversely, the average contribution of morbidity (diseases) is 23.9%. The development of Chronic Obstructive Pulmonary Disease (COPD) contribute to the largest morbidity related costs from air pollution.

The figures reported here are cited without uncertainty ranges. In this kind of study, uncertainty bounds are typically around 30-40%, implying that the figures reported here could be a factor 1/3 lower or 1/3 higher.

City air pollution stems from many sources: transport activities, household heating and a range of other activities including agriculture and industry. Without further analysis, the relative share of each source cannot be assessed with any certainty. In this study we did investigate the role of city transport in explaining these social costs using econometric methods. Although there is a severe lack of data at the level of individual cities, we do find evidence that transport policies impact the social costs of air pollution, using several proxy indicators that are available for many cities, including commuting times and car ownership. Our results show that a 1% increase in the average journey time to work increases the social costs of PM_{10} emissions by 0.29% and those of NO_2 emissions even by 0.54%. A 1% increase in the number of cars in a city increases overall social costs by almost 0.5%. This confirms that transport policies reducing commuting time and car ownerships can have important benefits in reducing the social costs from air pollution.

5.2 Research Findings

Our study relied on data available in official databases. The identified social costs are based on the reported level of air pollution in these databases, which may diverge from the actual situation. Given that air quality is still relatively sparsely monitored across Europe, the social costs reported are likely to be an underestimate in some cities. If air pollution levels are in fact higher than the figures reported in official statistics, the social costs will increase accordingly.

Comparison of our study's findings regarding welfare losses with those from other research shows that our results are sometimes higher than previously found. To a large extent this can be explained by the more recent figures used here for valuing the adverse impacts of air pollution. The present valuation was taken from the update of the peer-reviewed Handbook of External Costs published by the European Commission's Directorate General for Mobility and Transport, DG MOVE.

5.3 Recommendations

This leads to the following recommendations:

- The findings in this research paper show that impacts of poor air quality on human welfare are very substantial and larger than previously understood. Our findings provide additional evidence that reducing air pollution in European cities should be among the top priorities in any attempt to improve the welfare of city populations in Europe.
- The costs calculated in this study are likely to become higher if the costs because of the COVID-19 pandemic would be properly included. Comorbidities feature prominently in the mortality of COVID-19 patients and among the most important of these are those associated with air pollution. Various research papers have evidenced that poor air quality tends to increase mortality from COVID-19 cases. Therefore, social costs of poor air quality may be higher than estimated in this research.
- Air quality is, to a large extent, influenced by transportation habits which in turn are influenced by transport policies, both at the national and the city level. Hence governments have an important role to play here. Car possession and journey times to work tend to be positively correlated with higher levels of air pollution. The social costs should be taken into account by transport policy decisions affecting urban mobility and they can be assessed when calculating the transition of urban mobility from the internal

combustion engine to zero- and low emission alternatives, including e-mobility. The relationship between transport policies at the local level and air pollution should be investigated in more detail in future research. Transport policies improving air quality can have co-benefits for public health if they stimulate increased physical activity such as walking or cycling.

- The present analysis is based on reported air quality. In general we also observe that much could be improved with respect to the monitoring of air quality: some large European cities have only a limited number of monitoring stations. Without a good network of monitoring stations, air pollution may seriously be underestimated and social costs determined in this study may be even modest. Therefore our final recommendation is to improve the monitoring network so that a more accurate relationship between human health and air pollution can be assessed.

Literature

Badyda, A. J., Grellier, J. & Dąbrowiecki, P. 2017. Ambient PM2.5 Exposure and Mortality Due to Lung Cancer and Cardiopulmonary Diseases in Polish Cities. *In:* Pokorski, M. (ed.) *Respiratory Treatment and Prevention.* Cham: Springer International Publishing.

Bañeras, J., Ferreira-González, I., Marsal, J. R., Barrabés, J. A., Ribera, A., Lidón, R. M., Domingo, E., Martí, G. & García-Dorado, D. 2018. Short-term exposure to air pollutants increases the risk of ST elevation myocardial infarction and of infarct-related ventricular arrhythmias and mortality. *International Journal of Cardiology,* 250**,** 35-42.

Barbier, E. B., Czakowsky, M. & Hanley, N. 2015. Is the income elasticity of the willingnes to pay for pollution control constant.

Bell, M. L., Davis, D. L. & Fletcher, T. 2004. A retrospective assessment of mortality from the London smog episode of 1952: the role of influenza and pollution. *Environmental health perspectives,* 112**,** 6-8.

Beták, J., Šúri, M., Cebecauer, T. & Skoczek, A. 2012. Solar Resource and Photovoltaic Electricity Potential in EU-MENA Region. Bratislava: SolarGIS.

CE Delft 2018a. Health impacts and costs of diesel emissions in the EU. Delft: CE Delft.

CE Delft 2018b. Environmental Prices Handbook EU28 version : Methods and numbers for valuation of environmental impacts. Delft: CE Delft.

CE Delft 2020. Further explanation of methods used for monetizing impacts from air pollution Delft: CE Delft.

CE Delft, INFRAS, TRT & Ricardo 2019. Handbook on the external costs of transport - version 2018. Delft: CE Delft.

COMEAP 2015. Statement on the evidence for the effects of nitrogen dioxide on health. Chilton: Committee on the Medical Effects of Air Pollutants (COMEAP).

COMEAP 2018. Associations of long-term average concentrations of nitrogen oxide with mortality. Chilton: Committee on the Medical Effects of Air Pollutants (COMEAP).

De Bruyn, S. M. 2000. *Economic growth and the environment : an empirical analysis,* Boston, Kluwer Academic Publishers.

De Jesus, A. L. & al., e. 2019. Ultrafine particles and PM2.5 in the air of cities around the world: Are they representative of each other? *Environmental International,* 129**,** 118-135.

Donaire-Gonzalez, D., Huss, A., Hoek, G. & Vermeulen, R. 2019. Effects of ultrafine particles on respiratory health in adults. *Environmental Epidemiology,* 3**,** 102.

EC 2011. Commission Staff Working Paper establishing guidelines for demonstration and subtraction of exceedances attributable to natural sources under the Directive 2008/50/EC on ambient air quality and cleaner air for Europe Brussels.

EEA 2010. Good practice guide on noise exposure and potential health effects. Copenhagen: European Environment Agency (EEA).

EPA 2016. Integrated Science Assessment for Oxides of Nitrogen - Health Criteria. North Carolina: Environmental Protection Agency (EPA).

Fang, D., Wang, Q. g., Li, H., Yu, Y., Lu, Y. & Qian, X. 2016. Mortality effects assessment of ambient PM2.5 pollution in the 74 leading cities of China. *Science of the Total Environment,* 569-570, 1545-1552.

Finnish Institute for Occupational Health 2016. 149. Diesel Engine Exhaust. Gothenburg: Nordic Expert Group & Dutch Expert Committee on Occupational Safety

Garrett, P. & Casimiro, E. 2011. Short-term effect of fine particulate matter (PM2.5) and ozone on daily mortality in Lisbon, Portugal. *Environmental Science and Pollution Research,* 18, 1585-1592.

HEI 2018. State of Global Air. Boston: Boston: Health Effects Institute (HEI).

Hoevenagel, R. 1994. The contingent valuation method : scope and validity. Amsterdam: Free University.

Hubbell, B. J. 2006. Implementing QALYs in the Analysis of Air Polution Regulations. *Environmental &Resource Economics,* 34, 365-384.

ICCT 2019. A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015. he International Council on Clean Transportation (ICCT.

Jonson, J., Borken-Kleefeld, J., Simpson, D., Nyiri, A., Posch, M. & Heyes, C. 2017. Impact of excess NO x emissions from diesel cars on air quality, public health and eutrophication in Europe. *Environmental Research Letters,* 12.

Kiesewetter, G. & Amann, M. 2014. Urban PM2.5 levels under theEU Clean Air Policy Package. TSAP Report #12. Version 1.0. . International Institute for Applied Systems Analysis IIASA.

King's College 2015. Understanding the Health Impacts of Air Pollution in London. London King's College.

Lammers, A., Janssen, N. A. H., Boere, A. J. F., Berger, M., Longo, C., Vijverberg, S. J. H., Neerincx, A. H., Maitland-van der Zee, A. H. & Cassee, F. R. 2020. Effects of short-term exposure to ultrafine particles near an airport in healthy subjects. *Environment International,* 141.

Lavigne, E., Donelle, J., Hatzopoulou, M., Van Ryswyk, K., Van Donkelaar, A., Martin, R. V., Chen, H., Stieb, D. M., Gasparrine, A., Crighton, E., et al. 2019. Spatiotemporal variations in ambient ultrafine particles and the incidence of childhood asthma. *American Journal of Respiratory and Critical Care Medicine,* 199, 1487-1495.

Lelieveld, J., Klingmüller, K., Pozzer, A., Pöschl, U., Fnais, M., Daiber, A. & Münzel, T. 2019. Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions. *European Heart Journal,* 40, 1590-1596.

Martinez, G. S., Spadaro, J., Chapizanis, D., Kendrovski, V., Kochubovski, M. & Mudu, P. 2018. Health Impacts and Economic Costs of Air Pollution in the Metropolitan Area of Skopje. *International Journal of Environmental Research and Public Health,* 15, 626.

NEEDS 2008a. NEEDS deliverable No 1.1.-RS 3a Report on the procedure and data to generate averaged/aggregated data. Priority 6.1 (...) Sub-priority 6.1.3.2.5: Socio-economic tools and cencepts for energy strategy. Brussels: European Commission.

NEEDS 2008c. NEEDS deliverable 6.7 Final report on the monetary valuation of mortality and morbidity risks from air pollution. Priority 6.1 (...) Sub-priority 6.1.3.2.5.: Socio-economic tools and concepts for energy strategy. Brussels: European Commission.

OECD 2012. The value of statistical life : a meta analysis ENV/EPOC/WPNEP(2010)9/FINAL, version 30-Jan-2012. Paris: OECD.

Ohlwein, S., Kappeler, R., Joss, M. K., Künzli, N. & Hoffmann, B. 2019. Health effects of utlrafine particles: a systematic literature review update of epidemiological evidence. *International Journal of Public Health,* 64, 547-559.

Rabl, A., Spadaro, J. V. & Holland, M. 2014. How Much Is Clean Air Worth?: Calculating the Benefits of Pollution Control. Cambridge: Cambridge University Press.

Ready, R., Malzubris, J. & Senkane, S. 2002. The relationship between environmental values and income in a transition economy: Surface water quality in Latvia. *Environment and Development Economics,* 7, 147-156.

RIVM. 2013. *Roet als extra indicator voor de nadelige gezondheidseffecten van deeltjes naast PM10 en PM2.5* [Online]. RIVM. Available: http://slideplayer.nl/slide/2211029/ [Accessed May 2018].

Rizza, V., Stabile, L., Vistocco, D., Russi, A., Pardi, S. & Buonanno, G. 2019. Effects of the exposure to ultrafine particles on heart rate in a healthy population. *Science of the Total Environment*, 2403-2410.

Schraufnagel, D. E. 2020. The health effects of ultrafine particles. *Experimental & Molecular Medicine*, 1-7.

TNO, FACIT, VTT, GRAZ, T., PTV, DAI, CLU, VCC, SAFER, UNIS, et al. 2014. Impact assessment and user perception of cooperative systems : D11.4 of the Drive C2X project. Delft: TNO.

UBA 2019. Methodenkonvention 3.0 zur Ermittlung von Umweltkosten - Kostensätze Stand 02/2019. Dessau Roßlau: Umweltbundesamt (UBA).

Vlachokostas, C., Achillas, C., Moussiopoulos, N., Kalogeropoulos, K., Sigalas, G., Kalognomou, E.-A. & Banias, G. 2012. Health effects and social costs of particulate and photochemical urban air pollution: a case study for Thessaloniki, Greece. *Air Quality, Atmosphere & Health,* 5, 325-334.

Weichenthal, S., Olaniyan, T., Christidis, T., Lavigne, E., Hatzopoulou, M., Van Ryswyk, K., Tjepkema, M. & Burnett, R. 2020. Within-city spatial variations in ambient ultrafine particle concentrations and incident brain tumors in adults. *Epidemiology* 31, 177-183.

WHO 2012. Health effects of black carbon. Geneva: Health effects of black carbon.

WHO 2013. Health risks of air pollution in Europe – HRAPIE project. Recommendations for concentration-response functions for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide. Geneva: World Health Organization (WHO).

WHO Europe. 2018. *Over half a million premature deaths annually in the European Region attributable to household and ambient air pollution* [Online]. Available: http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/news/news/2018/5/over-half-a-million-premature-deaths-annually-in-the-european-region-attributable-to-household-and-ambient-air-pollution [Accessed 2020].

A Description of data

A.1 Pollution data

We have used two sources of data for annual concentration means in cities and merged these:

1. Source: Urban Audit Data, Eurostat.

Data availability in 2013:
- 373 cities with PM_{10} data;

Of these:
- 329 cities with NO_2 data;
- 311 cities with O_3 data.

2. Source: [Air quality statistics, European Environment Agency]

Data availability in 2018:
- 556 cities with PM_{10} data;

Of these:
- 521 cities with NO_2 data in 2018;
- 435 cities with O_3 data in 2018;
- 387 cities with $PM_{2.5}$ data in 2018.

We combined both datasets using an average of all monitoring stations in (2), so that:
- For PM_{10}: 372 cities with data from (1), adjusted to 2018 level using the difference in 2013 and 2018 average from all monitoring stations in a city from (2), and 60 cities using an average of monitoring stations from (2). The corresponding values are annual means of µg/m^3/year.
- For NO_2: 329 cities with data from (1), adjusted to 2018 level using the difference in 2013 and 2018 average from all monitoring stations in a city from (2), and 103 cities using an average of monitoring stations from (2). The corresponding values are annual means of µg/m^3/year.
- For O_3: the unit of measurement differs between (1) and (2). After ample considerations, it was found that the unit of measurement of (2) was more in line with the recommended CRFs from WHO, so we took for O_3 for 432 cities an average from all monitoring stations from (2). The corresponding values are µg/m^3/day converted to µg/m^3/year.
- For $PM_{2.5}$, no data have been reported in (1), so we took for 432 cities an average of all monitoring stations from (2) to create a single data point for each city.

For cities for which PM_{10} was available, but $PM_{2.5}$ was not, the $PM_{2.5}$ data have been imputed based on the average share of $PM_{2.5}$ in PM_{10}. This share is calculated as an average based on the cities for which both data points were available in 2018. The result of this calculation is an average share of 0.62 $PM_{2.5}$ in PM_{10}, with a standard deviation of 0.12.

Some commentators asked us if we could adjust a correction figure for cities in central European countries that may underreport their levels of pollution. However, such corrections go beyond the scope of the present report that deals with reported levels of air quality.

A.2 Population data

Source: Population on 1 January by age groups and sex – cities and greater cities, City statistics, Eurostat: Population on 1 January by age groups and sex - cities and greater cities

For each city (usually grouped by country) the recorded year of data is chosen based on completeness of data for the cities in the database. The result is a variety of years from which population data is included for the health cost calculations. For each city, the year from which population data is used is indicated in the dataset.

The following age cohorts were available: 0-4; 5-9; 10-14; 15-19; 20-24; 25-34; 35-44; 45-54; 55-64; 65-74; 75+. In the health cost calculations, where a fraction of an age cohort was needed, a proportional share of the relevant age group is used (e.g. infants aged 0-1 are 20% of the age cohort 0-4).

The following adjustments have been made to the population data in order to fill the gaps:
- German cities: the number of inhabitants aged 0-4 is deduced from total population minus all other age cohorts, as cohort 0-4 was the only one missing.
- Norway, cities Trondheim, Bergen, Oslo: the number of inhabitants aged 0-4 is deduced from total population minus all other age cohorts, as cohort 0-4 was the only one missing.
- Geneva: age cohorts 55-64; 20-24; 25-34; 35-44; 45-54 are calculated based on the average share of these age cohorts in the total population in the other Swiss cities available in the database.
- France: for all French cities the total population has been sourced from the following website due to inaccuracy of the Eurostat data: City Population.
- Subsequently, the age cohorts have been determined based on the average share of these cohorts in the total population in the Eurostat data available in the database.
- Iceland: for Reykjavik, population data for all age cohorts and total population are sourced from the following website: Statistics Iceland: Municipalities and urban nuclei (Statistics Iceland).

A.3 Economically active population data

Source: Labour market — cities and greater cities, City statistics, Eurostat

For each city, the same recorded year of data is used as was used for the population statistics. Two statistics are recorded for each city: total economically active population and the economically active population aged 20-64. The latter is used in the health cost calculations.

The following adjustments have been made to the economically active population data to fill the gaps:
- Czech Republic: Total economically active population used instead of economically active population aged 20-64.
- All cities in Romania, Poland, Norway, Luxembourg, Iceland: no data for economically active population is available. These are filled with the average share of labour force in total population, as calculated from World Bank data, applied to the total population from Eurostat.
- Source: Labor force, total, World Bank
- Source: Population, total, World Bank
- The same data is used to calculate average shares of economically active population in the total population for the UK and Germany, in order to estimate the economically

active population in the following cities: Düren (DE), Bocholt (DE), Belfast (UK), Derry and Strabane (UK).

A.4 GDP data

Source: Gross domestic product (GDP) at current market prices by metropolitan regions

The most recent data has been compiled, namely for each city the year 2016. The unit of measurement is GDP in purchasing power standard (PPS). For cities with missing data, the national average GDP in PPS of the relevant country is used as estimation. Moreover, the GDP in PPS for the EU is recorded in order to relate the city GDP to the EU average.

A.5 List of cities included in this research

The following table gives a list of cities or urban areas that have been included in the present research.

Austria	**Czech Republic (cont.)**	**France(cont.)**
Graz	Ostrava	Brest
Innsbruck	Pardubice	Brive-la-Gaillarde
Klagenfurt	Plzen	Caen
Linz	Praha	Calais
Salzburg	Ústí nad Labem	Châlons-en-Champagne
Wien	Zlín	Chalon-sur-Saône
Belgium	**Denmark**	Chambéry
Antwerpen	Århus	Charleville-Mézières
Bruxelles / Brussel	København	Chartres
Charleroi	Odense	Châteauroux
Gent	**Estonia**	Cherbourg
Liège	Narva	Clermont-Ferrand
Mons	Tallinn	Colmar
Bulgaria	Tartu	Creil
Burgas	**Finland**	Dijon
Plovdiv	Helsinki/Helsingfors	Douai
Ruse	Kuopio	Dunkerque
Shumen	Lahti/Lahtis	Evreux
Sofia	Oulu	Fréjus
Stara Zagora	Tampere/Tammerfors	Grenoble
Varna	**France**	La Rochelle
Vratsa	Aix-en-Provence	Le Havre
Croatia	Ajaccio	Le Mans
Osijek	Albi	Lens - Liévin
Zagreb	Amiens	Lille
Cyprus	Angers	Limoges
Lefkosia	Angoulême	Lorient
Czech Republic	Annecy	Lyon
Brno	Annemasse	Marseille
Ceské Budejovice	Arras	Martigues
Hradec Králové	Avignon	Melun
Jihlava	Bayonne	Metz

Karviná	Besançon	Montbéliard
Kladno	Bordeaux	Montpellier
Liberec	Boulogne-sur-Mer	Mulhouse
Most	Bourges	Nancy

France(cont.)	Germany (cont.)	Germany (cont.)
Nantes	Frankfurt (Oder)	Rostock
Nice	Frankfurt am Main	Saarbrücken
Nîmes	Freiburg im Breisgau	Schweinfurt
Niort	Friedrichshafen	Solingen
Orléans	Fulda	Stuttgart
Paris	Gera	Tübingen
Pau	Göttingen	Ulm
Perpignan	Halle an der Saale	Villingen-Schwenningen
Poitiers	Hamburg	Wetzlar
Quimper	Hanau	Wiesbaden
Reims	Hannover	Wolfsburg
Rennes	Heidelberg	Wuppertal
Roanne	Heilbronn	Würzburg
Rouen	Jena	**Greece**
Saint-Brieuc	Kaiserslautern	Athina
Saint-Etienne	Karlsruhe	Pátra
Saint-Nazaire	Kassel	**Hungary**
Saint-Quentin	Kiel	Budapest
Strasbourg	Koblenz	Debrecen
Tarbes	Köln	Győr
Toulon	Konstanz	Pécs
Toulouse	Krefeld	**Ireland**
Tours	Leipzig	Cork
Troyes	Leverkusen	Dublin
Valence	Lübeck	**Italy**
Germany	Ludwigsburg	Ancona
Aachen	Ludwigshafen am Rhein	Asti
Augsburg	Lüneburg	Avellino
Berlin	Magdeburg	Bari
Bielefeld	Mainz	Barletta
Brandenburg an der Havel	Marburg	Bergamo
Braunschweig	Mönchengladbach	Bologna
Bremen	Mülheim a.d.Ruhr	Bolzano
Bremerhaven	München	Brescia
Chemnitz	Münster	Busto Arsizio
Cottbus	Neu-Ulm	Cagliari
Darmstadt	Nürnberg	Campobasso
Dortmund	Osnabrück	Catanzaro
Dresden	Pforzheim	Cosenza
Düsseldorf	Plauen	Cremona
Erfurt	Potsdam	Ferrara
Essen	Reutlingen	Forlì

Italy (cont.)	Lithuania	Poland (cont.)
Genova	Kaunas	Pabianice
La Spezia	Klaipeda	Piotrków Trybunalski
Latina	Panevezys	Plock
Lecce	Siauliai	Poznan
Lecco	Vilnius	Przemysl
Messina	**Luxembourg**	Radom
Milano	Luxembourg	Rybnik
Modena	**Malta**	Rzeszów
Napoli	Valletta	Slupsk
Novara	**Netherlands**	Szczecin
Padova	Breda	Tarnów
Palermo	Amsterdam	Torun
Parma	Eindhoven	Walbrzych
Pavia	Haarlem	Warszawa
Perugia	Heerlen	Wroclaw
Pesaro	Rotterdam	Zielona Góra
Pescara	's-Gravenhage	**Portugal**
Piacenza	Greater Utrecht	Coimbra
Pisa	Groningen	Faro
Ravenna	Nijmegen	Funchal
Reggio di Calabria	**Norway**	Lisboa
Reggio nell'Emilia	Bergen	Porto
Rimini	**Poland**	Setúbal
Roma	Bialystok	Sintra
Salerno	Bielsko-Biala	**Romania**
Sassari	Bydgoszcz	Alba Iulia
Savona	Czestochowa	Arad
Siracusa	Elblag	Baia Mare
Taranto	Elk	Bistrita
Terni	Gdansk	Botosani
Torino	Gdynia	Brasov
Trento	Gorzów Wielkopolski	Bucuresti
Treviso	Jelenia Góra	Calarasi
Trieste	Kalisz	Cluj-Napoca
Udine	Konin	Craiova
Varese	Kraków	Focsani
Venezia	Legnica	Galati
Verona	Lódz	Giurgiu
Vicenza	Lublin	Iasi
Latvia	Metropolia Silesia	Oradea
Liepaja	Olsztyn	Pitesti
Riga	Opole	Ploiesti

Romania (cont.)	**Spain (cont.)**	**United Kingdom (cont.)**
Râmnicu Vâlcea	Ourense	Greater Manchester
Satu Mare	Oviedo	Greater Nottingham
Suceava	Palencia	Kingston-upon-Hull
Timisoara	Palma de Mallorca	Leeds
Slovakia	Pamplona/Iruña	Leicester
Banská Bystrica	Pontevedra	London (greater city)
Bratislava	Salamanca	Norwich
Kosice	San Sebastián/Donostia	Plymouth
Nitra	Santa Cruz de Tenerife	Portsmouth
Zilina	Santander	Reading
Slovenia	Santiago de Compostela	Sheffield
Ljubljana	Talavera de la Reina	Stoke-on-trent
Maribor	Telde	Thurrock
Spain	Toledo	Tyneside conurbation
A Coruña	Torrejón de Ardoz	Warwick
Albacete	Valencia	West Midlands urban area
Alcalá de Henares	Valladolid	
Alcobendas	Vigo	
Alicante/Alacant	Zamora	
Arrecife	Zaragoza	
Avilés	**Sweden**	
Badajoz	Göteborg	
Barcelona	Lund	
Bilbao	Malmö	
Cáceres	Stockholm	
Cartagena	**Switzerland**	
Ciudad Real	Basel	
Coslada	Bern	
Elda	Genève	
Ferrol	Lausanne	
Gandia	Lugano	
Getafe	St. Gallen	
Gijón	Winterthur	
Guadalajara	Zürich	
Jerez de la Frontera	**United Kingdom**	
Leganés	Aberdeen City	
León	Belfast	
Logroño	Bristol	
Lugo	City of Edinburgh	
Madrid	Coventry	
Majadahonda	Derry & Strabane Local Government District	
Móstoles	Greater Glasgow	

B The impact-pathway framework

B.1 Indicators of physical incidence[14]

Health impacts from air pollution are usually expressed using a physical indicator expressing the number of life years (mortality) or certain quality of life (morbidity) 'lost'. The most commonly indicators used are: YOLL, DALY and QALY.[15] Table 15 provides a brief explanation of each indicator.

Table 15 - Indicators for human health impacts

Indicator	Meaning	Explanation	Used for environmental impacts in:
YOLL	Years of Lost Life	Number of years of life lost due to premature mortality	NEEDS, IIASA-TSAP, CAFE-CBA
DALY	Disability-Adjusted Life Years	Number of years of life lost due to impaired health	ReCiPe
QALY	Quality-Adjusted Life Years	Number of years of perfect health	Certain individual studies (e.g. Hubbell, 2006)

With these indicators, mortality is expressed in 'number of life years lost'. Morbidity (illness) is normally also expressed in these indicators using a conversion table in which illness and disability are expressed as partial mortality, as in Hubbell (2006) for the QALY framework, for example. Generally speaking, morbidity is more usually expressed in QALYs rather than DALYs or YOLL. Studies employing YOLL, such as NEEDS (2008a)often use the QALY framework for valuing the relative disease burden.[16]

YOLL, DALY and QALY essentially each measure a different aspect of health impacts. All the main European studies on the social costs of air pollution have adopted YOLL for premature mortality, with morbidity valued separately using the QALY framework. The reasoning is that the YOLL framework is more congruent with the actual action of environmental pollution, which tends to shorten life span, particularly through respiratory and cardiovascular disease towards the end of a person's life. YOLL then most accurately reflects mortality impacts. DALY and particularly QALY are used more in the realm of health care.

B.2 Valuation of impacts

All three indicators in Table 14 are quantified in 'years'. For use in SCBA, in the CSR context or for final weighting in LCAs they therefore need to be assigned a monetary value. The valuation methods most often used for this purpose are the VSL (Value of a Statistical Life) and VOLY (Value Of a Life Year) frameworks. The former is often used in the context

[14] This section is taken from CE Delft 2018b. Environmental Prices Handbook EU28 version : Methods and numbers for valuation of environmental impacts. Delft: CE Delft.
[15] YOLL is sometimes also expressed in LYL (Life Years Lost).
[16] Here the assumption is made that 1 additional YOLL equals the loss of 1 QALY. For more information see Annex B in the Dutch language version.

of transport policy, but also in health-care and environmental settings. OECD (2012)has carried out a meta-analysis of valuation using VSL. The results show that the median value of VSL for valuing the health impacts of pollution is around € 2.5 million. In NEEDS (2008c)it is rightly stated that, in the air-pollution context at any rate, mortality valuation via VOLY is better than via VSL, for the following reasons:

1. Air pollution can rarely be identified as the primary cause of an individual death, only as a contributing factor.
2. VSL makes no allowance for the fact that the loss of life expectancy through death is far less for mortality associated with air pollution than for typical accidents (30-40 years), the figure on which the VSL calculations are based. In other words, the main mortality impact of air pollution occurs later in life, while accidents are more likely to occur at an earlier stage.

For this reason, in the NEEDS project the indicator VOLY is used for valuing the mortality impacts of air pollution. This Value Of a Life Year is the value assigned to a life year on the basis of estimated life expectancy. It can be calculated using stated or revealed preferences.

Valuation of specific impacts can be found in Table 2 of this report.

B.3 Mortality impacts

For all-cause mortality of $PM_{2.5}$ and NO_2 and acute mortality of O_3, we use relative risks from WHO (2013). Table 16 gives information on the relative risks used in this research.

Table 16 - Relative risks used in this research for mortality from air pollution

Substance	Cause	Impact	Age Group	RR per 10ug/m^3	*Beta per ug/m^3*
$PM_{2.5}$	Chronic	A	30+	1.062	0.0062
$PM_{2.5}$	Acute	A	30+	1.0123	0.00123
O_3	Acute	B	All	1.0029	0.00029
NO_2	Chronic	B	All	*1.0076*	0.00076

For $PM_{2.5}$ and O_3, the relative risks have been taken from WHO (2013). For NO_2,WHO (2013) presents an RR of 1.055 per 10ug/m^3 for concentrations levels exceeding 20 ug/m^3 for adults aged 30+ but warns against double counting with all-cause mortality of $PM_{2.5}$ when both impacts are taken into account. In CE Delft et al. (2019)we have translated this into a specific concentration response function for NO_2 alone correcting for eventual double counting. In CE Delft (2020)this is further explained and a link with the recent research on NO_2 mortality from COMEAP (2018) is made where the majority of the members suggested a RR for all-cause mortality for all age groups and all concentration levels between 1,006 and 1,013.[17] In CE Delft (2020)it is calculated that a specific value of 1.00764 would be within

[17] One should notice that the authors of the COMEAP study did not reach agreement on the inclusion of the valuation of NO_2 next to $PM_{2.5}$. They state: "*We explored several approaches to account for possible confounding of the NO_2 mortality associations by associations of mortality with $PM_{2.5}$. However, we concluded that none of these potential approaches was appropriate and we have decided against formally deriving an NO_2 coefficient adjusted for effects associated with $PM_{2.5}$. Instead we have applied our judgement, informed by the available evidence, to propose a reduced coefficient which may be used to quantify the mortality benefits of reductions in concentrations of NO_2 alone, where this is necessary*". On quantification, this study suggest, very

the range suggested by the COMEAP (2018) study and is the implicit used value in the Handbook of External Costs of Transport (CE Delft et al., 2019). Therefore we use here this value.

From the RR values from the WHO (2013) we derive a so called beta, which presents the additional risk of dying from one microgram/m^3 increase in pollution concentration.

The following formula is used to estimate the YOLL (years of life lost) from a certain concentration in a city for a given pollutant:

$$YOLL_i = AF_i * POP * AGF * INC * AYL$$

In which *i* is the pollutant for which the YOLL is calculated, AF *is the Attributable Fraction,* POP the population in a city, AGF the Age group fraction (e.g. for $PM_{2.5}$ mortality the share of population above 30 years old), INC the incidence rate (the “natural mortality rate of the population”) and AYL the Average Years Lost, the average life years lost from somebody dying from air pollution. Below we explain some of these elements in more detail:

1. AF is the attributable fraction which is the proportion of incidents in the population that are attributable to the risk factor. This depends on the $ß_i$ (which are listed in Table 16) and the concentration in a city and can be determined in the epidemiology literature by the following formula:

$$AF_i = \frac{e^{\beta_i * CONC_i - 1}}{e^{\beta_i * CONC_i}}$$

Because the concentration level differs between cities, each city has a unique attributable fraction.

2. The Population data have been used at the level of individual cities.

3. The incidence rates have been taken from EEA (2019) and presented as the number of natural deaths occurring for the particular age group per 100,000 inhabitants. The incidence rates have been established at the level of individual countries, not cities. Of course, incidence rate is higher in the 30+ age group than in the whole age group.

4. The AYL is taken from EEA (2010) and is for all air pollutants set at 10.3 years.

The YOLLs have been valued using the values of Table 2 and an income elasticity of 0.8. In other words, the total social costs for a specific pollutant *i* in a city *j* was calculated as follows follows:

$$SC_{i,j} \approx YOLL_{ij} \cdot \left(\frac{GDP_j}{GDP_{EU28}}\right)^{0.8}$$

carefully, that one may consider as a reduced coefficient an all-cause RR of 1,006 to 1,013 per 10 µg/m^3 of NO_2 for estimating the effects attributable to NO_2 alone without thresholds or age groups. We have calculated what it would mean if we would not have used thresholds or age groups: in that case the CRF that we used would be based on a RR of 1.00764 per 10ug/m^3, so in the lower range of the COMEAP (2018) reduced coefficient. We have therefore used this coefficient for the entire population for any given concentration of NO2 in our city sample.

NB: The default assumption is that the income elasticity of WTP is 1. However, several studies suggest that it is typically smaller than 1 and often in the 0.4-0.7 range (Rabl et al., 2014).[18] An extensive meta-analysis of the OECD, however, comes at higher values and concludes that the income elasticity for the WTP of environmental and health related goods falls between 0.7 and 0.9. On the basis of this research, the handbook of external costs for the European Commission (DG Move) has suggested an income elasticity of 0.8 (CE Delft et al., 2019).

B.4 Impact tables and adjustments to NEEDS

The morbidity endpoints have been valued in accordance with the DG Move Handbook (CE Delft et al., 2019) using so-called lifetables.

For each morbitidy endpoint, the formula for physical impact is as follows:

PhysImp = CRF × AGF × RGF

The external cost is then calculated as follows:

External cost = PhysImp × {MonVal × ([city GDP/EU GDP]^IE)} × Pollutant factor

PhysImp = physical impact, 1/µg/m^3
CRF = Concentration response function, 1/µg/m^3
AGF = Age group factor, city specific
RGF = Risk group factor, endpoint specific
MonVal = Monetary value, endpoint specific, per case or per YOLL
City GDP = GDP PPP per city
EU GDP = GDP PPP average EU
IE = Income Elasticity
Pollutant factor = factor to convert concentration to damage cost, pollutant specific.

This calculation has been done for each city.

The Impact Table can now be given in Figure 3.

[18] Furthermore, literature indicates that WTP varies with income. For example, Barbier, E. B., Czakowsky, M. & Hanley, N. 2015. Is the income elasticity of the willingnes to pay for pollution control constant. Estimated an income elasticity of the WTP for eutrophication control of 0.1–0.2 for low-income respondents and 0.6–0.7 for high-income respondents. This result is consistent with earlier findings Ready, R., Malzubris, J. & Senkane, S. 2002. The relationship between environmental values and income in a transition economy: Surface water quality in Latvia. *Environment and Development Economics,* 7, 147-156.

Figure 3 - The Impact Table

Core morbidity endpoints	pollutant	risk group (RG)	RGF value	Age Group (AG)	AGF value	Factor	CRF [1/ug/m3]	phys. Impact per person per ug per m3 [1/ug/m3]	unit
Primary and SIA < 2.5 i.e. Particle < 2,5 um									
netto Restricted activity days (netRADs)	PM2.5	all	1	MIX	1	1	9.59E-03	9.59E-03	days
Work loss days (WLD)	PM2.5	all	1	Beroepsbevolking	0.4914113	1	2.07E-02	1.02E-02	days
Minor restricted activity days (MRAD)	PM2.5	all	1	Adults_18_to_64_years	0.6479405	1	5.77E-02	3.74E-02	days
Primary and SIA < 10 i.e. Particle < 10 um									
Increased mortality risk (infants)	PM10	infants	0.0019	Total	0.0101530	1	4.00E-03	7.72E-08	cases
New cases of chronic bronchitis	PM10	all	1	Adults_18andAboves	0.8179649	1	4.51E-05	3.68E-05	cases
respiratory hospital admissions	PM10	all	1	Total	1	1	7.03E-06	7.03E-06	cases
cardiac hospital admissions	PM10	all	1	Total	1	1	4.34E-06	4.34E-06	cases
medication use/bronchodilator use	PM10	Childrenv	0.045	Children_5_to_14	0.0919272	1	4.76E-03	1.97E-05	cases
Ozone [ug/m3] - from SOMO35									
CVD and respiratory hospital admissions	SOMO35	all	1	Elderly_65andAbove	0.1700244	1	3.43E-05	5.82E-06	cases
MRAD	SOMO35	all	1	Adults_18_to_64_years	0.6479405	1	1.15E-02	7.45E-03	days
Prevalence of bronchitis in asthmatich children	NO2	all	0.045	Children_5_to_14	0.0919272	1	5.25E-03	2.17E-05	cases
Hospital admissions due to respiratory diseases	NO2	all	1	Total	1	1	1.11E-05	1.11E-05	cases

- In green are the impacts that have been adjusted or added in the DG Move Handbook compared to the NEEDS impacts (CRFs and RGF).
- In orange are the age group values that differ for each city based on life cohorts from Eurostat at the city level. In case of missing data country averages have been taken. The orange cells are thus unique for each city.

B.5 More information

More information on the method used in calculating the environmental prices can be found in CE Delft (2018b) and CE Delft (2020)which are public source information documents on the CE Delft website.

C City results per country

The tables below provide the results per country. For city GDP we have used Eurostat Urban Audit data. If these data were not available we have used the country averages. Therefore GDP per capita (PPP) is only an approximation.

Austria

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Graz	€ 432 mln	€ 1,600	4.2%	19.27	22.11	25.64	16.10	269997 (2014)	€ 38,000	ac
Innsbruck	€ 141.1 mln	€ 1,133	2.8%	10.92	15.97	27.42	15.78	124579 (2014)	€ 40,000	
Klagenfurt	€ 117.2 mln	€ 1,213	3.2%	12.57	21.49	17.55	16.82	96640 (2014)	€ 38,000	ac
Linz	€ 286.1 mln	€ 1,476	3.6%	15.04	21.26	25.07	14.63	193814 (2014)	€ 41,000	ac
Salzburg	€ 226.4 mln	€ 1,544	3.2%	12.47	19.49	28.54	16.55	146631 (2014)	€ 49,000	
Wien	€ 2567.5 mln	€ 1,453	3.5%	15.89	20.73	17.85	19.69	1766746 (2014)	€ 41,000	ac

Belgium

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Antwerpen	€ 744.3 mln	€ 1,493	3.5%	14.24	23.48	26.16	6.85	498473 (2011)	€ 43,000	ac
Bruxelles / Brussel	€ 1585.8 mln	€ 1,395	3.0%	12.62	19.55	24.78	8.98	1136778 (2011)	€ 47,000	ac
Charleroi	€ 162.3 mln	€ 795	3.3%	11.86	19.35	21.93	12.20	204150 (2011)	€ 24,000	ac
Gent	€ 386.4 mln	€ 1,556	3.9%	15.06	27.50	29.11	9.19	248358 (2011)	€ 40,000	ac
Liège	€ 314.2 mln	€ 833	3.2%	10.74	19.44	25.33	13.94	377263 (2011)	€ 26,000	ac
Mons	€ 94.3 mln	€ 1,018	3.0%	10.84	18.32	26.23	9.74	92721 (2011)	€ 34,000	ac

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Bulgaria

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Burgas	€ 200.2 mln	€ 987	8.2%	20.12	32.30	12.96	8.53	202766 (2017)	€ 12,000	abc
Plovdiv	€ 354.8 mln	€ 1,033	8.6%	19.17	46.54	19.07	6.61	343424 (2017)	€ 12,000	ac
Ruse	€ 199.9 mln	€ 1,379	9.9%	24.14	38.87	20.05	12.51	144936 (2017)	€ 14,000	ac
Shumen	€ 92.9 mln	€ 1,208	8.6%	21.04	33.78	17.36	10.23	76967 (2017)	€ 14,000	abc
Sofia	€ 2575.3 mln	€ 2,084	7.7%	21.70	34.85	24.90	6.65	1236047 (2017)	€ 27,000	abc
Stara Zagora	€ 153.8 mln	€ 1,124	8.0%	21.28	22.24	15.91	3.40	136781 (2017)	€ 14,000	
Varna	€ 330.6 mln	€ 986	7.0%	15.94	26.98	24.27	13.24	335177 (2017)	€ 14,000	ac
Vratsa	€ 59 mln	€ 1,100	7.9%	18.21	29.25	20.39	7.67	53570 (2017)	€ 14,000	abc

Croatia

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Osijek	€ 135.5 mln	€ 1,288	7.2%	22.05	35.41	24.78	12.25	105236 (2017)	€ 18,000	b
Zagreb	€ 1312 mln	€ 1,635	6.5%	20.68	31.63	31.87	17.42	802701 (2017)	€ 25,000	

Cyprus

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Lefkosia	€ 222.4 mln	€ 929	3.7%	13.78	44.80	23.99	20.12	239277 (2011)	€ 25,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Czech Republic

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Brno	€ 485.3 mln	€ 1,281	5.1%	19.86	25.04	14.43	18.53	378965 (2011)	€ 25,000	ac
Ceské Budejovice	€ 101.9 mln	€ 1,088	4.2%	15.98	19.81	14.87	17.18	93620 (2011)	€ 26,000	ac
Hradec Králové	€ 120.3 mln	€ 1,287	5.0%	18.12	23.12	21.98	21.79	93490 (2011)	€ 26,000	a
Jihlava	€ 61.3 mln	€ 1,210	4.7%	18.66	21.75	12.40	18.77	50669 (2011)	€ 26,000	ac
Karviná	€ 113.4 mln	€ 1,927	7.4%	30.09	39.05	20.32	17.38	58833 (2011)	€ 26,000	ac
Kladno	€ 89.5 mln	€ 1,304	5.0%	18.98	27.45	15.90	20.35	68682 (2011)	€ 26,000	ac
Liberec	€ 122.8 mln	€ 1,203	4.6%	18.36	21.79	14.86	18.89	102005 (2011)	€ 26,000	ac
Most	€ 97.9 mln	€ 1,460	5.6%	21.65	31.28	21.53	18.39	67058 (2011)	€ 26,000	ac
Ostrava	€ 420.9 mln	€ 1,405	6.7%	25.49	34.12	19.63	19.12	299622 (2011)	€ 21,000	ac
Pardubice	€ 112.5 mln	€ 1,256	4.8%	18.30	24.63	15.92	17.26	89552 (2011)	€ 26,000	ac
Plzen	€ 176.8 mln	€ 1,057	4.4%	16.34	21.30	15.21	13.83	167302 (2011)	€ 24,000	ac
Praha	€ 2253.1 mln	€ 1,815	4.8%	19.15	25.58	21.15	17.92	1241664 (2011)	€ 38,000	ac
Ústí nad Labem	€ 118 mln	€ 1,252	4.8%	18.19	24.41	22.77	19.54	94258 (2011)	€ 26,000	ac
Zlín	€ 107.1 mln	€ 1,416	5.4%	21.63	25.97	13.66	17.89	75660 (2011)	€ 26,000	ac

Denmark

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Århus	€ 306.8 mln	€ 975	3.0%	12.70	22.42	18.68	9.12	314545 (2012)	€ 32,000	
København	€ 785.4 mln	€ 1,431	3.1%	12.91	26.30	23.43	7.20	549050 (2012)	€ 46,000	
Odense	€ 188 mln	€ 981	3.4%	14.28	22.94	13.82	12.14	191610 (2012)	€ 29,000	b

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Estonia

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Narva	€ 23.1 mln	€ 405	1.8%	5.43	12.91	4.40	0.00	57130 (2017)	€ 22,000	ac
Tallinn	€ 249.2 mln	€ 584	1.8%	6.13	13.07	5.29	0.00	426538 (2017)	€ 33,000	ac
Tartu	€ 44.8 mln	€ 481	2.2%	7.24	16.24	5.85	0.00	93124 (2017)	€ 22,000	ac

Finland

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Helsinki / Helsingfors	€ 493.7 mln	€ 777	1.9%	7.28	13.40	10.99	6.33	635181 (2017)	€ 42,000	ac
Kuopio	€ 50.4 mln	€ 428	1.3%	3.53	13.50	12.68	5.85	117740 (2017)	€ 32,000	
Lahti / Lahtis	€ 68.9 mln	€ 577	1.8%	5.19	16.83	15.43	5.18	119452 (2017)	€ 32,000	
Oulu	€ 105.9 mln	€ 528	1.6%	5.84	11.53	16.80	5.09	200526 (2017)	€ 32,000	
Tampere / Tammerfors	€ 117.3 mln	€ 514	1.8%	5.86	13.67	13.90	4.32	228274 (2017)	€ 29,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

France (1)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Aix-en-Provence	€ 133.8 mln	€ 939	3.0%	11.94	23.35	20.62	22.39	142482 (2017)	€ 31,000	ac
Ajaccio	€ 59.4 mln	€ 840	2.7%	11.95	19.19	14.52	15.01	70659 (2017)	€ 31,000	abc
Albi	€ 32.4 mln	€ 662	2.1%	9.12	14.65	13.68	12.99	48970 (2017)	€ 31,000	abc
Amiens	€ 86.7 mln	€ 647	2.7%	12.19	19.58	14.11	9.37	134057 (2017)	€ 24,000	abc
Angers	€ 85.3 mln	€ 558	2.2%	9.85	15.64	11.87	13.82	152960 (2017)	€ 25,000	ac
Angoulême	€ 28.1 mln	€ 672	2.2%	8.50	16.61	18.84	8.25	41740 (2017)	€ 31,000	ac
Annecy	€ 105.5 mln	€ 831	3.1%	12.07	18.22	24.53	17.28	126924 (2017)	€ 27,000	ac
Annemasse	€ 29.6 mln	€ 828	2.7%	10.99	17.62	20.17	19.15	35712 (2017)	€ 31,000	ac
Arras	€ 37.2 mln	€ 908	2.9%	13.06	20.97	15.36	13.26	41019 (2017)	€ 31,000	abc
Avignon	€ 78.5 mln	€ 854	2.8%	11.72	19.22	17.26	21.29	91921 (2017)	€ 31,000	ac
Bayonne	€ 37.8 mln	€ 737	2.4%	8.79	17.31	14.65	10.75	51228 (2017)	€ 31,000	ac
Besançon	€ 81.8 mln	€ 706	2.8%	12.06	16.21	20.71	20.65	115934 (2017)	€ 25,000	
Bordeaux	€ 185.1 mln	€ 728	2.4%	10.32	17.62	14.78	13.51	254436 (2017)	€ 30,000	ac
Boulogne-sur-Mer	€ 98.6 mln	€ 821	2.6%	12.78	19.41	7.81	6.65	120071 (2017)	€ 31,000	ac
Bourges	€ 40.6 mln	€ 628	2.0%	8.34	13.39	10.46	14.84	64551 (2017)	€ 31,000	abc
Brest	€ 70.1 mln	€ 501	2.0%	7.83	16.02	12.59	10.70	140064 (2017)	€ 25,000	ac
Brive-la-Gaillarde	€ 29.3 mln	€ 624	2.0%	8.47	13.61	13.67	13.12	46916 (2017)	€ 31,000	abc
Caen	€ 64.5 mln	€ 612	2.3%	8.91	17.12	20.12	9.07	105354 (2017)	€ 27,000	ac
Calais	€ 53.3 mln	€ 721	2.3%	9.76	22.88	13.58	8.24	73911 (2017)	€ 31,000	ac

Footnotes:

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

France (2)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Châlons-en-Champagne	€ 32.5 mln	€ 727	2.3%	10.23	16.42	13.24	13.43	44753 (2017)	€ 31,000	abc
Chalon-sur-Saône	€ 35 mln	€ 776	2.5%	11.00	13.63	18.37	18.56	45096 (2017)	€ 31,000	ac
Chambéry	€ 47.3 mln	€ 802	2.6%	10.43	16.29	22.34	16.76	58919 (2017)	€ 31,000	ac
Charleville-Mézières	€ 37.6 mln	€ 809	2.6%	11.43	18.36	15.40	12.58	46428 (2017)	€ 31,000	abc
Chartres	€ 28.2 mln	€ 730	2.4%	10.28	15.58	11.35	12.12	38578 (2017)	€ 31,000	ac
Châteauroux	€ 28.3 mln	€ 648	2.1%	9.24	14.84	9.36	14.42	43741 (2017)	€ 31,000	abc
Cherbourg	€ 59.7 mln	€ 754	2.4%	10.27	16.50	14.54	8.60	79200 (2017)	€ 31,000	abc
Clermont-Ferrand	€ 90.7 mln	€ 630	2.3%	9.76	14.04	16.81	15.10	143886 (2017)	€ 27,000	ac
Colmar	€ 62.5 mln	€ 904	2.9%	11.37	18.26	26.62	20.63	69105 (2017)	€ 31,000	abc
Creil	€ 29 mln	€ 814	2.6%	12.06	19.40	21.58	11.45	35657 (2017)	€ 31,000	ac
Dijon	€ 102.2 mln	€ 652	2.2%	8.43	16.74	15.38	18.37	156920 (2017)	€ 30,000	ac
Douai	€ 39.4 mln	€ 992	3.2%	14.92	20.85	16.03	12.85	39700 (2017)	€ 31,000	
Dunkerque	€ 68.2 mln	€ 781	2.9%	12.02	20.60	17.26	9.00	87353 (2017)	€ 27,000	ac
Evreux	€ 32.8 mln	€ 688	2.2%	9.48	15.23	14.45	12.74	47733 (2017)	€ 31,000	b
Fréjus	€ 52.1 mln	€ 990	3.2%	12.82	19.25	11.07	25.67	52672 (2017)	€ 31,000	
Grenoble	€ 120.1 mln	€ 758	2.6%	11.53	17.23	18.54	13.75	158454 (2017)	€ 29,000	ac
La Rochelle	€ 52.6 mln	€ 695	2.2%	9.04	18.40	9.51	12.17	75735 (2017)	€ 31,000	ac
Le Havre	€ 138.3 mln	€ 813	2.6%	10.51	19.96	20.10	10.74	170147 (2017)	€ 31,000	ac
Le Mans	€ 84.5 mln	€ 591	2.3%	9.41	15.30	12.04	12.43	142946 (2017)	€ 26,000	ac

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

France (3)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Lens - Liévin	€ 57.8 mln	€ 929	3.0%	13.52	21.71	17.18	10.63	62200 (2017)	€ 31,000	abc
Lille	€ 206.2 mln	€ 886	3.3%	14.78	22.27	24.37	10.25	232787 (2017)	€ 27,000	ac
Limoges	€ 69 mln	€ 522	2.1%	8.07	11.87	16.60	13.76	132175 (2017)	€ 25,000	ac
Lorient	€ 38.9 mln	€ 681	2.2%	9.37	15.05	10.94	10.38	57149 (2017)	€ 31,000	abc
Lyon	€ 585.3 mln	€ 1,134	2.8%	12.37	18.49	28.26	15.71	516092 (2017)	€ 41,000	ac
Marseille	€ 774.1 mln	€ 897	3.2%	12.49	22.26	23.69	21.54	863310 (2017)	€ 28,000	ac
Martigues	€ 44.7 mln	€ 928	3.0%	11.64	22.07	15.69	26.66	48188 (2017)	€ 31,000	ac
Melun	€ 40.6 mln	€ 1,015	3.3%	14.12	24.79	30.50	10.27	40032 (2017)	€ 31,000	
Metz	€ 105.7 mln	€ 907	2.9%	12.46	19.85	20.23	14.74	116429 (2017)	€ 31,000	ac
Montbéliard	€ 21.6 mln	€ 849	2.7%	11.18	19.66	19.03	20.84	25395 (2017)	€ 31,000	ac
Montpellier	€ 180.3 mln	€ 632	2.4%	10.36	12.56	23.18	18.54	285121 (2017)	€ 26,000	ac
Mulhouse	€ 86.6 mln	€ 791	3.2%	12.84	18.25	24.55	19.58	109443 (2017)	€ 25,000	ac
Nancy	€ 65.1 mln	€ 624	2.6%	10.79	16.52	19.89	14.67	104286 (2017)	€ 24,000	ac
Nantes	€ 216 mln	€ 698	2.3%	10.12	14.64	14.38	12.33	309346 (2017)	€ 31,000	ac
Nice	€ 383.4 mln	€ 1,128	3.6%	12.53	25.19	36.25	19.86	340017 (2017)	€ 31,000	
Nîmes	€ 84.2 mln	€ 559	2.7%	9.85	16.80	19.01	18.57	150610 (2017)	€ 21,000	
Niort	€ 38.7 mln	€ 660	2.1%	8.99	16.62	11.66	11.34	58707 (2017)	€ 31,000	ac
Orléans	€ 75.3 mln	€ 645	2.3%	10.76	12.98	11.84	14.41	116685 (2017)	€ 28,000	ac
Paris	€ 3505.3 mln	€ 1,602	3.1%	14.27	20.80	33.94	11.49	2187526 (2017)	€ 52,000	ac

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

France (4)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Pau	€ 36 mln	€ 467	1.7%	6.43	12.08	12.53	8.26	77130 (2017)	€ 27,000	ac
Perpignan	€ 57 mln	€ 474	2.4%	8.90	14.30	13.10	19.74	120158 (2017)	€ 20,000	b
Poitiers	€ 47.9 mln	€ 543	2.2%	9.92	13.97	14.60	10.40	88291 (2017)	€ 25,000	ac
Quimper	€ 47.7 mln	€ 757	2.4%	11.10	17.83	9.82	12.46	62985 (2017)	€ 31,000	b
Reims	€ 159.9 mln	€ 876	2.9%	13.20	19.45	19.63	14.22	182460 (2017)	€ 30,000	ac
Rennes	€ 130 mln	€ 600	2.0%	9.27	13.51	15.38	8.73	216815 (2017)	€ 30,000	ac
Roanne	€ 21.9 mln	€ 637	2.1%	7.63	12.26	17.85	14.87	34366 (2017)	€ 31,000	abc
Rouen	€ 107.2 mln	€ 973	3.1%	12.94	21.53	28.89	10.63	110145 (2017)	€ 31,000	ac
Saint-Brieuc	€ 36.9 mln	€ 832	2.7%	11.81	18.97	10.98	9.79	44372 (2017)	€ 31,000	abc
Saint-Etienne	€ 102.9 mln	€ 596	2.4%	9.22	14.59	19.34	17.58	172565 (2017)	€ 25,000	ac
Saint-Nazaire	€ 46.1 mln	€ 658	2.1%	8.92	14.89	9.29	13.87	69993 (2017)	€ 31,000	
Saint-Quentin	€ 51.6 mln	€ 959	3.1%	14.26	17.51	19.46	12.38	53816 (2017)	€ 31,000	ac
Strasbourg	€ 268.4 mln	€ 955	3.2%	14.37	20.54	21.66	17.91	280966 (2017)	€ 30,000	ac
Tarbes	€ 26.6 mln	€ 641	2.1%	8.91	14.31	13.02	10.66	41518 (2017)	€ 31,000	abc
Toulon	€ 168.4 mln	€ 979	3.2%	12.06	20.61	21.49	23.14	171953 (2017)	€ 31,000	ac
Toulouse	€ 392.7 mln	€ 819	2.2%	9.79	16.27	17.22	15.62	479553 (2017)	€ 37,000	ac
Tours	€ 89.1 mln	€ 656	2.4%	10.34	16.17	12.39	15.55	135787 (2017)	€ 27,000	ac
Troyes	€ 50.4 mln	€ 817	2.6%	11.82	17.54	14.37	15.13	61652 (2017)	€ 31,000	ac
Valence	€ 54.5 mln	€ 855	2.8%	11.39	19.10	15.77	19.89	63714 (2017)	€ 31,000	ac

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c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Germany (1)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Aachen	€ 276.3 mln	€ 1,124	3.2%	11.91	19.12	13.84	14.75	245885 (2016)	€ 35,000	abc
Augsburg	€ 383.7 mln	€ 1,340	3.8%	13.13	16.57	26.11	16.98	286374 (2016)	€ 35,000	ac
Berlin	€ 5237.3 mln	€ 1,488	4.6%	16.14	22.11	25.43	14.00	3520031 (2016)	€ 32,000	ac
Bielefeld	€ 433.1 mln	€ 1,300	3.5%	11.87	19.06	24.53	12.20	333090 (2016)	€ 37,000	abc
Brandenburg an der Havel	€ 108.8 mln	€ 1,520	4.2%	13.92	21.50	19.92	14.75	71574 (2016)	€ 36,000	ac
Braunschweig	€ 373.5 mln	€ 1,486	3.1%	12.24	15.29	11.98	16.25	251364 (2016)	€ 48,000	ac
Bremen	€ 730.2 mln	€ 1,310	3.6%	12.80	17.97	20.37	11.11	557464 (2016)	€ 36,000	ac
Bremerhaven	€ 104.7 mln	€ 918	3.7%	12.32	17.17	18.00	9.99	114025 (2016)	€ 25,000	ac
Chemnitz	€ 340.3 mln	€ 1,369	3.8%	13.69	14.99	16.71	17.84	248645 (2016)	€ 36,000	ac
Cottbus	€ 144.5 mln	€ 1,449	4.0%	14.71	18.07	12.03	18.04	99687 (2016)	€ 36,000	ac
Darmstadt	€ 196.8 mln	€ 1,267	3.1%	9.95	15.98	28.68	15.60	155353 (2016)	€ 41,000	abc
Dortmund	€ 830.1 mln	€ 1,416	3.9%	13.39	19.31	25.74	14.68	586181 (2016)	€ 36,000	ac
Dresden	€ 618.7 mln	€ 1,138	3.9%	14.30	16.64	17.42	12.53	543825 (2016)	€ 29,000	ac
Düsseldorf	€ 1178.5 mln	€ 1,925	3.7%	13.08	20.67	27.62	12.36	612178 (2016)	€ 52,000	ac
Erfurt	€ 222.5 mln	€ 1,059	3.5%	11.90	16.08	17.16	14.79	210118 (2016)	€ 30,000	ac
Essen	€ 877.2 mln	€ 1,506	4.2%	13.97	21.11	27.59	14.66	582624 (2016)	€ 36,000	ac
Frankfurt (Oder)	€ 89 mln	€ 1,532	4.3%	15.38	18.96	13.83	17.79	58092 (2016)	€ 36,000	ac
Frankfurt am Main	€ 1344.6 mln	€ 1,835	3.7%	13.07	19.42	29.17	14.00	732688 (2016)	€ 50,000	ac
Freiburg im Breisgau	€ 235.6 mln	€ 1,041	3.0%	10.67	14.00	17.18	20.99	226393 (2016)	€ 35,000	ac

Footnotes:

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c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Germany (2)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Friedrichshafen	€ 70.4 mln	€ 1,191	3.3%	9.77	15.70	30.14	19.82	59108 (2016)	€ 36,000	b
Fulda	€ 93.9 mln	€ 1,396	3.9%	14.35	17.51	22.83	14.53	67253 (2016)	€ 36,000	ac
Gera	€ 134.9 mln	€ 1,405	3.9%	12.74	20.46	17.73	14.52	96011 (2016)	€ 36,000	abc
Göttingen	€ 114.2 mln	€ 961	3.2%	12.08	12.14	14.94	17.13	118914 (2016)	€ 30,000	ac
Halle an der Saale	€ 284.4 mln	€ 1,200	4.1%	14.80	19.35	14.45	16.19	236991 (2016)	€ 29,000	ac
Hamburg	€ 2936.4 mln	€ 1,643	3.7%	13.29	20.12	22.03	12.18	1787408 (2016)	€ 45,000	ac
Hanau	€ 114.6 mln	€ 1,237	3.4%	11.07	17.78	25.09	18.94	92643 (2016)	€ 36,000	b
Hannover	€ 723.7 mln	€ 1,360	3.5%	12.73	16.73	18.86	15.62	532163 (2016)	€ 39,000	ac
Heidelberg	€ 177.2 mln	€ 1,134	3.2%	9.75	15.66	30.51	16.85	156267 (2016)	€ 36,000	b
Heilbronn	€ 234.5 mln	€ 1,914	4.1%	13.32	21.45	39.71	16.79	122567 (2016)	€ 47,000	
Jena	€ 122.1 mln	€ 1,115	3.1%	11.07	17.79	13.87	14.51	109527 (2016)	€ 36,000	abc
Kaiserslautern	€ 101.6 mln	€ 1,031	3.7%	12.50	16.42	20.83	13.38	98520 (2016)	€ 28,000	ac
Karlsruhe	€ 439.1 mln	€ 1,427	3.2%	11.61	15.98	18.77	19.59	307755 (2016)	€ 45,000	ac
Kassel	€ 263.5 mln	€ 1,331	3.4%	11.83	18.10	21.28	16.37	197984 (2016)	€ 39,000	ac
Kiel	€ 279.2 mln	€ 1,134	3.7%	13.30	17.85	17.50	10.49	246306 (2016)	€ 31,000	ac
Koblenz	€ 174.6 mln	€ 1,551	3.7%	11.76	19.25	35.11	8.56	112586 (2016)	€ 42,000	
Köln	€ 1786.9 mln	€ 1,685	3.7%	13.55	18.72	26.14	13.25	1060582 (2016)	€ 45,000	ac
Konstanz	€ 85.5 mln	€ 1,032	3.2%	11.11	16.56	19.64	18.85	82859 (2016)	€ 32,000	ac
Krefeld	€ 253.9 mln	€ 1,128	3.1%	8.34	13.39	38.53	13.07	225144 (2016)	€ 36,000	ab

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c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Germany (3)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Leipzig	€ 625.8 mln	€ 1,117	3.9%	13.69	17.12	16.23	15.97	560472 (2016)	€ 29,000	ac
Leverkusen	€ 254.7 mln	€ 1,558	4.3%	14.91	15.65	33.97	12.09	163487 (2016)	€ 36,000	ac
Lübeck	€ 211.3 mln	€ 977	3.3%	10.94	16.13	14.22	14.07	216253 (2016)	€ 30,000	ac
Ludwigsburg	€ 107.7 mln	€ 1,158	3.2%	10.35	16.62	22.42	18.74	92973 (2016)	€ 36,000	abc
Ludwigshafen am Rhein	€ 255 mln	€ 1,548	3.7%	13.10	19.98	23.35	15.43	164718 (2016)	€ 42,000	ac
Lüneburg	€ 77.9 mln	€ 1,052	2.9%	10.17	16.34	15.61	15.04	74072 (2016)	€ 36,000	abc
Magdeburg	€ 260.3 mln	€ 1,104	3.9%	13.79	17.38	14.47	14.53	235723 (2016)	€ 28,000	ac
Mainz	€ 326.9 mln	€ 1,559	3.7%	12.48	20.75	29.70	14.76	209779 (2016)	€ 42,000	ac
Marburg	€ 90.8 mln	€ 1,230	3.4%	13.61	17.04	17.58	14.00	73836 (2016)	€ 36,000	ac
Mönchengladbach	€ 323.5 mln	€ 1,244	3.9%	12.18	17.36	31.23	13.89	259996 (2016)	€ 32,000	a
Mülheim a.d.Ruhr	€ 246.4 mln	€ 1,455	4.0%	13.31	21.38	23.58	13.88	169278 (2016)	€ 36,000	abc
München	€ 2877.8 mln	€ 1,984	3.4%	13.51	15.94	19.89	15.97	1450381 (2016)	€ 59,000	ac
Münster	€ 443.2 mln	€ 1,430	3.4%	12.86	20.65	16.79	14.65	310039 (2016)	€ 42,000	abc
Neu-Ulm	€ 80 mln	€ 1,398	3.9%	13.18	18.24	27.23	18.17	57237 (2016)	€ 36,000	ac
Nürnberg	€ 948.3 mln	€ 1,859	4.3%	13.91	26.46	36.02	10.80	509975 (2016)	€ 43,000	
Osnabrück	€ 197.2 mln	€ 1,214	3.7%	13.35	15.29	22.18	13.99	162403 (2016)	€ 33,000	ac
Pforzheim	€ 138.8 mln	€ 1,136	3.5%	10.92	16.99	30.69	14.28	122247 (2016)	€ 32,000	
Plauen	€ 87.8 mln	€ 1,347	3.7%	11.58	18.60	23.52	16.66	65201 (2016)	€ 36,000	b
Potsdam	€ 222.4 mln	€ 1,326	3.7%	13.96	16.20	14.24	15.44	167745 (2016)	€ 36,000	ac

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c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Germany (4)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Reutlingen	€ 149.4 mln	€ 1,307	3.4%	12.88	12.29	20.11	15.07	114310 (2016)	€ 38,000	ac
Rostock	€ 204.3 mln	€ 992	3.7%	13.09	15.93	13.21	7.34	206011 (2016)	€ 27,000	ac
Saarbrücken	€ 219.4 mln	€ 1,231	3.5%	11.90	16.16	22.94	11.23	178151 (2016)	€ 35,000	ac
Schweinfurt	€ 65.6 mln	€ 1,262	3.3%	10.97	17.61	21.27	13.45	51969 (2016)	€ 38,000	b
Solingen	€ 213.2 mln	€ 1,343	3.7%	11.87	19.06	27.30	16.87	158726 (2016)	€ 36,000	abc
Stuttgart	€ 1061.2 mln	€ 1,701	3.4%	12.57	15.56	25.00	17.50	623738 (2016)	€ 50,000	ac
Tübingen	€ 95.7 mln	€ 1,094	3.0%	11.11	16.14	19.05	17.96	87464 (2016)	€ 36,000	ac
Ulm	€ 164 mln	€ 1,337	3.3%	11.93	14.89	21.42	15.43	122636 (2016)	€ 41,000	ac
Villingen-Schwenningen	€ 82.3 mln	€ 971	2.7%	8.85	14.21	14.32	22.60	84674 (2016)	€ 36,000	abc
Wetzlar	€ 61.3 mln	€ 1,188	3.8%	12.43	19.96	25.04	7.69	51649 (2016)	€ 31,000	b
Wiesbaden	€ 418.8 mln	€ 1,516	3.4%	11.93	16.65	26.53	14.58	276218 (2016)	€ 44,000	ac
Wolfsburg	€ 186.5 mln	€ 1,504	3.1%	11.35	18.23	15.28	15.90	124045 (2016)	€ 48,000	abc
Wuppertal	€ 447.6 mln	€ 1,279	3.7%	12.00	20.56	22.60	13.44	350046 (2016)	€ 35,000	ac
Würzburg	€ 165.4 mln	€ 1,325	3.7%	11.90	15.73	33.45	14.86	124873 (2016)	€ 36,000	a

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Greece

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Athina	€ 1126.6 mln	€ 1,697	6.3%	16.00	33.79	61.34	18.29	664046 (2011)	€ 27,000	ac
Pátra	€ 200.1 mln	€ 1,171	5.9%	18.66	34.76	30.28	10.65	170896 (2011)	€ 20,000	ac

Hungary

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Budapest	€ 3272.1 mln	€ 1,860	6.2%	19.09	30.66	21.25	15.43	1759407 (2016)	€ 30,000	abc
Debrecen	€ 165.3 mln	€ 814	5.8%	15.17	24.36	21.46	15.45	203059 (2016)	€ 14,000	abc
Győr	€ 153.4 mln	€ 1,184	5.9%	16.61	27.70	24.08	11.14	129568 (2016)	€ 20,000	ac
Pécs	€ 132.1 mln	€ 909	7.0%	18.01	26.97	31.48	4.40	145347 (2016)	€ 13,000	

Ireland

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Cork	€ 89.7 mln	€ 756	1.5%	8.22	14.18	10.80	5.67	118713 (2011)	€ 52,000	
Dublin	€ 431.5 mln	€ 836	1.4%	7.86	11.33	19.67	5.21	516255 (2011)	€ 59,000	ac

Footnotes:

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Italy (1)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Ancona	€ 117.2 mln	€ 1,161	4.1%	13.51	26.12	17.57	14.38	100926 (2011)	€ 28,000	
Asti	€ 101 mln	€ 1,367	4.9%	16.52	26.54	20.62	20.10	73885 (2011)	€ 28,000	abc
Avellino	€ 77.4 mln	€ 1,423	5.1%	16.54	34.64	22.73	23.49	54347 (2011)	€ 28,000	
Bari	€ 319.8 mln	€ 1,011	4.8%	15.48	24.06	25.53	13.26	316483 (2011)	€ 21,000	ac
Barletta	€ 99.1 mln	€ 1,055	3.8%	13.69	22.31	18.78	19.39	93921 (2011)	€ 28,000	
Bergamo	€ 217.8 mln	€ 1,891	5.9%	21.33	26.49	31.45	25.72	115213 (2011)	€ 32,000	ac
Bologna	€ 658.2 mln	€ 1,781	4.5%	16.32	20.62	22.29	15.93	369653 (2011)	€ 40,000	ac
Bolzano	€ 108 mln	€ 1,059	3.8%	11.12	17.86	35.87	13.37	101941 (2011)	€ 28,000	b
Brescia	€ 399.2 mln	€ 2,106	6.4%	22.90	33.98	30.49	29.30	189576 (2011)	€ 33,000	ac
Busto Arsizio	€ 106.6 mln	€ 1,342	4.8%	15.03	24.14	32.43	23.95	79463 (2011)	€ 28,000	b
Cagliari	€ 216.9 mln	€ 1,441	5.8%	18.82	30.14	28.41	2.11	150531 (2011)	€ 25,000	
Campobasso	€ 47.1 mln	€ 963	3.4%	10.40	16.70	30.06	11.50	48921 (2011)	€ 28,000	b
Catanzaro	€ 82.2 mln	€ 916	3.3%	10.48	21.35	16.06	21.55	89727 (2011)	€ 28,000	
Cosenza	€ 79.1 mln	€ 1,136	4.1%	12.75	22.79	24.92	16.26	69627 (2011)	€ 28,000	
Cremona	€ 132.3 mln	€ 1,890	6.8%	23.39	33.70	29.20	22.28	70003 (2011)	€ 28,000	ac
Ferrara	€ 191.9 mln	€ 1,444	5.2%	16.66	26.61	23.07	15.84	132880 (2011)	€ 28,000	ac
Forlì	€ 148.3 mln	€ 1,277	4.6%	15.84	22.16	19.03	18.66	116121 (2011)	€ 28,000	ac
Genova	€ 687.6 mln	€ 1,170	3.3%	10.35	16.03	23.01	23.65	587680 (2011)	€ 35,000	ac
La Spezia	€ 97.7 mln	€ 1,052	3.8%	12.12	18.57	19.89	13.33	92790 (2011)	€ 28,000	ac

Footnotes:

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Italy (2)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Latina	€ 117.6 mln	€ 999	3.6%	12.19	21.15	19.85	5.79	117731 (2011)	€ 28,000	ac
Lecce	€ 102.7 mln	€ 1,150	4.1%	12.72	23.54	23.05	24.46	89368 (2011)	€ 28,000	
Lecco	€ 59.1 mln	€ 1,268	4.5%	15.48	21.18	21.20	25.58	46583 (2011)	€ 28,000	ac
Messina	€ 202.7 mln	€ 831	4.6%	13.96	22.42	30.15	11.24	243846 (2011)	€ 18,000	b
Milano	€ 3498.9 mln	€ 2,843	6.0%	22.12	33.21	38.82	24.08	1230912 (2011)	€ 47,000	ac
Modena	€ 265.8 mln	€ 1,487	5.3%	17.78	28.58	26.38	22.24	178828 (2011)	€ 28,000	ac
Napoli	€ 812.7 mln	€ 844	4.4%	13.85	28.66	20.50	19.71	962661 (2011)	€ 19,000	ac
Novara	€ 145.6 mln	€ 1,426	5.1%	17.73	23.66	26.89	16.00	102105 (2011)	€ 28,000	ac
Padova	€ 508.1 mln	€ 2,455	7.2%	27.10	35.80	31.57	20.71	206936 (2011)	€ 34,000	ac
Palermo	€ 493.4 mln	€ 748	4.2%	10.60	28.19	34.51	11.28	659326 (2011)	€ 18,000	
Parma	€ 335.6 mln	€ 1,915	5.2%	18.80	28.15	23.48	21.52	175229 (2011)	€ 37,000	ac
Pavia	€ 128.1 mln	€ 1,868	6.7%	23.32	31.03	28.66	20.70	68546 (2011)	€ 28,000	ac
Perugia	€ 171.2 mln	€ 1,059	3.8%	14.10	21.18	9.16	9.17	161722 (2011)	€ 28,000	ac
Pesaro	€ 121.6 mln	€ 1,287	4.6%	15.82	26.08	18.67	10.60	94534 (2011)	€ 28,000	
Pescara	€ 141.5 mln	€ 1,203	4.3%	15.73	24.85	13.70	0.13	117631 (2011)	€ 28,000	
Piacenza	€ 162.2 mln	€ 1,622	5.8%	20.55	27.77	22.72	24.67	100023 (2011)	€ 28,000	ac
Pisa	€ 104.4 mln	€ 1,210	4.3%	14.67	22.11	17.38	14.20	86285 (2011)	€ 28,000	ac
Ravenna	€ 235.3 mln	€ 1,541	5.5%	19.49	26.39	20.39	20.66	152734 (2011)	€ 28,000	ac
Reggio di Calabria	€ 160.7 mln	€ 887	3.2%	10.63	21.14	18.34	3.55	181178 (2011)	€ 28,000	

Footnotes:

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Italy (3)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Reggio nell'Emilia	€ 288.6 mln	€ 1,786	5.1%	19.59	27.33	22.43	18.76	161615 (2011)	€ 35,000	ac
Rimini	€ 185.2 mln	€ 1,333	4.8%	16.59	23.81	19.97	21.16	138993 (2011)	€ 28,000	ac
Roma	€ 4144.3 mln	€ 1,589	4.3%	14.39	24.17	31.63	11.80	2608530 (2011)	€ 37,000	ac
Salerno	€ 131.8 mln	€ 992	3.5%	10.03	20.43	31.24	13.27	132847 (2011)	€ 28,000	
Sassari	€ 75.2 mln	€ 607	2.2%	5.45	20.89	12.21	8.05	123729 (2011)	€ 28,000	ac
Savona	€ 72.5 mln	€ 1,191	4.3%	14.50	18.28	15.48	23.46	60933 (2011)	€ 28,000	ac
Siracusa	€ 148 mln	€ 1,241	4.4%	16.56	26.59	16.91	1.89	119333 (2011)	€ 28,000	b
Taranto	€ 122 mln	€ 608	3.4%	10.68	19.71	8.79	20.52	200573 (2011)	€ 18,000	ac
Terni	€ 182.7 mln	€ 1,668	6.0%	21.82	30.61	15.64	20.99	109480 (2011)	€ 28,000	
Torino	€ 1815.4 mln	€ 2,076	6.5%	23.05	31.33	35.04	18.20	874320 (2011)	€ 32,000	ac
Trento	€ 137.7 mln	€ 1,211	4.3%	14.00	19.61	33.82	16.43	113736 (2011)	€ 28,000	ac
Treviso	€ 139.5 mln	€ 1,731	6.2%	21.20	31.83	29.10	20.46	80617 (2011)	€ 28,000	ac
Trieste	€ 232.9 mln	€ 1,148	4.1%	12.59	19.63	25.18	18.86	202878 (2011)	€ 28,000	
Udine	€ 127.1 mln	€ 1,292	4.6%	16.09	19.57	20.35	20.44	98318 (2011)	€ 28,000	ac
Varese	€ 124.2 mln	€ 1,555	5.6%	19.19	24.46	29.18	24.06	79902 (2011)	€ 28,000	
Venezia	€ 552.3 mln	€ 2,106	6.6%	23.89	31.42	27.73	20.36	262254 (2011)	€ 32,000	ac
Verona	€ 482.5 mln	€ 1,902	5.6%	20.55	28.97	24.27	23.01	253597 (2011)	€ 34,000	ac
Vicenza	€ 203.8 mln	€ 1,815	6.5%	23.66	32.17	27.59	18.00	112288 (2011)	€ 28,000	ac

Footnotes:

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Lithuania

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Kaunas	€ 318.6 mln	€ 1,088	4.9%	12.50	29.02	21.18	3.78	292691 (2017)	€ 22,000	
Klaipeda	€ 232.2 mln	€ 1,535	7.0%	20.39	30.12	23.93	2.38	151309 (2017)	€ 22,000	
Panevezys	€ 83.5 mln	€ 917	4.2%	11.11	17.84	16.00	5.97	91054 (2017)	€ 22,000	abc
Siauliai	€ 150.4 mln	€ 1,486	6.8%	19.05	30.59	23.60	3.78	101214 (2017)	€ 22,000	b
Vilnius	€ 753 mln	€ 1,381	4.3%	13.28	20.76	17.35	4.31	545280 (2017)	€ 32,000	ac

Latvia

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Liepaja	€ 80.8 mln	€ 1,144	6.0%	16.43	23.95	19.59	5.84	70610 (2016)	€ 19,000	
Riga	€ 895.6 mln	€ 1,401	5.6%	16.06	18.66	20.06	4.80	639342 (2016)	€ 25,000	ac

Luxembourg

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Luxembourg	€ 166.1 mln	€ 1,748	2.3%	10.32	17.24	31.05	8.75	95058 (2011)	€ 76,000	a

Footnotes:

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b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Malta

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Valletta	€ 279.6 mln	€ 1,246	4.3%	14.43	43.08	34.62	7.99	224437 (2017)	€ 29,000	

The Netherlands

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Breda	€ 199.9 mln	€ 1,113	3.0%	12.62	20.74	22.71	13.29	179623 (2014)	€ 37,000	ac
Amsterdam	€ 1054.8 mln	€ 1,301	2.8%	13.25	18.96	20.09	8.30	810938 (2014)	€ 46,000	ac
Eindhoven	€ 281.9 mln	€ 1,276	3.0%	13.01	20.90	25.25	7.97	220920 (2014)	€ 42,000	b
Haarlem	€ 176.9 mln	€ 1,140	3.1%	12.66	20.34	25.55	5.31	155147 (2014)	€ 37,000	b
Heerlen	€ 90.3 mln	€ 1,023	2.8%	10.69	17.89	17.67	14.76	88259 (2014)	€ 37,000	ac
Rotterdam	€ 750.3 mln	€ 1,213	3.1%	13.51	20.51	26.14	5.62	618357 (2014)	€ 39,000	ac
s-Gravenhage	€ 521.2 mln	€ 1,024	2.6%	10.20	19.17	24.72	6.83	508940 (2014)	€ 40,000	ac
Utrecht	€ 396.2 mln	€ 1,207	2.7%	11.96	20.83	24.49	7.89	328164 (2014)	€ 45,000	
Groningen	€ 201.5 mln	€ 1,016	2.4%	10.55	22.82	17.71	8.32	198317 (2014)	€ 42,000	
Nijmegen	€ 162.3 mln	€ 964	3.0%	12.04	21.71	26.16	10.44	168292 (2014)	€ 32,000	

Norway

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Bergen	€ 156.1 mln	€ 583	1.5%	5.78	9.96	21.83	6.88	267950 (2013)	€ 39,000	ac

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Poland (1)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Bialystok	€ 242.3 mln	€ 820	5.1%	17.69	25.19	14.06	11.22	295459 (2014)	€ 16,000	ac
Bielsko-Biala	€ 313.4 mln	€ 1,811	8.6%	32.39	37.38	32.43	15.21	173013 (2014)	€ 21,000	ac
Bydgoszcz	€ 501.7 mln	€ 1,403	6.7%	24.75	31.23	20.47	7.90	357652 (2014)	€ 21,000	ac
Czestochowa	€ 296.2 mln	€ 1,287	7.6%	26.48	34.83	18.81	13.46	230123 (2014)	€ 17,000	ac
Elblag	€ 127.7 mln	€ 1,044	5.2%	19.11	25.65	13.37	11.30	122368 (2014)	€ 20,000	ac
Elk	€ 47.7 mln	€ 794	4.0%	14.39	23.11	11.72	12.05	60103 (2014)	€ 20,000	b
Gdansk	€ 485.6 mln	€ 1,052	4.6%	15.72	26.75	17.64	5.99	461489 (2014)	€ 23,000	ac
Gdynia	€ 211.5 mln	€ 853	4.3%	13.73	22.05	20.05	8.96	247820 (2014)	€ 20,000	abc
Gorzów Wielkopolski	€ 124.8 mln	€ 1,005	5.0%	16.96	25.81	22.02	8.70	124145 (2014)	€ 20,000	ac
Jelenia Góra	€ 97.8 mln	€ 1,202	6.0%	21.26	27.24	11.94	20.99	81408 (2014)	€ 20,000	ac
Kalisz	€ 136.7 mln	€ 1,322	6.6%	23.87	32.19	18.20	17.96	103373 (2014)	€ 20,000	ac
Konin	€ 79.8 mln	€ 1,043	5.2%	17.80	28.59	13.98	18.89	76547 (2014)	€ 20,000	abc
Kraków	€ 1490.1 mln	€ 1,956	8.1%	31.58	39.02	26.19	14.23	761873 (2014)	€ 24,000	ac
Legnica	€ 141.4 mln	€ 1,396	7.0%	24.98	35.44	21.32	15.60	101343 (2014)	€ 20,000	a
Lódz	€ 1083.9 mln	€ 1,535	7.0%	23.92	36.97	22.36	15.01	706004 (2014)	€ 22,000	ac
Lublin	€ 385.7 mln	€ 1,129	6.3%	21.73	30.63	21.61	11.51	341722 (2014)	€ 18,000	ac
Metropolia Silesia	€ 3596.2 mln	€ 1,899	8.6%	32.10	41.61	29.14	14.95	1893271 (2014)	€ 22,000	
Olsztyn	€ 150.7 mln	€ 867	5.4%	18.77	26.01	14.71	10.84	173831 (2014)	€ 16,000	ac

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Poland (2)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Opole	€ 131.2 mln	€ 1,097	6.1%	20.37	32.66	15.57	12.91	119574 (2014)	€ 18,000	ac
Pabianice	€ 102.5 mln	€ 1,525	7.6%	26.43	42.45	19.93	12.26	67207 (2014)	€ 20,000	ab
Piotrków Trybunalski	€ 113.4 mln	€ 1,500	7.5%	28.16	37.11	18.86	13.22	75608 (2014)	€ 20,000	ac
Plock	€ 149.7 mln	€ 1,225	6.1%	22.06	31.10	19.65	8.66	122224 (2014)	€ 20,000	ac
Poznan	€ 989.7 mln	€ 1,814	5.7%	21.86	30.40	22.55	12.65	545680 (2014)	€ 32,000	ac
Przemysl	€ 83.7 mln	€ 1,320	6.6%	24.83	31.26	14.07	15.86	63441 (2014)	€ 20,000	ac
Radom	€ 223 mln	€ 1,027	7.3%	24.75	36.45	23.14	8.20	217201 (2014)	€ 14,000	ac
Rybnik	€ 239.3 mln	€ 1,708	8.5%	31.54	50.65	22.21	14.38	140052 (2014)	€ 20,000	abc
Rzeszów	€ 197.9 mln	€ 1,069	6.3%	22.85	31.36	18.10	14.29	185123 (2014)	€ 17,000	ac
Slupsk	€ 88.3 mln	€ 947	4.7%	16.89	22.24	13.69	8.44	93206 (2014)	€ 20,000	ac
Szczecin	€ 484.9 mln	€ 1,191	5.2%	18.41	24.38	20.90	9.97	407180 (2014)	€ 23,000	a
Tarnów	€ 110.7 mln	€ 994	7.6%	24.96	33.22	24.92	16.05	111376 (2014)	€ 13,000	ac
Torun	€ 239.6 mln	€ 1,179	5.6%	20.57	30.34	13.16	13.67	203158 (2014)	€ 21,000	ac
Walbrzych	€ 143.7 mln	€ 1,231	6.2%	21.58	28.81	15.21	20.51	116691 (2014)	€ 20,000	a
Warszawa	€ 4222.7 mln	€ 2,433	5.5%	22.35	34.14	21.84	9.58	1735442 (2014)	€ 44,000	ac
Wroclaw	€ 1239.5 mln	€ 1,954	5.9%	22.33	30.26	27.84	18.75	634487 (2014)	€ 33,000	a
Zielona Góra	€ 118.9 mln	€ 1,000	5.0%	17.28	25.34	15.16	16.23	118920 (2014)	€ 20,000	ac

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Portugal

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Coimbra	€ 85.8 mln	€ 598	3.0%	9.10	14.61	14.37	9.36	143589 (2011)	€ 20,000	b
Faro	€ 50.1 mln	€ 775	3.4%	11.26	18.09	10.24	22.56	64600 (2011)	€ 23,000	b
Funchal	€ 67.6 mln	€ 603	2.6%	4.75	18.53	36.11	15.57	111990 (2011)	€ 23,000	
Lisboa	€ 635.6 mln	€ 1,159	3.9%	12.34	20.56	23.75	11.35	548422 (2011)	€ 30,000	ac
Porto	€ 226.1 mln	€ 950	4.5%	10.98	17.64	56.15	6.41	238046 (2011)	€ 21,000	abc
Setúbal	€ 115.6 mln	€ 954	4.1%	14.44	23.18	14.13	14.71	121257 (2011)	€ 23,000	abc
Sintra	€ 236.1 mln	€ 625	2.7%	8.38	18.17	12.81	15.23	377680 (2011)	€ 23,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Romania

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Alba Iulia	€ 71.2 mln	€ 955	5.6%	14.76	23.70	21.53	11.72	74574 (2017)	€ 17,000	abc
Arad	€ 192 mln	€ 1,082	6.4%	17.87	25.15	14.46	14.72	177464 (2017)	€ 17,000	ac
Baia Mare	€ 124.5 mln	€ 851	5.0%	13.72	22.04	16.88	5.65	146241 (2017)	€ 17,000	abc
Bistrita	€ 66.7 mln	€ 710	4.2%	10.57	16.97	24.58	0.83	93950 (2017)	€ 17,000	b
Botosani	€ 124.3 mln	€ 1,028	6.0%	14.83	32.53	29.39	7.12	120902 (2017)	€ 17,000	a
Brasov	€ 495.6 mln	€ 1,710	8.1%	21.34	31.11	45.58	0.50	289878 (2017)	€ 21,000	
Bucuresti	€ 6345.1 mln	€ 3,004	7.3%	21.46	34.17	49.95	11.32	2112483 (2017)	€ 41,000	
Calarasi	€ 77.1 mln	€ 1,009	5.9%	15.98	25.66	21.54	18.40	76380 (2017)	€ 17,000	b
Cluj-Napoca	€ 495.5 mln	€ 1,532	6.7%	16.93	27.19	47.23	0.17	323484 (2017)	€ 23,000	ab
Craiova	€ 297.9 mln	€ 984	7.6%	19.59	31.46	22.86	8.20	302783 (2017)	€ 13,000	b
Focsani	€ 73.2 mln	€ 787	4.6%	12.56	20.17	12.73	7.44	92936 (2017)	€ 17,000	b
Galati	€ 186.4 mln	€ 615	5.6%	13.18	21.17	18.11	12.09	303069 (2017)	€ 11,000	b
Giurgiu	€ 76.1 mln	€ 1,123	6.6%	16.34	26.25	33.46	13.28	67721 (2017)	€ 17,000	b
Iasi	€ 456.1 mln	€ 1,221	9.4%	27.01	31.07	28.72	9.43	373507 (2017)	€ 13,000	ac
Oradea	€ 244.4 mln	€ 1,102	6.5%	17.44	19.96	30.61	7.54	221796 (2017)	€ 17,000	
Pitesti	€ 140.2 mln	€ 801	4.7%	11.44	18.37	23.60	12.10	175047 (2017)	€ 17,000	b
Ploiesti	€ 311.8 mln	€ 1,358	7.1%	19.39	27.68	30.93	6.53	229641 (2017)	€ 19,000	
Râmnicu Vâlcea	€ 110.4 mln	€ 935	5.5%	13.96	27.28	20.56	9.90	118111 (2017)	€ 17,000	
Satu Mare	€ 89 mln	€ 737	4.3%	10.96	17.59	20.94	2.55	120736 (2017)	€ 17,000	b
Suceava	€ 107.6 mln	€ 881	5.2%	14.87	23.88	14.25	6.76	122231 (2017)	€ 17,000	ab
Timisoara	€ 542.2 mln	€ 1,643	6.8%	18.57	29.67	35.61	5.38	330014 (2017)	€ 24,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Slovakia

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Banská Bystrica	€ 90.4 mln	€ 1,129	4.7%	17.28	25.78	22.25	16.17	80003 (2011)	€ 24,000	
Bratislava	€ 891.5 mln	€ 2,168	4.0%	17.39	23.10	22.03	20.35	411228 (2011)	€ 54,000	ac
Kosice	€ 221.6 mln	€ 922	5.1%	17.46	29.03	28.05	17.29	240433 (2011)	€ 18,000	a
Nitra	€ 89.3 mln	€ 1,132	4.7%	17.32	26.27	22.72	20.26	78916 (2011)	€ 24,000	
Zilina	€ 106.2 mln	€ 1,303	5.4%	21.70	26.90	25.24	12.69	81494 (2011)	€ 24,000	

Slovenia

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Ljubljana	€ 434 mln	€ 1,502	4.4%	18.78	24.17	26.19	15.75	288919 (2017)	€ 34,000	ac
Maribor	€ 107.2 mln	€ 965	4.8%	16.94	27.89	22.30	19.30	111079 (2017)	€ 20,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Spain (1)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
A Coruña	€ 251.9 mln	€ 1,033	4.1%	14.18	31.64	22.59	6.24	243978 (2016)	€ 25,000	
Albacete	€ 131.8 mln	€ 765	2.8%	10.24	24.63	13.54	16.78	172426 (2016)	€ 27,000	
Alcalá de Henares	€ 172.8 mln	€ 882	3.3%	11.76	18.89	28.31	21.68	195907 (2016)	€ 27,000	b
Alcobendas	€ 88.7 mln	€ 783	2.9%	10.44	16.76	27.27	20.90	113340 (2016)	€ 27,000	b
Alicante/Alacant	€ 220.9 mln	€ 668	3.2%	10.98	19.58	22.65	16.23	330525 (2016)	€ 21,000	
Arrecife	€ 26.2 mln	€ 448	1.7%	4.64	20.76	8.68	13.45	58537 (2016)	€ 27,000	ac
Avilés	€ 66 mln	€ 823	3.0%	10.46	22.42	19.42	1.95	80114 (2016)	€ 27,000	
Badajoz	€ 89 mln	€ 593	2.2%	8.85	14.22	9.77	16.83	149946 (2016)	€ 27,000	abc
Barcelona	€ 2020.4 mln	€ 1,256	3.9%	15.80	22.00	28.18	11.15	1608746 (2016)	€ 32,000	ac
Bilbao	€ 316.4 mln	€ 917	2.7%	9.42	17.90	26.45	3.12	345122 (2016)	€ 34,000	ac
Cáceres	€ 55.9 mln	€ 584	2.2%	8.48	13.61	7.71	21.91	95814 (2016)	€ 27,000	abc
Cartagena	€ 166.4 mln	€ 775	3.5%	13.62	21.88	19.47	22.20	214759 (2016)	€ 22,000	ab
Ciudad Real	€ 68 mln	€ 918	3.4%	14.16	22.73	12.82	16.81	74054 (2016)	€ 27,000	abc
Coslada	€ 87.3 mln	€ 1,033	3.8%	13.12	21.07	41.26	13.80	84533 (2016)	€ 27,000	b
Elda	€ 35.5 mln	€ 672	2.5%	10.16	14.31	8.63	19.38	52745 (2016)	€ 27,000	a
Ferrol	€ 40.1 mln	€ 588	2.2%	8.12	12.91	8.20	12.53	68308 (2016)	€ 27,000	ac
Gandia	€ 47.7 mln	€ 637	2.4%	9.03	14.50	14.33	15.74	74814 (2016)	€ 27,000	b

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Spain (2)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Getafe	€ 153.6 mln	€ 869	3.2%	11.12	17.85	33.37	18.54	176659 (2016)	€ 27,000	b
Gijón	€ 226.1 mln	€ 827	3.1%	10.44	21.57	19.19	6.07	273422 (2016)	€ 27,000	ac
Guadalajara	€ 99 mln	€ 1,183	4.4%	18.32	29.43	20.14	16.19	83633 (2016)	€ 27,000	abc
Jerez de la Frontera	€ 195.8 mln	€ 920	3.4%	14.27	22.92	14.12	20.23	212830 (2016)	€ 27,000	abc
Leganés	€ 179.6 mln	€ 959	3.6%	12.41	19.93	35.12	16.41	187173 (2016)	€ 27,000	b
León	€ 84.7 mln	€ 671	2.5%	8.92	14.73	14.40	13.97	126192 (2016)	€ 27,000	ac
Logroño	€ 139.1 mln	€ 922	3.4%	13.25	21.28	23.21	7.68	150876 (2016)	€ 27,000	abc
Lugo	€ 71.1 mln	€ 723	2.7%	11.35	13.87	11.08	3.31	98268 (2016)	€ 27,000	
Madrid	€ 3383.4 mln	€ 1,069	3.0%	10.64	17.45	31.90	16.41	3165541 (2017)	€ 36,000	ac
Majadahonda	€ 43 mln	€ 608	2.3%	8.10	13.01	22.74	18.25	70755 (2016)	€ 27,000	abc
Móstoles	€ 167.1 mln	€ 813	3.0%	10.69	17.16	26.68	16.37	205614 (2016)	€ 27,000	abc
Ourense	€ 86 mln	€ 812	3.0%	9.62	23.57	25.59	2.28	105893 (2016)	€ 27,000	
Oviedo	€ 153.6 mln	€ 696	3.0%	11.33	16.88	15.21	6.56	220567 (2016)	€ 23,000	ac
Palencia	€ 53.5 mln	€ 676	2.5%	10.09	16.20	6.03	11.48	79137 (2016)	€ 27,000	b
Palma de Mallorca	€ 412.4 mln	€ 1,024	3.5%	13.34	21.43	34.85	4.87	402949 (2016)	€ 29,000	b
Pamplona/Iruña	€ 149.8 mln	€ 765	2.3%	8.93	14.35	20.54	2.90	195650 (2016)	€ 33,000	b
Pontevedra	€ 68 mln	€ 824	3.1%	11.42	18.81	22.18	7.24	82549 (2016)	€ 27,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Spain (3)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Salamanca	€ 107.7 mln	€ 743	2.8%	10.67	17.13	7.96	19.50	144949 (2016)	€ 27,000	abc
San Sebastián/Donostia	€ 159.6 mln	€ 858	2.5%	8.91	15.47	21.56	10.07	186064 (2016)	€ 35,000	
Santa Cruz de Tenerife	€ 77.8 mln	€ 382	1.7%	4.83	13.35	15.08	12.12	203585 (2016)	€ 22,000	ac
Santander	€ 141.3 mln	€ 818	3.4%	12.77	20.51	16.80	8.97	172656 (2016)	€ 24,000	abc
Santiago de Compostela	€ 72.6 mln	€ 756	2.8%	10.33	19.47	12.58	12.24	95966 (2016)	€ 27,000	ac
Talavera de la Reina	€ 80.4 mln	€ 956	3.5%	14.73	23.65	15.71	18.25	84119 (2016)	€ 27,000	ab
Telde	€ 53.2 mln	€ 521	1.9%	5.98	21.27	9.11	10.43	102164 (2016)	€ 27,000	ac
Toledo	€ 80.9 mln	€ 970	3.6%	14.46	22.15	20.76	21.55	83459 (2016)	€ 27,000	
Torrejón de Ardoz	€ 111.8 mln	€ 880	3.3%	12.43	20.61	24.90	16.83	126981 (2016)	€ 27,000	ac
Valencia	€ 670.8 mln	€ 849	3.5%	13.75	18.83	22.28	10.07	790201 (2016)	€ 24,000	ac
Valladolid	€ 253 mln	€ 838	3.1%	11.50	15.58	22.05	15.46	301876 (2016)	€ 27,000	
Vigo	€ 218.8 mln	€ 747	3.4%	11.49	20.50	25.82	9.87	292817 (2016)	€ 22,000	
Zamora	€ 37.5 mln	€ 593	2.2%	8.42	13.52	5.81	18.64	63217 (2016)	€ 27,000	b
Zaragoza	€ 522.4 mln	€ 790	2.7%	10.40	13.56	22.43	13.27	661108 (2016)	€ 29,000	ac

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

Sweden

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Göteborg	€ 418.1 mln	€ 751	2.1%	7.72	15.03	18.20	8.96	556640 (2017)	€ 36,000	ac
Lund	€ 93.1 mln	€ 785	2.2%	9.64	15.48	11.42	7.07	118542 (2017)	€ 36,000	b
Malmö	€ 262.8 mln	€ 800	2.6%	11.17	16.02	12.47	6.92	328494 (2017)	€ 31,000	ac
Stockholm	€ 682.9 mln	€ 730	1.5%	6.07	11.07	9.25	8.42	935619 (2017)	€ 50,000	ac

Switzerland

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Basel	€ 182.4 mln	€ 1,109	2.4%	10.60	15.17	21.91	18.50	164516 (2012)	€ 45,400	ac
Bern	€ 160.8 mln	€ 1,280	2.8%	14.09	14.61	18.01	15.90	125681 (2012)	€ 45,400	ac
Genève	€ 96 mln	€ 510	1.9%	10.45	16.77	30.17	15.14	188234 (2012)	€ 27,000	abc
Lausanne	€ 118.6 mln	€ 917	2.0%	8.43	13.54	25.25	15.97	129383 (2012)	€ 45,400	b
Lugano	€ 72.5 mln	€ 1,314	2.9%	12.81	17.92	23.63	25.53	55151 (2012)	€ 45,400	ac
St. Gallen	€ 76 mln	€ 1,034	2.3%	9.12	14.65	33.39	12.37	73505 (2012)	€ 45,400	b
Winterthur	€ 97.6 mln	€ 947	2.1%	9.38	15.07	16.12	20.30	103075 (2012)	€ 45,400	abc
Zürich	€ 432.5 mln	€ 1,147	2.5%	11.08	15.40	25.04	15.92	376990 (2012)	€ 45,400	ac

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

United Kingdom (1)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
Aberdeen City	€ 216.5 mln	€ 944	2.1%	6.87	14.30	32.60	3.60	229320 (2017)	€ 44,000	a
Belfast	€ 313.4 mln	€ 922	2.8%	10.01	15.53	37.99	1.90	339900 (2017)	€ 33,000	
Bristol	€ 482.6 mln	€ 1,055	3.1%	12.04	19.26	34.09	8.08	457609 (2017)	€ 34,000	ac
City of Edinburgh	€ 405.6 mln	€ 795	2.0%	6.31	10.66	34.44	4.61	510190 (2017)	€ 39,000	ac
Coventry	€ 307.5 mln	€ 862	2.7%	10.63	19.39	24.92	5.87	356682 (2017)	€ 32,000	
Derry & Strabane Local Government District	€ 99.6 mln	€ 663	2.1%	9.67	12.41	9.64	5.06	150320 (2017)	€ 31,000	
Greater Glasgow	€ 725.6 mln	€ 728	2.3%	7.15	12.44	36.01	2.71	996545 (2017)	€ 31,000	
Greater Manchester	€ 2409.5 mln	€ 864	2.8%	11.02	16.39	24.02	4.78	2789822 (2017)	€ 31,000	
Greater Nottingham	€ 573.4 mln	€ 853	2.8%	9.99	17.17	30.82	3.49	671930 (2017)	€ 31,000	
Kingston-upon-Hull	€ 180.8 mln	€ 694	3.0%	10.68	20.50	24.32	5.49	260354 (2017)	€ 23,000	ac
Leeds	€ 681.3 mln	€ 870	3.0%	11.36	17.49	31.27	3.85	782967 (2017)	€ 29,000	
Leicester	€ 256.9 mln	€ 731	2.9%	10.42	22.52	29.51	4.39	351527 (2017)	€ 25,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

United Kingdom (2)

City	Total annual damage	Per capita damage	Damage as % of GDP	PM2.5 2018 (µg/m3/year)	PM10 2018 (µg/m3/year)	NO2 2018 (µg/m3/year)	O3 2018 (µg/m3/year)	Population (in year)	GDP per capita (PPP)	Foot-notes
London (greater city)	€ 11380.7 mln	€ 1,294	2.8%	11.53	16.32	31.14	4.51	8797330 (2017)	€ 47,000	ac
Norwich	€ 90 mln	€ 643	2.4%	10.24	15.72	11.64	5.07	140109 (2017)	€ 27,000	ac
Plymouth	€ 163 mln	€ 620	2.7%	9.92	16.25	18.73	7.12	262713 (2017)	€ 23,000	ac
Portsmouth	€ 178.9 mln	€ 836	3.0%	12.02	19.30	24.63	3.22	214027 (2017)	€ 28,000	b
Reading	€ 125.5 mln	€ 771	2.5%	9.11	15.08	27.82	7.93	162888 (2017)	€ 31,000	ac
Sheffield	€ 449.7 mln	€ 781	3.3%	12.77	15.99	28.99	5.24	575920 (2017)	€ 24,000	
Stoke-on-trent	€ 175 mln	€ 688	3.1%	9.45	19.19	38.22	4.23	254519 (2017)	€ 22,000	ac
Thurrock	€ 139.4 mln	€ 823	2.7%	10.06	16.41	25.66	5.07	169411 (2017)	€ 31,000	ac
Tyneside conurbation	€ 693.5 mln	€ 815	2.6%	8.97	13.86	33.82	3.44	850700 (2017)	€ 31,000	
Warwick	€ 107.2 mln	€ 767	2.5%	9.80	14.00	17.25	5.06	139885 (2017)	€ 31,000	a
West Midlands urban area	€ 1806.6 mln	€ 715	2.7%	10.54	17.51	21.95	5.90	2527245 (2017)	€ 26,000	

Footnotes:

a) Average PM10 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

b) Average PM2.5 emissions have been imputed using an average factor of PM2.5/PM10

c) Average NO2 emissions from EEA have been adjusted for reported figures in Urban Audit data (Eurostat)

D Country totals and averages of damage costs

Annex C has provided information on the total damage and per capita damage in individual cities in all the 30 countries. Table 17 below presents this information but now as a total number for each country and lists how many cities have been included.

Table 17 – Total damage costs and damage costs per inhabitant of the cities included in this research averaged over countries

Symbol	Country	Number of cities included	Total damage costs (€mln)	Total population (mln)	Damage cost/inhabitant (€/cap)
AT	Austria	6	3770	2.60	1451
BE	Belgium	6	3287	2.56	1285
BG	Bulgaria	8	3966	2.53	1568
CH	Switzerland	8	1236	1.22	1016
CY	Cyprus	1	222	0.24	929
CZ	Czechia	14	4381	2.88	1520
DE	Germany	71	33427	22.77	1468
DK	Denmark	3	1280	1.06	1213
EE	Estonia	3	317	0.58	550
EL	Greece	2	1327	0.83	1589
ES	Spain	48	12138	13.11	926
FI	Finland	5	836	1.30	643
FR	France	76	10953	11.62	943
HR	Croatia	2	1448	0.91	1594
HU	Hungary	4	3723	2.24	1664
IE	Ireland	2	521	0.63	821
IT	Italy	56	20820	13.56	1535
LT	Lithuania	5	1538	1.18	1301
LU	Luxemburg	1	166	0.10	1748
LV	Latvia	2	976	0.71	1375
MT	Malta	1	280	0.22	1246
NL	Netherlands	10	3835	3.28	1170
NO	Norway	1	156	0.27	583
PL	Poland	35	18392	11.27	1632
PT	Portugal	7	1417	1.61	882
RO	Romania	21	10627	5.87	1810
SE	Sweden	4	1457	1.94	751
SI	Slovenia	2	541	0.40	1353
SK	Slovakia	5	1399	0.89	1568
UK	United Kingdom	23	21962	21.99	999
Total		**432**	**166400**	**130.36**	**1276**