CONVENTION ON LONG-RANGE TRANSBOUNDARY AIR POLLUTION
UN/ECE INTERNATIONAL CO-OPERATIVE PROGRAMME
ON EFFECTS ON MATERIALS, INCLUDING HISTORIC
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ENEA
Italian National Agency for New Technologies, Energy and sustainable economic development. (ENEA), Italy
INTERNATIONAL CO-OPERATIVE PROGRAMME ON EFFECTS ON MATERIALS, INCLUDING HISTORIC AND CULTURAL MONUMENTS (ICP Materials)

Report 77

Pilot study on the inventory and condition of stock of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO) cultural heritage sites.

Part IV The relationship between the environment and the artefact

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1 Introduction

Air pollution is a key factor in the degradation of the surfaces of historical buildings and cultural monuments exposed outdoors. Corrosion and soiling cause huge economic losses but, above all, lead to the damage of our cultural heritage, an important component of our individual and collective identity. The impact of pollutants emitted into the atmosphere on the materials is potentially enormous and irreversible because, unlike the natural ecosystems, materials have no possibility of self-regeneration.

The International Co-operative Programme on Effects on Materials including Historic and Cultural Monuments (ICP Materials) is one of the six effect-oriented ICPs of the Working Group on Effects (WGE) established under the Convention on Long-range Transboundary Air Pollution (CLRTAP). The six ICPs and the Task Force on Health identify the most endangered areas, ecosystems and other receptors by considering damage to human health, terrestrial and aquatic ecosystems and materials. ICP Materials is dedicated at studying the harmful effect of air pollution on materials.

The series of reports on the “Pilot study on inventory and condition of stock of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO) cultural heritage sites” presents an assessment on five important UNESCO sites in Europe. Part I (Methodology)\(^1\), Part II (Determination of stock of materials at risk)\(^2\) and Part III (Economic evaluation)\(^3\) of the series were prepared in 2011, 2012, and 2013, respectively.

This Part IV (The relationship between the environment and the artefact) stems from the simple consideration that monuments are not independent “islands”. Hence, a central aim of the present report is to better understand the role of the anthropogenic activities in cities and the relevant connections at other spatial scales in determining the levels of pollutants affecting the studied UNESCO sites and thus the damage of the materials these objects are built with. This Part was not focused on all the five UNESCO sites previously studied but only on the three individual monuments located in the heart of European capitals.

This report is structured as follows. For three UNESCO sites (the Parthenon, Athens, Greece; the Klementinum, Prague, Czech Republic; and the Neues Museum, Berlin, Germany), the general framework of the socio-economic context of the cities where the cultural monuments are located is presented (geography and climate, population, energy profile, industry, transportation). Then, the main features of the development of air pollution in the cities are described and the major contributors of air pollution-related problems at the studied UNESCO sites are listed. Thereafter, maps showing the spatial distribution of selected pollutants (SO\(_2\), PM\(_{10}\), NO\(_2\), O\(_3\) and HNO\(_3\)) are shown. The impact of air pollution on materials is presented through corrosion and soiling maps derived by applying dose-response functions. Finally, some general consideration is made on the possible improvement of air quality close to these sites in order to prolong the maintenance intervals for restoration works.


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2 The Parthenon, Athens, Greece.

2.1 Geographic and climate profile of Athens

Athens, the capital and largest city of Greece, is located in the south-east of the country at 37° 58’ N and 23° 43’ E and extends across the central plain of the peninsula of Attica (3,808 km²). The basin is surrounded by high mountains: Parnitha Mt. (1,413 meters above sea level, asl) in the northern sector, Penteli Mt. (1,109 m asl) in the northeast, Hymettus Mt. (1,026 m asl) in the east and Aegaleo Mt. (468 m asl) in the north-northwest. The basin has an opening to the Saronic Gulf in the southwest (Figure 1).

Athens is built around a number of hills. The core municipality of Athens is located approximately 8 km from the Bay of Phaleron, an inlet of the Aegean Sea where the port of Piraeus is situated. The ancient site of Athens, where the Acropolis and the Parthenon are located, is centred on a rocky promontory 156 m asl. The Greater Athens Area (GAA), which extends beyond the metropolitan city of Athens, is typically urbanized. The areas around Parnitha are covered with forests, whereas areas to the south and the west of Athens are grassy or barren. Mount Hymettus is partly forested.

Athens has a subtropical Mediterranean climate, with alternation between prolonged hot and dry summers and mild, wet winters (Sindosi et al., 2003). The average temperature during summer is approximately 24° C while the average winter temperature (October to March) is approximately 13° C. January is generally the coldest month.

The city of Athens is affected by a strong urban heat island (UHI) effect, mainly caused by the accelerated industrialization and urbanization during the recent decades and linked to limited green and open space areas (Giannopoulou et al., 2011). In Athens, the daily heat island intensity exceeded 4° C in 20% of studied cases and was found to be as high as 10° C (Kassomenos and Katsoulis, 2006). Increased urban temperatures increase energy consumption and peak energy demand in summer. Furthermore, higher temperatures accelerate the rate of photochemical ozone production and increase the emissions of ozone precursors.

With an average of 400 millimetres of yearly precipitation, rainfall occurs largely between the months of October and April. July and August are the driest months. Flash floods are common in the area.

The Greater Athens Area is subject to sea and land breeze local circulation phenomena. The prevailing wind axis is along the axis of the basin (northeast/southwest), with anabatic/catabatic flows from the surrounding mountains (Melas et al., 1995).

The complex geomorphology of the basin entails significant difficulty in the dispersion of air masses over the city, especially during low ventilation periods and favour high pollutants concentrations (Ziomas, 1998; Chaloulakou et al., 2003; Grivas et al., 2008). Air pollution episodes may occur in Athens during all seasons of the year but most of these episodes are associated with the development of sea-breeze (Kallos et al., 1993). Athens plume is transported mainly towards south-east over the East Mediterranean Sea (Kanakidou et al., 2011).
2.2 Population

According to the Census performed by the Hellenic Statistical Authority (ELSTAT, 2013), the total population of Greece in 2011 was 10.815 million inhabitants, with 35.34% (3,827,624) of the total population living in the greater Athens area. The Athens urban area, spanning over 412 km$^2$, is among the most dense in the developed world with a population density of about 7,500 inhabitants per square kilometre. The municipality of Athens (the historic core city) has a population of 664,000 within its administrative limits and a land area of 39 km$^2$. At a population density of nearly 17,000 per square kilometre, Athens is among the most dense municipalities in the world.

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*Figure 1. The Athens Urban Area within the Attica Basin from space*. 

4 By NASA ([el:Athens_Landsat.jpg] [Public domain], via Wikimedia Commons
http://upload.wikimedia.org/wikipedia/commons/0/0f/%CE%97_%CE%B8%CE%AE%CE%BD%CE%B1_%CE%B1%CF%80%CF%8C_%CF%88%CE%B7%CE%BB%CE%AC.jpg
2.3 Energy

Greece relies on fossil fuel combustion for meeting the bulk of energy requirements. In 2011, Greece consumed about 27.5 million tons of oil equivalent (Mtoe). The total energy demand was covered mainly by solid fuels and oil products (79.5% of total consumption), followed by natural gas (13.5%), renewable energy sources as hydropower, solar, wind energy and geothermal (3.4%) and biomass (2.6%) (Hellenic Republic, 2014).

Lignite is a fuel of strategic importance for Greece since it is found in the Greek subsoil and has a low excavation cost and stable price. An important advantage of Greek lignite is its low sulphur content. Thermal power plants that are located near Athens use oil because the emissions of pollutants are less than those of the lignite. Almost all of the crude oils used in Greece are imported. Seven of the ten oil terminals and two of the four refineries in Greece are located in the Attica area. Natural gas has only been available in Greece since 1997. In 2004, natural gas covered only 7% of the total energy used in industry.

The electric power accounts for 27% of the country’s final energy requirements. Electrical power is mainly produced from fossil fuels, mainly lignite (52%), followed by natural gas (23.5%) and liquid fuels (diesel, heavy fuel oil and refinery gas), with a share of 8.5%. The rest of electricity production, i.e. around 16%, derives from renewable energy sources as hydropower, photovoltaic, wind energy and biogas. A high share of industries located in Attica such as machinery or transport equipment industries mainly use electricity, a clean final energy form.

Buildings and transportation are the most energy-consuming sectors in Greece. The transport sector consumed 46% of Greece’s total oil demand in 2008 while buildings account for approximately 36% of the total energy consumption. In general, Greek buildings are old and have no built-in state-of-the-art technology (partial or total lack of heat insulation; outdated technology windows/doors; inadequate maintenance of heating/air conditioning systems).

Although the use of natural gas for domestic heating purposes has increased lately in Greece, fuel oil is still primarily used for central heating. The most popular heating system in Greek buildings is a central oil-fired boiler (Papadopoulos et al., 2008). According to the Hellenic Statistical Authority (ELSTAT, 2014), 74.6% of the building stock in Greece was constructed before 1980 and have no thermal insulation protection. Energy saving measures (upgrading heating systems, use of automatic temperature control systems, thermal insulation of houses, etc.) could ensure fuel savings (Nikolaidis et al., 2009) and reduced atmospheric pollutants. The “Save at home” project was launched in 2010 to upgrade the energy efficiency of houses but it seems that it has not been exploited as fully as it could have been. Additional measures for dealing with local heating could be the development of Combined Heat and Power (CHP) systems and the improved use of Greece’s high solar potential since Greece and Athens have the privilege of sunshine almost all year round.

2.4 Industry

Greece is a services dominated economy. Some 72% of GDP is generated in the services sector, followed by industry (22%) and agriculture (6%). Within the services sector, tourism activities provide 15% of GDP.

More than 50% of Greek industry is located in the Greater Athens Area and Athens accounts for half of the jobs in industry and handicrafts. The industrial zones are located in the SSW part of the city of Athens and the Thriassion plain. Some other sources are located around the harbour of
Piraeus. The majority of the large size plants (refineries, cement industries, glass industries, metal industries, etc) are located in the west and southwest of the Attica Basin and the nearby Thriassion plain, several kilometres to the west of the GAA (Figure 2). The Thriassion plain is separated from the Athens basin by mount Aigaleo that acts as a barrier preventing most of the exchange of air pollutants between the industrialized area and the city (Melas et al., 1998).

To discourage new factories from further adding to the problem of atmospheric pollution and to stimulate the economic growth of other regions, an industrial wage tax has been imposed in the Athens area, and tax incentives have been offered to new factories that set up in other areas. However, the situation in the Athens area has to be associated with the situation in neighbouring prefectures since air movements transport air pollutants to long distances and the Athens’ atmospheric environment is influenced by all surrounding emissions sources.

Figure 2. Distribution of E-PRTR (The European Pollutant Release and Transfer Register)\textsuperscript{5} Facilities in the Attica region in the year 2011.

\textsuperscript{5}http://prtr.ec.europa.eu/
2.5 Transports and infrastructures

Over the past years, the city's infrastructure and the region-wide transport network have improved, in part due to the preparations for the Olympic Games in August 2004. Major infrastructure projects were funded, including the Eleftherios Venizelos International Airport, the expansion of the Athens Metro system, the construction of an extended high speed suburban railway network and new urban highways and ring roads to decrease congestion (like the Attiki Odos Motorway).

The Athens Mass Transit System includes the city's Metro, a commuter rail service, a bus fleet, a trolleybus fleet that mainly serves Athens's city centre, and a tram network which connect the city centre and the southern suburbs.

The Athens Metro network, that was expanded between 2000-2003, entailed the construction of 2 new lines (lines 2 and 3) that complemented the existing old and only line until 2000 (line 1). This resulted in the decongestion of on-road traffic, lower noise levels, improvement of the air quality of the Attica region as well as energy savings.

The bus service consists of an extended network of lines on which normal buses, electrically driven buses (trolleys), and natural gas buses run, serve Athens and the suburbs (and the airport). Additional urban transport systems consist of the tram, which runs from the city centre to the south suburbs and was inaugurated in the summer of 2004.

The Athens International Airport "Eleftherios Venizelos", which acts as a connecting node between the airport network of Greece and south-eastern Europe, was opened in March 2001. The airport is located about 20 km to the east of central Athens. According to data released by the Athens International Airport S.A. (AIA, 2013), in 2012 the airport welcomed 12.9 million passengers (8.4 million international and 4.5 domestic). Due to the seasonality characteristics of most Greek airports, a major increase in air traffic is observed during the peak months (July - August). The airport is served by air freight operators (total cargo uplift: 76.4 thousand tonnes in 2012). The total aircraft movements were 153.3 thousand in 2012.

Piraeus is the main port of Athens, the largest port in Greece, one of the leading ports in the Mediterranean (second largest in the Mediterranean Sea after Marseilles in France) and an important centre of the merchant marine, industry and transportation (20 million passengers and 1.5 million containers per year).

Although the percentage of car ownership in Greece is still lower than the EU average, economic development and improved living standards over the previous decades had a significant effect on the ownership of passenger cars. In 1990, the number of passenger cars in Greece was 1.7 million cars (1 car for every 6 inhabitants), while in 2010 this figure reached 5.2 million cars. Similar trends are also observed for the number of trucks, buses and motorcycles. This trend is shown to being decelerating as a consequence of the economic crisis.

The geographical distribution of motor vehicles in Greece follows the spatial distribution of population: Athens accounts for more than half of the cars and almost half of the buses and motorcycles in use in the nation (Table 1).
Table 1. Motor vehicles in circulation in Greece and Attica in 2012.

<table>
<thead>
<tr>
<th></th>
<th>Passenger cars</th>
<th>Trucks</th>
<th>Buses</th>
<th>Motorcycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Greece</td>
<td>5 167 557</td>
<td>1 318 918</td>
<td>26 962</td>
<td>1 546 306</td>
</tr>
<tr>
<td>Attica</td>
<td>2 757 460</td>
<td>281 240</td>
<td>12 503</td>
<td>695 799</td>
</tr>
<tr>
<td>Attica, % of total</td>
<td>53.4</td>
<td>21.3</td>
<td>46.4</td>
<td>45.0</td>
</tr>
</tbody>
</table>

Greece has one of the oldest fleet of vehicles in circulation in the European Union. The average age of passenger cars in Greece is 10.5 years, compared to an EU average of 8.2 years. The average age of trucks and buses, meanwhile, is 18 years in Greece, a figure that is partly due to the fact that many such vehicles are imported in used condition, mainly from Germany. The number of older and, hence, more polluting vehicles, is a significant part of passenger cars population (32%) as well as of light duty vehicles (40%), buses (42%) and two-wheel vehicles population (43%). The corresponding number for heavy duty vehicles (HDV) is much more important, representing the 71% the HDVs population (Progiou and Ziomas, 2011).

The passenger car fleet is dominated by gasoline fuelled cars falling in the <1.4 l class. The percentage of diesel passenger cars, 2% in 2006 and 4% in 2010, is very low compared with other European countries: about 70% in France, Spain, Belgium, Portugal, Luxemburg and about 50% in Italy, UK, Austria, Denmark, Finland and Ireland. In Greater Athens area and Thessaloniki circulation of diesel passenger cars has until 2012 been prohibited. The reason for introducing such a measure was the increasing atmospheric pollution in Athens. However, the ban on movement for passenger cars with diesel engines in Athens was cancelled in 2012. Diesel vehicles are known to be significant emitters of both NO\textsubscript{2} and PM\textsubscript{10}. Dieselisation has different impacts on pollutant emissions and these should not be neglected in order to make proper policy decisions.

In 2009, the Ministry of Environment, Energy and Climate Change introduced a package of measures for addressing air pollution from road traffic in urban centres. These measures concerned the application of new circulation taxes for all new vehicles according to their CO\textsubscript{2} emissions, a new withdrawal system for old passenger cars with financial incentives (set in early 2011 but with poor results because of the economic crisis) and the adoption in 2012 of traffic restriction measures for the older technology cars in the centre of Athens. There are two schemes. In the city centre (small ring or Athens ring, Figure 3) vehicles up to 2.2 tonnes are only allowed entry to the area on alternating days depending on the last digit of their license plate (odds or evens). In the whole Athens area (big ring or green ring) only vehicles over 2.2 tonnes and buses registered after 1.1.1990 (for 2013) are allowed (each calendar year the date is increased by a year). Exemptions are allowed for residents within the Athens ring road and for non polluting vehicles. The measures do not apply on Saturdays, Sundays, public holidays, days of 24-hour strikes of public transport and during the night.

One of the most important state-of-the-art infrastructure systems for the management of road traffic in Athens is the “Athens Greater Area Traffic Management System” (TMS). The system was first planned in 2002 and was completed in 2004. In addition, an internet-based map (http://www.transport.ntua.gr/map/) developed by the Laboratory of Railways and Transport of the National Technical University of Athens and referred to as the Athens Dynamic Traffic Map (ADTM), provide multimodal travel information about the complete metropolitan transport network (Figure 4). Traffic conditions are shown in colour (red for a congested section, green otherwise). The ADTM can support the decisions of road and public transport users to consider different mode choice options for a particular journey depending on the prevailing traffic conditions and/or the existence of incidents and special events (Stathopoulos & Tsekeris, 2008).
Figure 3. Boundary of the Athens (small) green ring. (Source: http://urbanaccessregulations.eu/countries-mainmenu-147/greece/athens).

Figure 4. Screenshot of the website Athens Dynamic Traffic Map (ADTM).
2.6 Emission inventories

Emission inventories for the reference year 2003 in a 2-km resolution grid (Markakis et al., 2010a) provide details of sector contribution to the air pollution over Athens (Table 2).

Table 2. Sector contribution (%) to the annual 2003 emission totals for Athens. 
(Source: Markakis et al., 2010a)

<table>
<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Central heating</th>
<th>Industry</th>
<th>Distribution of fuels</th>
<th>Solvents use</th>
<th>Road transport</th>
<th>Maritime</th>
<th>Industrial/household</th>
<th>Agriculture*</th>
<th>Total (kt year⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>-</td>
<td>8.0</td>
<td>3.2</td>
<td>-</td>
<td>-</td>
<td>75.6</td>
<td>0.2</td>
<td>12.9</td>
<td>0.1</td>
<td>473</td>
</tr>
<tr>
<td>NOₓ</td>
<td>2.6</td>
<td>3.1</td>
<td>22.4</td>
<td>-</td>
<td>-</td>
<td>51.0</td>
<td>3.1</td>
<td>17</td>
<td>0.8</td>
<td>78</td>
</tr>
<tr>
<td>SO₂</td>
<td>25.9</td>
<td>14.9</td>
<td>29.1</td>
<td>8.4</td>
<td>-</td>
<td>3.2</td>
<td>11.3</td>
<td>6.9</td>
<td>0.3</td>
<td>31</td>
</tr>
<tr>
<td>NMVOCs</td>
<td>2.1</td>
<td>3.2</td>
<td>2.1</td>
<td>2.0</td>
<td>13.8</td>
<td>70.6</td>
<td>0.5</td>
<td>5.6</td>
<td>0.1</td>
<td>93.2</td>
</tr>
</tbody>
</table>

* Including agricultural off-road machinery exhaust emissions and agricultural activities emissions

Im and Kanakidou (2012) calculated the contribution of major sectors to the total anthropogenic emissions of the major primary air pollutants in 2008 and how this changes between winter and summer. These changes are marked by the contribution of heating during winter (Table 3).

Table 3. Winter (December 2008) and summer (July 2008) sectoral contributions (in %) to the anthropogenic emissions in GAA. 
(Source: Im and Kanakidou, 2012. Supplement, Table S1).

<table>
<thead>
<tr>
<th></th>
<th>Heating</th>
<th>Industry*</th>
<th>Road</th>
<th>Non-road</th>
<th>Maritime</th>
<th>Solvent</th>
<th>Other**</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>Winter</td>
<td>21</td>
<td>56</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td></td>
<td>67</td>
<td>31</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>Winter</td>
<td>9</td>
<td>5</td>
<td>49</td>
<td>16</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td></td>
<td>4</td>
<td>51</td>
<td>22</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td>Winter</td>
<td>28</td>
<td>37</td>
<td>4</td>
<td>22</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td></td>
<td>45</td>
<td>8</td>
<td>37</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>NMVOC</td>
<td>Winter</td>
<td>6</td>
<td>2</td>
<td>37</td>
<td>43</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td></td>
<td>2</td>
<td>38</td>
<td>50</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>PM10</td>
<td>Winter</td>
<td>60</td>
<td>7</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td></td>
<td>16</td>
<td>31</td>
<td>24</td>
<td>18</td>
<td>11</td>
</tr>
</tbody>
</table>

* Industry includes energy, industrial combustion and industrial processes
** Other include agriculture, waste management, coal extraction and fuel distribution
A chemically speciated PM$_{10}$ emission inventory has been compiled for Greece in 10-km spatial resolution for the reference year 2003 (Markakis et al., 2010b). The PM$_{10}$ emission in Athens is estimated to 20596 t/year (11.3% of the national total). In Athens, the industrial sector appears to hold the majority of PM$_{10}$ emissions (Table 4).

Table 4. Sectoral contribution (%) to annual emission totals of PM$_{10}$ for Athens.
(Source: Markakis et al., 2010b)

<table>
<thead>
<tr>
<th>Source</th>
<th>% contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power plants</td>
<td>-</td>
</tr>
<tr>
<td>Industry</td>
<td>57.2%</td>
</tr>
<tr>
<td>Central heating</td>
<td>18.0%</td>
</tr>
<tr>
<td>Road transport*</td>
<td>13.0%</td>
</tr>
<tr>
<td>Maritime</td>
<td>1.9%</td>
</tr>
<tr>
<td>Agriculture**</td>
<td>0.8%</td>
</tr>
<tr>
<td>Industrial machinery</td>
<td>5.5%</td>
</tr>
<tr>
<td>Waste</td>
<td>3.6%</td>
</tr>
<tr>
<td><strong>Total (t/year)</strong></td>
<td>20 596</td>
</tr>
</tbody>
</table>

* Road transport includes exhaust emissions and non-exhaust emissions from tire wear, break lining and road abrasion.
** Agriculture includes off-road machinery exhaust emissions as well as other agricultural activities emissions that fall under the SNAP category.

These data do not contradict gridded emission data used for modelling purposes on the 50 km x 50 km EMEP grid and on the new gridding system at a resolution of 0.1° × 0.1° longitude-latitude in the WGS84 geographic coordinate system covering the Parthenon and based on officially reported emissions under CLRTAP.

From the above reported emission inventories, three main sources of pollutants can be identified in GAA: vehicular traffic (particularly for CO and NOx), industrial activities including energy (SO$_2$) and central heating emissions (SO$_2$ and PM$_{10}$). The two main source areas of pollutants are the city of Athens (mainly road traffic) and the industrial area around Elefsis, in the Thriasson Plain.

Shipping activities in the Piraeus harbour are also important sources of pollutants with influence on air quality in Athens. Although port emissions are not significantly contributing to the overall picture of ship-generated emissions, the impact of ship exhaust pollutants in urbanized ports has a direct effect on the human population and structures of cultural value, for which Athens has a particular interest. Mitigation strategies such as improved fuel quality (reduced sulphur and aromatics content) and the introduction of exhaust gas cleaning systems are effective and should be implemented on EU-scale (Viana et al., 2014). The low sulphur European directive for marine fuel use at berth (with less than 0.1% sulphur by weight) went into effect from the 1st of January 2010, whereas Greece has been exempted from compliance till the 1st of January 2012 (Tzannatos, 2010). The higher contribution of SO$_2$ emissions reflects the high sulphur content of marine fuels, as opposed to the significantly lower sulphur content of auto diesels.
2.7 Air Quality - Ground level air pollutants

In Greece, an extended air pollutant measurement network operates under the supervision of the Hellenic Ministry for the Environment, Physical Planning and Public Works. In the greater Athens area, the network consists of 18 stations that measure air pollutants of which 16 measure ground level ozone. The data are available to the public on the internet (www.minenv.gr) and reported through the European Environmental Agency (AirBase). Geographically, the stations cover places with different source characteristics (areas with dense road traffic emissions as well as residential urban, suburban and background areas).

Concentrations of air pollutants in the greater metropolitan area of Athens show a general declining trend. Figure 5 shows the measured concentrations of the main pollutants measured at the monitoring station GR0002A, situated approximately 800 meters from the Parthenon, for the period 1990-2011.

![Figure 5. Temporal trend of main atmospheric pollutants measured at station GR0002A, Athens, Greece.](image.png)

During the last decades, the Greater Athens Area (GAA) has suffered from severe air pollution problems mainly from particulates, nitrogen dioxide and less from ozone levels. The air pollution phenomenon in Athens is known as “the nephos” (the cloud, in Greek) a name that underlines its visible character.

As pointed out by several studies (Kallos et al., 1993; Moussiopoulos et al., 1995, Kassomenos and Koletsis, 2005; Aleksandropoulou et al., 2011; Progiou and Ziomas, 2011) air pollution problems in the Athens basin are associated with the emissions in the greater Athens area (mainly road traffic in
the city of Athens and the industrial area around Elefsis on the Thriasson Plain coast), the physiographic characteristics of the region (the Athens basin is surrounded by relatively steep mountains), and specific meteorological patterns (clear sky, intense sunlight, temperature inversions, sea-breeze circulations, low mixing layer height, etc).

A series of mitigation measures taken by the Greek authorities throughout the 1990s and adopted for the long-term abatement of air pollution (technological upgrade of passenger vehicles and public transport on-road fleet, introduction of various emissions control measures, use of higher quality fuels, promotion of railway transportation, further penetration of natural gas in the tertiary sector and households, etc.) resulted in the improvement of air quality. The appearance of smog has become less common; nevertheless, air pollution still remains an issue for Athens, particularly during the hottest summer days.

Non-exhaust sources (tyre-wear, break-lining, road abrasion, etc.) together with re-suspension of dust load, already deposited on the surface, contribute substantially to primary PM from road traffic. In Athens, Karanasiou et al. (2009) estimated a road dust contribution to be up to 34% of PM$_{10}$ of the urban background. Unlike the traffic exhaust emissions, this coarse part of the PM$_{10}$ load cannot be tackled by improving vehicles emissions.

Observations derived from three different satellite instruments revealed a large reduction, about 30 to 40 per cent, in the tropospheric NO$_2$ vertical columns over Athens from 2008 to 2010 (Vrekoussis et al., 2013). The decrease in ambient NO$_2$ was attributed to reductions in on-road traffic and industrial activities and energy use accelerated not only because of the measures taken but mainly as a consequence of the economic crisis Greece is suffering from. The Authors of the study also found that up to 30% of small-scale industries and enterprises around Athens ceased their activities adding both directly, via reduced industrial emissions and indirectly, via reduced on-road traffic, to the reduction in NOx emissions.

In recent years, new air pollution problems have occurred in Athens. In winters, the city sometimes is covered by smog caused by the particulate released into the atmosphere while burning firewood, which is more prevalent than usual because of the higher price of domestic heating fuel. PM$_{10}$ concentrations of 150 $\mu$g/m$^3$ have been measured in parts of the city.

PM$_{10}$ levels in Athens deserve a separate discussion. Over Athens, beside local anthropogenic activities, the particulate matter atmospheric load is expected to origin also from maritime aerosols produced at the sea surface by the winds. Additionally, increased PM$_{10}$ concentrations can be attributed to long range transport of aerosols such as desert dust originating from the North African arid regions (Samoli et al., 2011) or other extreme natural events, i.e., large forest fires and/or volcanic dust intrusions.

Kallos et al. (2007) indicated that 30–70% of violations of the Air Quality Standard (AQS) in Southern Europe occur as a result of Sahara dust transport. Grivas et al. (2008) analysed PM$_{10}$ concentration data collected by the Greek air quality monitoring network at 8 sites over the GAA, for the period of 2001-2004. The association of the PM$_{10}$ levels with backward trajectories indicated that a notable part of area-wide episodic events exceeding the AQS could be attributed to trans-boundary transport of particles. Aleksandropoulou and Lazaridis (2013) found that the contribution from African dust to PM$_{10}$ concentrations over the Athens Metropolitan Area on days with exceedances of the AQS during the period 2001-2010 was approximately 50% at traffic urban stations and 72% at the background suburban stations. Most of the African dust events contributed, on average, about 22.2% to the annual PM$_{10}$ concentrations.
The Parthenon (Figure 6), a cult temple dedicated to the goddess Athena, is part of the Athenian Acropolis, a group of four of the greatest masterpieces of classical Greek art of the 5th century B.C. representing the apex of ancient Greek architectural development: the Parthenon (447-432); the Propylaea (437-432); the Temple of Athena Nike (448-407); and Erechtheion, completed in 406.

The monuments and the site have been damaged many times since their original construction. The first incidence of damage to the monumental heritage of the Acropolis came at the time of the Herulian raid in 267 AD. The Parthenon was converted into a church by the Byzantines in the 5th century. After the fall of the Byzantine Empire in 1204, Athens was into the hands of Frankish lords from 1225 to 1308, which turned the Propylaea into a castle and catholic services were celebrated in the Parthenon. In 1456, the Parthenon was converted into a mosque by the Turks. In 1687, the Parthenon, used by the Turks as a gun powder magazine, was hit by cannon fire during a siege of Athens by the Venetian fleet of Admiral Morosini and exploded destroying the roof and much of the south facing columns. The east façade was severely damaged during the 1981 earthquake, when many marble fragments fell. In recent decades, atmospheric pollution has been one of the main factors causing damage to the surface of the monument.

Art treasures were pillaged on several occasions, starting with the Byzantines who brought them to Constantinople, continuing with the Venetians which pillaged the Parthenon for some of its admirable sculptures and ending in the 19th century when Lord Elgin, ambassador of the King of

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6 “The Parthenon Athens” by Steve Swayne - originally posted to Flickr as The Parthenon Athens. Licensed under CC BY-SA 2.0 via Wikimedia Commons - https://commons.wikimedia.org/wiki/File:The_Parthenon_Athens.jpg#/media/File:The_Parthenon_Athens.jpg
England, transferred panels of the marble to the British Museum with the official authorization from the Sultan.

The Acropolis and its surroundings are currently strongly protected under the provisions of the Greek legislative framework and the international Charters and Conventions for the protection of antiquities and cultural heritage. It was awarded UNESCO World Heritage Status in 1987. The World Heritage site extends over an area of 3.04 ha and is surrounded by a buffer zone of 117 ha. The legislative framework excludes any kind of industrial activities from the core and buffer zone. No indigenous peoples are resident in or regularly using the World Heritage property and/or buffer zone. Vehicle circulation is not permitted in and around the site. Furthermore, the Acropolis area is a no-fly zone.

The Acropolis has been operating as an archaeological site since 1833, shortly after the establishment of the modern Greek State. Between 1923 and 1933 a Greek engineer named Nikaloas Balanos rebuilt the north colonnade and part of the south colonnade. His efforts were something of a disaster, because he put column drums and whole blocks back in the wrong place and used iron clamps to hold blocks together. Uncovered iron clamps corroded and expanded, cracking and even destroying the marble.

For the restoration, conservation, protection and monitoring of the Acropolis, a multidisciplinary advisory body, the Committee for the Conservation of the Acropolis Monuments (ESMA), was founded in 1975. In the year 1999, the establishment of the Acropolis Restoration Service (YSMA), a special peripheral service of the Ministry of Culture & Sports, made possible the organization and development of a restoration and conservation project on the Acropolis for treating the structural problems of the monuments and the degradation of their surfaces. The project, co-funded by the Greek State and the European Union, may not be completed until 2020 and nearly $90 million will be needed to finish the work. The Acropolis restoration project is the biggest renovation ever conducted on a monument in the world.

The project aims to restore damage caused to the Acropolis by three different means: mechanical (damage caused by earthquakes, explosions, bombardments, fires, freezing, plunders, alterations and displacements connected with errors of previous restorations), chemical (erosion suffered by the marble mainly as a result of acid rain and air pollution), and biological (corrosion caused by lichens, moulds, bird-droppings, plant roots, etc.).

The Parthenon restoration project included the dismantling, block by block, and repairing nearly every piece of the Parthenon (each of the Parthenon's 70,000 pieces is unique and fits in only one place), removal of all the inappropriate materials placed during previous restorations, and the reintegration of scattered ancient material spread around the Acropolis. The monument was reassembled using the old stones, new stone infills (in Pentelic marble as the original) replacing missing stonework and consolidating materials that are compatible with the old structure.

Damage caused by modern air pollution was repaired by cleaning the surfaces of sculptured architectural members (e.g. the Parthenon Frieze, the high-relief metopes) with a dual-wavelength laser, with pulsed beams of ultra-red and ultraviolet radiation. With this cleaning method, soot deposits and black crust were removed to the desired depth without damage to the underlying layer of marble and preserving the features of ancient sculpting, traces of the ancient stone-cutter’s tools and the coloured layers on the surface.

Measures have been taken in order to reduce damage caused by air pollution, with the use of reversible materials. Air pollution is checked in an annual basis. Moreover, the architectural
sculptures that remained on the monuments (the Caryatids, the Western Frieze, etc.) were moved to
the Acropolis Museum and were replaced by copies. Furthermore, the provisions made for the
accessibility of the site (pedestrianization of peripheral to the property streets, the construction of
the new Acropolis metro station) helped reduce the atmospheric pollution of the area.

More than 1 million people visit the Acropolis each year producing a major flow of economic
benefits to local communities from activities in and around the World Heritage site but also an
anthropogenic pressure. Being located in the heart of the city (Figure 7), the Parthenon is subject to
the environmental pressure caused by air pollution from the metropolis. While major restoration
work will never be needed on the Acropolis for generations to come, degradation due to air
pollution will continue in the future if appropriate countermeasures will not be taken.

Figure 7. Location of the Parthenon in the heart of Athens.

The spatial distribution of air pollutants in Athens for the years 2001-2010 was derived from the
data of air pollutants collected by the local network of monitoring stations and reported to the
European Environmental Agency (AirBase, 2014).

The spatial distribution of SO$_2$ concentrations in the GAA in 2001 (Figure 8) clearly indicates two
spots with relatively high values. The first is located close to the Piraeus and reflects SO$_2$ released
by the harbour activities, the ship traffic or by the small industries located there, the second is
associated with the Metropolitan area of Athens and probably reflects the techniques used for
central heating based on oil combustion. In 2010 (Figure 9), SO$_2$ concentrations are markedly
reduced in Athens (at the Parthenon, from 12.6 µg/m$^3$ in 2001 to 6.5 µg/m$^3$ in 2010) but a new hot
spot appears (lower left of Figure 9) showing the high concentrations recorded at the GR0120A-
Koropi air quality monitoring station (not active in 2001) and probably associated with the activities
of the nearby airport.
The spatial distribution of NO₂ over Athens in the year 2001 and 2010 is reported in Figure 10 and Figure 11, respectively. NO₂ emissions are mainly due to the traffic either directly or through the transformation of NO. The highest levels are found in the central zone of the Metropolitan area of Athens and the western suburbs of Athens, where the Piraeus harbour, some industrial activity, and main road axes are located. NO₂ concentrations have a weak seasonal variability. Lower concentrations in the warm period could be associated to the reduction of the industrial activity and the vacations of Athenians in the summer. However, the enhanced traffic of the harbour during summer should increase the NO₂ concentration in the Piraeus area. Overall, there has been a general reduction in NO₂ concentrations in Athens. In the Parthenon area the reduction was from 73.9 µg/m³ in 2001 to 45.9 µg/m³ in 2010.

In general, the Metropolitan area of Athens presents serious problems of photochemical pollution. The highest annual average levels of O₃ concentration are found in the urban background stations while the O₃ concentration is reduced in the central zone of the metropolitan area. This could be attributed to differences of the traffic densities since NO destroys O₃ in the photochemical circle. O₃ presents strong seasonal variability due to its photochemical formation. High O₃ concentrations are usually found in the warm period of the year. However, in the Metropolitan area of Athens the problem is significant in winter as well. Small differences were found between the spatial distribution of mean annual concentration of O₃ over Athens between 2001 (Figure 12) and 2010 (Figure 13).

In 2001, high concentrations of PM₁₀ appear uniformly spread over large areas of the GAA (Figure 14). In the year 2010 (Figure 15) the centre of the city appears as the largest single PM₁₀ source. Average annual concentrations of PM₁₀ estimated at the Acropolis and the Parthenon are 53.3 µg/m³ in 2001 and 47.1 µg/m³ in 2010.

Nitric acid is not measured by the Athens Air Quality Monitoring Network, so atmospheric nitric acid concentrations were calculated from NO₂, O₃, relative humidity (Rh) and temperature (T) by using the following empirical function derived within the MULTI-ASSESS project (MULTI-ASSESS, 2005):

\[ HNO₃ = 516 \times e^{−3400/(T + 273)} \times \left[NO₂ \times [O₃] \times Rh\right]^{0.5} \]

where

\[ [HNO₃] \quad \text{= annual average concentration, µg m}^{-3} \]
\[ [NO₂] \quad \text{= concentration, µg m}^{-3} - \text{annual average} \]
\[ [O₃] \quad \text{= concentration, µg m}^{-3} - \text{annual average} \]
\[ T \quad \text{= temperature, °C – annual average} \]
\[ Rh \quad \text{= relative humidity, % - annual average} \]

The spatial distribution of the mean annual concentrations of HNO₃ over Athens is shown in Figures 16 and 17 for the years 2001 and 2010, respectively.
Figure 8. Spatial distribution of mean annual concentration of SO$_2$ ($\mu$g/m$^3$) over Athens (year: 2001).

Figure 9. Spatial distribution of mean annual concentration of SO$_2$ ($\mu$g/m$^3$) over Athens (year: 2010).
Figure 10. Spatial distribution of mean annual concentration of NO\textsubscript{2} (µg/m\textsuperscript{3}) over Athens (year: 2001).

Figure 11. Spatial distribution of mean annual concentration of NO\textsubscript{2} (µg/m\textsuperscript{3}) over Athens (year: 2010).
Figure 12. Spatial distribution of mean annual concentration of $O_3$ (µg/m³) over Athens (year: 2001).

Figure 13. Spatial distribution of mean annual concentration of $O_3$ (µg/m³) over Athens (year: 2010).
Figure 14. Spatial distribution of mean annual concentration of PM$_{10}$ (µg/m$^3$) over Athens (year: 2001).

Figure 15. Spatial distribution of mean annual concentration of PM$_{10}$ (µg/m$^3$) over Athens (year: 2010).
Figure 16. Spatial distribution of mean annual concentration of $\text{HNO}_3$ ($\mu\text{g/m}^3$) over Athens (year: 2001).

Figure 17. Spatial distribution of mean annual concentration of $\text{HNO}_3$ ($\mu\text{g/m}^3$) over Athens (year: 2010).
The methodology used for the estimation of the damage due to attack of atmospheric pollutants at the selected UNESCO cultural heritage sites is based on the use of the dose-response functions, first year exposure, for the multi-pollutant situation:

\[ R = 4.0 + 0.0059[SO_2]_{Rh60} + 0.054Rain[H^+] + 0.078[HNO_3]_{Rh60} + 0.0258PM_{10} \]

where

- \( R \) = surface recession, \( \mu m \)
- \( Rh_{60} \) = \( Rh - 60 \) when \( Rh > 60 \), 0 otherwise (\( Rh \) = relative humidity, % - annual average)
- \( Rain \) = amount of precipitation, mm year\(^{-1}\) - annual average
- \([SO_2]\) = concentration, \( \mu g \) m\(^{-3}\) - annual average
- \([H^+]\) = concentration, mg l\(^{-1}\) - annual average
- \([HNO_3]\) = annual average concentration, \( \mu g \) m\(^{-3}\)
- \( PM_{10}\) = annual average concentration, \( \mu g \) m\(^{-3}\)

The multi-pollutant dose-response function relates damage to limestone, expressed as surface recession rate, to a range of atmospheric pollutants: sulphur dioxide (\( SO_2 \)), nitric acid (\( HNO_3 \)), total acidity of rainfall (\( H^+ \)), and particulate matter (\( PM_{10} \)). Environmental parameters also play a role, as reflected by the presence in the dose-response function of the two terms amount of precipitation (\( Rain \)) and relative humidity (\( Rh \)).

Figure 18 and Figure 19 show the corrosion maps for limestone based on the pollution data for the city of Athens related to the year 2001 and 2010, respectively. The maps show some differences between areas, with a higher rate of corrosion in the area of the port of Piraeus. Between 2001 and 2010 it is also possible to observe a slight decrease of the recession rate for limestone in most of the city of Athens. The decrease in correspondence of the Parthenon is about 4% (5.5 \( \mu m \) year\(^{-1}\) in 2000 and 5.3 \( \mu m \) year\(^{-1}\) in 2010).

Predicted soiling rate of limestone in the Great Athens Area was calculated by applying the dose-response function:

\[ \Delta R/Ro = 1 - \exp(-PM_{10} \times t \times 6.5 \times 10^{-6}) \]

where \( \Delta R/Ro \) is the relative loss of reflectance, \( PM_{10} \) is the concentration of \( PM_{10} \) (\( \mu g \) m\(^{-3}\)), \( t \) is the time (days) and 6.5 \( \times 10^{-6} \) is a soiling constant for limestone.

This dose-response function was used to predict the loss in reflectance after 5 years as a function of the ambient \( PM_{10} \) concentrations to which the material is exposed. The maps showing the predicted 5-years loss in reflectance for limestone in Athens are reported in Figures 20 and 21 for the years 2001 and 2010, respectively.

Despite the decrease in atmospheric concentrations of \( PM_{10} \), the loss of reflectance after five years estimated for the marbles of the Parthenon according to the 2010 concentrations is still approximately 43%. The “tolerable soiling before action”, which represents the threshold triggering significant adverse public reaction of what constitutes acceptable soiling, is generally set at 35%. This means that the time period for which the Parthenon could remain without cleaning should not exceed 4-5 years. For cultural heritage objects a period of 10-15 years is considered to be appropriate.
Part IV – The relationship between the environment and the artefact

Fig. 18. Limestone corrosion map (µm year⁻¹) for the city of Athens (year: 2001)

Fig. 19. Limestone corrosion map (µm year⁻¹) for the city of Athens (year: 2010).
Figure 20. Limestone soiling map (% loss in reflectance after 5 years) for Athens (year: 2001).

Figure 21. Limestone soiling map (% loss in reflectance after 5 years) for Athens (year: 2010).
2.9 References


3 The Klementinum, Prague, Czech Republic.

3.1 Geographic and climate profile of Prague

Prague is situated in the centre of Europe (distance from the Baltic Sea 365 km, from the North Sea 495 km and from the Adriatic Sea 490 km). It is the capital of Czech Republic and is located in the north west of the country, at latitude 50° 05’ N, longitude 14° 25’ E. It is not only the largest city of Czech Republic, but it is also the largest industrial, political, cultural and religious centre.

The city is situated in the centre of the Bohemian Basin on the banks of the Vltava River, upstream of the confluence of this river in the Elba and downstream of the confluence of the Berounka and Sazava in it. The city is spread over several hills, covering an area of 496 km². The highest point of the city (399 m) lies in the south-west, on the plateau of Zličín, while the lowest (177 m) is the River Vltava at the northern edge. Bohemia is surrounded by relatively low mountains, including Ore, Giant (Krkonose) Mountains and the Sumava (Czech Forest) mountains. Mount Sněžka (1,602 m) in the Giant Mountains at the northeast edge is also the highest point of Czech Republic.

Prague has a temperate continental climate. The average yearly air temperature in the city centre reaches 9°C. The temperature in Prague is influenced markedly by the urban heat island (UHI) (Brázdil and Budíková, 1999) and the mean temperature in the city centre (Praha-Karlov) is 1-2 °C higher than the outskirt of Prague (Praha-Ruzyně). The intensification of the UHI is usually correlated with an increase in the size of the urban population, the extension of the urban built-up areas and the increasing consumption of energy. Highest temperatures are detected in summer, with maximum average temperature of 20.2 °C in the centre of the city. The coldest months are January and February, where temperatures drop below the zero.

Long-term averages of annual precipitations for the period 1961-1990 are 446.6 mm at Prague Karlov and 525.9 mm at Prague Ruzyně. May, June, July and August are the months when rainfall is more plentiful (Czech Statistical Office, 2013).

The prevailing wind direction at the most representative meteorological station of the region at Praha-Ruzyně (the Prague airport) is from the west. The mean speed keeps usually under 3 m/s inside the city centre. In the outskirts, the wind speed exceeds 3.5 m/s and even 4 m/s towards the north and the west, mainly due to orografic features (Hošek and Sládek, 2007).

Prague lies in a depression of Vltava Valley, so it is often the subject of air pollution events. Temperature inversions are relatively common between mid-October and mid-March bringing foggy, cold days and sometimes moderate air pollution.

3.2 Population

Population of Prague, at 31 December 2012, was 1,246,780 inhabitants (2,156,000 in the metropolitan area), that is almost 12% of the total population of the Czech Republic (10,516,125), while population density per km² was 2,503. For comparison, the population density of the Czech Republic is 133 inhabitants per km² on a total territory of 78,866 km².

Prague is divided into 22 administrative districts. These city districts are significantly different in urbanization level, population density, technical infrastructure quality and socio-economic life conditions of their inhabitants. The historical centre of Prague, where the Klementinum is located, is designed as Praha 1 district and has an area of 5.54 km² and 34,581 inhabitants (density: 5,275
inh./km² The districts adjacent to Praha 1 are characterized by a high number of inhabitants or a large population density.

### 3.3 Energy

In 2010, Czech Republic consumed 44.7 million tons of oil equivalent (Mtoe). The total energy demand was covered mainly by solid fuels, crude oil and petroleum products (60% of total consumption), followed by natural gas (18%), nuclear (16%) and renewable energy (6%). In the same year gross electricity generation was 85.91 TWh. Electrical power is mainly produced from solid fuels (55%), followed by nuclear (32.7%), natural gas (4.8%) and renewable (7.6%).

The highest final energy consumption is the industry sector (36.6% in 2011) due to the high proportion of energy-intensive industries in the Czech economy (production of metals and metallurgical processing, production of non-metallic mineral products and the chemical and petrochemical industries). Household is another important sector in energy consumption in the Czech Republic (24.6%) while the transport sector accounted for 24.9% of the total consumption in 2011.

Prague is mainly powered by combined heat and power (CHP) stations fuelled primarily by coal and gas, but is also supplied with nuclear power and some hydroelectricity. The consumption of fuels and energy in the Capital City of Prague in 2011 is shown in Table 5 (Czech Statistical Office, 2013).

Table 5. Consumption of fuels and energy in Prague.

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking coal/other bituminous coal</td>
<td>1.473.580</td>
<td>Tonnes</td>
</tr>
<tr>
<td></td>
<td>32.341.783</td>
<td>GJ</td>
</tr>
<tr>
<td>Lignite/brown coal</td>
<td>25.829.792</td>
<td>Tonnes</td>
</tr>
<tr>
<td></td>
<td>298.171.482</td>
<td>GJ</td>
</tr>
<tr>
<td>Coke</td>
<td>18.452</td>
<td>Tonnes</td>
</tr>
<tr>
<td></td>
<td>424.259</td>
<td>GJ</td>
</tr>
<tr>
<td>Natural gas</td>
<td>806.228</td>
<td>Thousand m³</td>
</tr>
<tr>
<td></td>
<td>27.411.742</td>
<td>GJ</td>
</tr>
<tr>
<td>Low sulphur fuel oil</td>
<td>11.435</td>
<td>Tonnes</td>
</tr>
<tr>
<td></td>
<td>461.979</td>
<td>GJ</td>
</tr>
<tr>
<td>High sulphur fuel oil</td>
<td>1</td>
<td>Tonnes</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>GJ</td>
</tr>
<tr>
<td>Motor gasolines</td>
<td>73.057</td>
<td>Thousand litres</td>
</tr>
<tr>
<td></td>
<td>2.362.415</td>
<td>GJ</td>
</tr>
<tr>
<td>Diesel oil</td>
<td>467.666</td>
<td>Tonnes</td>
</tr>
<tr>
<td></td>
<td>19.969.324</td>
<td>GJ</td>
</tr>
<tr>
<td>Heat energy</td>
<td>619.256.667</td>
<td>GJ</td>
</tr>
<tr>
<td>Electricity</td>
<td>14.339.982</td>
<td>MWh</td>
</tr>
</tbody>
</table>

Source: Statistical Yearbook of Prague 2011.
Energy consumption has declined slightly in recent years, with a decrease in traditionally more polluting sources, and a small increase in renewable and gaseous fuels. Even the percentage of electricity consumption increases.

Prague has a high residential energy consumption level. Prague has gradually increased spending to subsidize the replacement of fossil-fuel-based energy sources with cleaner and/or renewable sources. The primary focus is on shifting fuel use by residents away from coal and towards natural gas, or on connecting them to the city’s central heating system. The residential stock of the eastern part of the city is currently connected to a wide municipal district heating system. Thermal energy from the Mělník power plant, located close to Prague, is used to heat and supply hot water to approximately one third of Prague. No district heating system is present in the city centre (Prague 1 and Prague 2 districts), where protected heritage zones are located. In these districts, most of the buildings were built before 1900 and typically are heated with natural gas-fired boilers.

3.4 Industry

Czech Republic is a services dominated economy. About 60% of GDP is generated in the services sector, followed by industry (37%) and agriculture (2%). The auto industry is the largest single industry. About 25% of the Czech GDP is generated in the city of Prague.

Prague has a dynamically developing services sector but is also a strong and prominent industrial centre. Registered companies with more than 100 employees in the industrial sector were 226 in 2011, the employees were 80148. Most industries present in the territory of Prague are related to food products manufacture (36 enterprises with 10,607 employees in 2012), electrical equipment (17 enterprises with 13,877 employees), machinery and equipment not elsewhere classified (21 enterprises and 6,440 employees), metal products, except machinery and equipment (16 enterprises and 2,804 employees), other non-metallic mineral products (16 enterprises and 5,736 employees), motor vehicles (10 enterprises and 4318 employees), repair and installation of machinery and equipment (15 enterprises). Figure 22 shows the location of the facilities in Prague and surroundings inscribed in the E-PRTR register.

Figure 22. Distribution of E-PRTR (The European Pollutant Release and Transfer Register) facilities in Prague and surroundings in 2011.
3.5 Transport and infrastructure

Prague Integrated Public Transport (PID) serves the whole City of Prague and part of the adjacent territory of the Central Bohemian Region. PID includes metro, trams, urban and suburban bus lines, railways, ferries and the Petřín funicular (Department of Transportation Engineering, 2013).

Prague has a relatively well functioning public transport with a backbone system of the metro and networks of tram railways and buses. The metro network in Prague comprises three lines with an operating length of 59.1 km and 57 stations (transfer stations counted twice). The tram network (30 lines) has an operating length of 142.4 km (52% dedicated track bed). The bus network is based on 135 urban lines with a total length of 1629 km (687 km operating length in Prague). The PID railway network within Prague is based on 16 lines and 11 tracks with an operating length of 160.0 km and 44 stations.

Annually, more than 1.3 billion passengers use public transport vehicles. Passengers using subway are the most common (589 million in 2012, 45.65% of the total), followed by passengers in buses (358 million passengers, 27.74 %) and by passengers in trams (322 million passengers per year, 24.97%). The PID railway network only transports 18.8 million passengers per year (1.46%). River ferries across the Vltava and the Petřín funicular are minor elements of PID and serve specific needs, i.e. the primary importance of ferries is for recreational travel.

The network is completed by 3966 km of roads, of which 10 km are motorways and 98 km are main motor roads within the city. Many motorways depart from Prague including D1 to Brno and Bratislava, D8 from Prague to Dresden and Berlin, D5 to Nürnberg (under construction) and the planned motorway to Linz.

The cycle route network in the City of Prague has a total length of 530 kilometers. However, only 1% of trips on city territory over the workday are performed by bicycle transport.

The performance of the existing infrastructure is optimized by the Traffic Information Centre (TIC) of Prague, which offer information services in monitoring and classifying traffic levels. New traffic signals are equipped with technologies that provide priority for public transport vehicles.

The largest airport of Prague (Vaclav Havel International Airport) is located in Praha-Ruzyně, at the northwest edge of the city, about 11 km from the center. In 2012 a total of 10.8 million passengers were checked through at the airport in Prague (the overall capacity of terminals is 15.5 million passengers per year). In 2012, a total volume of 52,977 t was transported by air freight (capacity of 200,000 t/year). The number of aircraft movements in 2012 totaled 131,564, less than in 2011 (a fall of 12.6 %). The airport is served by several PID bus lines. Long-distance and regional bus lines also pass through it. However, individual automobile transport is the predominant method used by people between the airport and the city. In the absence of any rail connection, this creates a traffic and environment burden on the surrounding area.

In comparison with other Czech cities, Prague is well above average in terms of road traffic. In 2012, the number of registered motor vehicles in Prague was 895,581 with a number of passenger cars of 696,457 (Table 5). In the same year, the number of motor vehicles registered in the Czech Republic was 6,356,522, with 4,706,325 passenger cars. In 2011, the motorisation rate in Prague was at the level of 538 passenger cars per 1,000 inhabitants (Czech Republic = 435 cars per 1,000 inhabitants), above the average EU28 of 484 (EUROSTAT, 2015). Within the EU28, the motorisation rate in the Czech Republic is below average, however, among the EU12 new member states, it is one of the highest (EU12 average is 368 vehicles x 1,000 inhab.⁵).
Table 6. Number of registered motor vehicles in Prague.

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger cars, including vans</td>
<td>649,707</td>
<td>671,335</td>
<td>696,457</td>
</tr>
<tr>
<td>Lorries</td>
<td>118,427</td>
<td>113,429</td>
<td>109,198</td>
</tr>
<tr>
<td>Road tractors</td>
<td>1,677</td>
<td>1,539</td>
<td>1,219</td>
</tr>
<tr>
<td>Semi-trailers</td>
<td>4,221</td>
<td>4,608</td>
<td>5,294</td>
</tr>
<tr>
<td>Buses</td>
<td>3,616</td>
<td>3,715</td>
<td>3,790</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>75,702</td>
<td>77,393</td>
<td>79,623</td>
</tr>
</tbody>
</table>

Source: Statistical Yearbook of Prague 2013. Czech Statistical Office, Prague

For all categories except for vans up to 3.5 t, the age of the vehicle fleet in the Czech Republic is very high. The average age of the passenger-car fleet is 13.7 years in the Czech Republic and 13.11 years in Prague, compared to an EU average of 8.2 years. Assuming economic growth, the sales of new vehicles can be expected to gradually increase and the age of the vehicle fleet to decline. However, given the high proportion of older vehicles in the vehicle fleet, fleet renewal will only be very slow in absence of measures to support the scrapping of vehicles from the register.

The proportion of diesel passenger cars in the total number of registered passenger cars has been growing significantly, accounting currently for about one quarter of the total vehicle fleet. Based on new vehicle registrations, where diesel accounted for a 39.9% share in 2010, it is likely to continue growing. Alternative fuels and propulsions (CNG passenger cars, electric cars and hybrid vehicles) account for a very small proportion in the passenger-car fleet and have only a marginal role. Only conversions of petrol engines to LPG being relatively more frequent (approximately 135,500 such conversions registered in 2010).

Although the vehicle mix according to the EURO emission standards is gradually improving, it is still unfavourable in the Czech Republic. Approximately 18% of the passenger-car and light commercial vehicle fleet did not comply with any emission standard in 2010 and only 7.3% of the vehicles complied with the most stringent EURO 5 emission standard. The largest proportion of vehicles without any EURO emission standard was in the bus fleet (27.6%). By contrast, the situation was relatively favourable for trucks, where approximately 75% of these vehicles were compliant with EURO 3 to 5 emission standards.

Road transport is a factor significantly affecting the quality of environment in Prague. With the aim to minimize the impacts due to traffic congestion, Prague administration has realized different schemes in place, including a cycle route network, the creation of new pedestrian zones, the introduction of a low emission zone (LEZ) starting 01.01.2016, a Permit Scheme for lorries and an Access Control Scheme (ARS) for coaches/tour buses.

Prague is the first city in the Czech Republic to declare a low-emission zone on part of its territory (Figure 23). Only vehicles that meet certain emission standards (Euro 1 for petrol fuelled vehicles and Euro 3 for diesel vehicles) will be allowed to enter into the LEZ while the most polluting vehicles are restricted from entering or fined if they enter in the LEZ. Exemptions will be allowed for vehicles owned by anyone residing in the LEZ and special vehicles.
3.6 Emission inventory

In the Czech Republic, emission inventories of air pollutants and greenhouse gases are carried out by the Czech Hydrometeorological Institute (CHMI) at national and administrative units (region or districts) scale. In the Register of Emissions and Air Pollution Sources (the corresponding Czech acronym is REZZO), sources are divided into four categories: REZZO 1 (large stationary pollution sources) include combustion plants with thermal output above 5 MW and major technologies; REZZO 2 (mid-sized stationary pollution sources) encompasses combustion plants with thermal output between 0.2 and 5 MW and medium-sized technologies; REZZO 3 (small stationary pollution sources) includes all local furnaces and minor boilers with a power not exceeding 200 kW; REZZO 4 includes mobile pollution sources (road and motor vehicles, railway vehicles, boats, vessels, and aircraft).

The number of registered air pollution sources in Prague in 2011 was 3093 (213 in category REZZO 1 and 2880 in category REZZO 2). Regarding this latter category, 21 sources used solid fuel, 36 liquid fuel and 2495 gaseous fuel (Prague City Hall, 2013). The emissions generated by stationary and mobile sources in 2008-2010 are reported in Table 6 (Czech Statistical Office, 2013).
Table 7. Emissions of main pollutants into air in the Capital City of Prague (Tonnes)

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REZZO 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>96.1</td>
<td>93.3</td>
<td>94.0</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>1257.7</td>
<td>1142.0</td>
<td>975.9</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>2488.9</td>
<td>2377.7</td>
<td>1968.4</td>
</tr>
<tr>
<td>CO</td>
<td>552.0</td>
<td>466.1</td>
<td>428.5</td>
</tr>
<tr>
<td><strong>REZZO 1-3</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>575.2</td>
<td>586.5</td>
<td>572.3</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>1717.4</td>
<td>1635.0</td>
<td>1513.9</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>3103.2</td>
<td>3020.6</td>
<td>2657.6</td>
</tr>
<tr>
<td>CO</td>
<td>2204.3</td>
<td>1872.1</td>
<td>2056.7</td>
</tr>
<tr>
<td><strong>REZZO 1-4</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>2320.4</td>
<td>2164.9</td>
<td>2121.7</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>1768.9</td>
<td>1684.4</td>
<td>1559.5</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>8603.6</td>
<td>8107.0</td>
<td>6914.0</td>
</tr>
<tr>
<td>CO</td>
<td>19666.9</td>
<td>18343.9</td>
<td>15288.3</td>
</tr>
</tbody>
</table>

Air emissions were reduced in recent years due to the decrease in fuel consumption, the change in fired fuel structure and the improvement in technologies. Large stationary pollution sources (REZZO 1) account for about 62.6% of SO$_2$ emissions while mobile sources (REZZO 4) account for about 62% and 73% of NO$_x$ and PM$_{10}$ emissions, respectively.

These emission data do not contradict gridded emission data used for modelling purposes on the 50 km x 50 km EMEP grid and on the new gridding system at a resolution of 0.1° × 0.1° longitude-latitude in the WGS84 geographic coordinate system covering the Klementinum and based on officially reported emissions under CLRTAP.

### 3.7 Air Quality - Ground level air pollutants

The City of Prague monitors its air quality through a network of 17 automated measuring stations covering places with different source characteristics (areas with dense road traffic emissions as well as industrial, urban and suburban background areas) and supplemented with manual measuring stations. This network is managed by the Czech Hydrometeorological Institute, CHMI (www.chmi.cz). All information on ambient air quality in the Czech Republic (including emission sources and atmospheric deposition) is summarised annually in tabular overviews and yearbooks (available also in English) published by the CHMI (2012). Aggregated information about environmental pollution is presented on the Internet by the Municipality of Prague.

Figure 24 reports the annual mean concentrations of the main pollutants measured at the monitoring station CZ0AREP, Praha 1 Namesti Republiky, situated approximately 900 meters from the Klementinum, for the period 1996-2011.
Although there has been a large decrease in the industrial emissions in recent years, air quality is still the biggest problem of Prague’s environment. Infrastructural changes in the early nineties had a strong positive effect on Prague air quality. Closing down of many inefficient and outdated small industries, termination of operation of a large coal fired power plant situated in the vicinity of the city centre, modernization of technologies for local heating with the use of natural gas in place of low quality coal, and the adoption of environmental legislation resulted in improvements of urban environmental quality. However, Prague is still amongst the most polluted areas in the Czech Republic.

The data collected by the monitoring stations show that the urban atmosphere in Prague is now, similarly to other European cities with dense traffic, dominated by automotive emissions (Braniš, 2009). However, domestic heating is also an important pollution source.

Concentrations of $\text{SO}_2$ have dropped significantly in Prague and now does not represent an important air polluting compound. $\text{NO}_2$ and $\text{PM}_{10}$ concentrations decreased significantly in the first half of the nineties but have remained rather stable or increased since 2000. These trends can be explained by a reduction of importance of traditional urban sources of pollution, such as coal and oil combustion for local and central heating, together with a decrease in transport from large emission sources situated outside of Prague being replaced by a rapid increase of traffic density and pollutants from automotive transport (namely $\text{PM}_{10}$ and $\text{NO}_2$) (Braniš, 2008). It seems that, in addition to traffic, incomplete biomass combustion with current heating appliances (e.g. domestic boilers, wood stoves and fireplaces) can be a major source of particulate pollution in Prague. It was calculated that the contribution of biomass combustion to $\text{PM}_{2.5}$ in Prague ranged between 27% and 53% (Saarikoski et al., 2008).
3.8 Implications on the UNESCO Cultural Heritage Site: The Klementinum

The historic centre of Prague is a rare example of continuous urban and architectural development of a city from the Middle Ages to the present day. Built between the 11th and 18th centuries, the Old Town (Staré Město), the Lesser Town (Malá Strana) and the New Town (Nové Město) highlight the prominent role of Prague in the political, economic, social, and cultural evolution of central Europe. Thanks to its exceptional cultural and historical values, the historical core of Prague was inscribed on the UNESCO World Heritage List in 1992. The boundaries of the site define a property constituted of two components: the Historic Centre (866 ha in size) and Průhonice Park (251 ha). The World Heritage property is surrounded by a buffer zone covering an area of 9,887 ha. In this buffer zone the development of disproportional volumes and buildings that may impact on panoramic views is prohibited.

Prague is rich in outstanding monuments from all periods of its history. The large complex of the Klementinum (Figure 25) is located right in the historical centre of Prague (Old Town). With an area of almost 2 hectares, it is the second largest historical complex after Prague Castle and ranks among the largest architectural complexes in Europe. The complex was founded by the Jesuits after

![Figure 25. The Klementinum, Prague, Czech Republic](https://commons.wikimedia.org/wiki/File:Klementinum,_z%C3%A1pad.jpg#/media/File:Klementinum,_z%C3%A1pad.jpg)

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7 "Klementinum, západ" by Daniel Baránek. Licensed under CC BY-SA 3.0 via Wikimedia Commons - https://commons.wikimedia.org/wiki/File:Klementinum,_z%C3%A1pad.jpg#/media/File:Klementinum,_z%C3%A1pad.jpg
their arrival in Bohemia in 1556. Initially, members of the order lived in a former Dominican monastery of St. Clement (this small church later gave a name to the entire complex, The Klementinum) but then they started to build a Jesuit College in several stages. The first buildings were erected between 1560 and 1561, followed by an addition of a school wing in the years between 1576 and 1577 and of the Church of the Most Holy Saviour (or Salvator). The most intensive period of building activity took place between the years 1653 and 1726, with subsequent work on the decoration of the interiors. During their residence the Jesuits established the Klementinum as a centre of education and in 1616 their college was elevated to the status of university.

Some of the most attractive features of the complex include the Clock Tower, the Astronomical Tower (52 metres high, where meteorological measurements have been collected since 1775) with a statue of Atlas on its top, the Church of the Immaculate Conception of the Virgin Mary, the Mirror Chapel (formerly called the Chapel of the Annunciation of the Virgin Mary), the Baroque Library Hall and the Meridian Hall. The Klementinum is nowadays the home of the National Library. The façades are early and high Baroque, more decorative on the street side and more simple and plain on the insides. The public areas such as the corridors, classrooms, chapels or the library are richly decorated.

During the whole 18th and 19th centuries there weren’t any major architectural changes in the Klementinum. Significant building alterations of the complex for library purposes were carried out between the years 1924 and 1936. In August 2002 heavy rainfall led to the worst flood in Prague in five hundred years. The Klementinum, which is situated near the Vltava river with a minimum difference in altitude, was not as much affected with floods as other buildings, but the damage was still serious. The collections of the National Library of the Czech Republic and the Prague Municipal Library were inundated. Statics of the Klementinum was not disturbed but some damage became evident in the Klementinum area later. The damage is being recovered step by step.

A major restoration maintenance and renovation program of the historic buildings of Prague has been promoted and implemented by the Czech Government and by the City of Prague. In 2005, repair work was done on the peripheral cladding of the Klementinum's Main Courtyard and Vine Courtyard. The facades, cornices and extant architectural elements in the Main Courtyard were repaired and got a new coat of paint, while conserving the original plaster to the greatest possible degree. Windows were also repaired. Sundials in the Vine Courtyard and the fountain in the middle of the courtyard, a rare work from 1676, were restored as well. In 2007, the reconstruction of the area to Karlova Street (which had been in the state of disrepair as it had not been used for many years) and the repairs to the internal façades including the window repair and renovation was completed.

The most recent modernization of the user facilities and the restoration work within the Klementinum complex commenced in 2010. The objective of the project, divided into four phases, is the maximum restoration of the original layout of the complex and, at the same time, the securing of library operations with the use of state-of-the-art information technologies. The completion of the overall rehabilitation of the Klementinum complex is planned at the turn of 2017 and 2018. A substantial part of the works is a restoration of art elements and art-craft decorations of the Klementinum.

In September 2012, the second phase commenced with the renovation of the west wing along Křižovnická Street (the oldest part of Klementinum, built after 1653) and of the buildings around the Student Courtyard. The construction work largely consisted in the replacement of roofing and the removal of floor layers on all floors of the west wing, the cleaning and repair of the main façade
of the western wing along Křižovnická Street and cleaning the ceiling frescoes on the second floor. A number of unique historical elements have been discovered during the reconstruction. Extensive archaeological excavations revealed construction remains of buildings prior to the founding of the monastery. Archaeological surveys have proved that the Jesuit buildings had made use of most of the walls of the medieval monastery.

The rapid economic development of Prague during the last two decades has generated many pressures on the historic areas ranging from the change of the population structure to building substitution and transformation, to the growth of private traffic and the development of tourist-related activities (hotels, restaurants and shops). Resident population in the historic centre in the past two decades decreased about 25%. At the same time, the pressure for the location of offices and business agencies in the centre has increased.

Being located in the heart of the city (Figure 26), the Klementinum is exposed to air pollution from local sources but mainly to traffic due to the adjacent main road Křižovnická street. According to the Department of Transportation Engineering (2013) the intensity of car traffic was about 23,400 vehicles on this very busy road during a working day in 2012. For example, Figure 27 shows NOx emissions (t year\(^{-1}\) km\(^{-1}\)) in central Prague and around the Klementinum.
The spatial distribution of air pollutants in Prague for the years 2000 and 2010 was derived from air pollutants data collected by the local network of monitoring stations and reported to the European Environmental Agency (AirBase, 2014).

Figures 28 and 29 show the spatial distribution of mean annual ground concentration of $\text{SO}_2$ over Prague for the years 2000 and 2010, respectively. A decrease in concentrations within ten years of the order of about 50% is clearly observable on the whole metropolitan area. At the Klementinum, the air concentrations of $\text{SO}_2$ decreased from 10.6 $\mu$g m$^{-3}$ in 2000 to 5.1 $\mu$g m$^{-3}$ in 2010. In the second half of the 20th century brown coal had been the most widely used fuel for energy and heat production in the Czech Republic. Lignite was burned both in the great majority of the thermal power plants and it was also used in local heating facilities. The situation began to change in the middle of the last decade of the 20th century when desulphurization technologies were introduced and domestic heating facilities were switched from brown coal to different types of fuel such as natural gas, oil or electricity. In some parts of cities also central heating is used now and this central heating changed the local home heating facilities. This process led to improving the air quality and nowadays $\text{SO}_2$ does not represent an important pollution factor in Prague. The downward trend of ambient concentration of $\text{SO}_2$ is still observable in the time interval analyzed in this study.

The annual mean concentrations of $\text{NO}_2$ (Figures 30 and 31) appear to slightly increase in the territory of Prague during the period investigated. At the Klementinum, the calculated air concentrations of $\text{NO}_2$ increased from 37.3 $\mu$g m$^{-3}$ in 2000 to 42.2 $\mu$g m$^{-3}$ in 2010. The main source of this type of air-pollution is motor traffic. The total amount of cars in Prague has increased enormously since the beginning of the last decade of the 20th century. Technical state and composition of the car fleet has improved but it is still unfavourable. Moreover, despite that the city...
infrastructure gradually improving, the number of cars and the intensity of the traffic has increased
enormously. Car traffic is not the only source of NOx pollution. Nitrogen oxides are also created
when natural gas is burned in boilers or local heating facilities and this kind of NOx sources can be
as important as car traffic emissions. Moreover, the situation is also complicated by the complex
geometry of the city that affects the flow field pattern within the street canyons and vertical
temperature stability field.

Maps showing the O\textsubscript{3} ground concentration in 2000 and 2010 are shown in Figure 32 and Figure
33, respectively. In Prague as in many cities located at the same latitude in Europe the ground
concentration of ozone as a typical component of summer photochemical smog can reach relatively
high values. The highest values are found in sites located in the outskirts of the city. Ozone levels in
Prague appear nearly unchanged during the studied period, with a slightly increasing trend. At the
Klementinum, the calculated air concentrations of O\textsubscript{3} increased from 31.9 µg m\textsuperscript{-3} in 2000 to 36.9 µg
m\textsuperscript{-3} in 2010.

As a consequence of the higher levels of O\textsubscript{3} and NO\textsubscript{2} in 2010, calculated nitric acid (HNO\textsubscript{3})
concentrations also appear, on average, higher in 2010 (Figure 35) than in 2000 (Figure 34). Nitric
acid is not measured by the Czech Hydrometeorological Institute, so atmospheric nitric acid
concentrations were calculated from NO\textsubscript{2}, O\textsubscript{3}, relative humidity (Rh) and temperature (T) by using
the following empirical function derived within the MULTI-ASSESS project (MULTI-ASSESS,
2005):

\[
\text{HNO}_3 = 516 \times e^{-3400/(T+273)} (\text{[NO}_2\text{]} \times \text{[O}_3\text{]} \times \text{Rh})^{0.5}
\]

where

\[
\begin{align*}
[H\text{NO}_3] & = \text{annual average concentration, µg m}^{-3} \\
[\text{NO}_2] & = \text{concentration, µg m}^{-3} - \text{annual average} \\
[\text{O}_3] & = \text{concentration, µg m}^{-3} - \text{annual average} \\
T & = \text{temperature, °C – annual average} \\
\text{Rh} & = \text{relative humidity, % - annual average}
\end{align*}
\]

At the Klementinum, the calculated air concentrations of HNO\textsubscript{3} increased from 0.95 µg m\textsuperscript{-3} in 2000
to 1.12 µg m\textsuperscript{-3} in 2010.

The spatial distribution of mean annual concentration of PM\textsubscript{10} over Prague in the years 2000
(Figure 36) and 2010 (Figure 37) indicate a small reduction of ground concentrations of this
pollutant. In 2010, the highest concentrations of PM\textsubscript{10} were observed in the central part of the city.
At the Klementinum, the calculated air concentrations of PM\textsubscript{10} decreased from 37.2 µg m\textsuperscript{-3} in 2000
to 29.8 µg m\textsuperscript{-3} in 2010. Ambient concentrations of PM\textsubscript{10} in Prague followed the social and
economical changes of the city, which significantly influenced the principal sources of urban air
pollution. Traditional urban sources of pollution, such as coal and oil combustion for local and
central heating, lost their importance as a result of their substitution with cleaner natural gas or
electricity. Most of the industry was moved from the city to surrounding localities or closed down.
The contribution from large emission sources situated outside of Prague was reduced, too. At the
same time the number of vehicles registered in the Prague-county and entering the city from
surrounding municipalities increased substantially, making the automotive transport the main
sources of PM\textsubscript{10} in Prague.
Figure 28. Spatial distribution of mean annual concentration of SO$_2$ (µg/m$^3$) over Prague (year: 2000).

Figure 29. Spatial distribution of mean annual concentration of SO$_2$ (µg/m$^3$) over Prague (year: 2010).
Figure 30. Spatial distribution of mean annual concentration of NO$_2$ (µg/m$^3$) over Prague (year: 2000).

Figure 31. Spatial distribution of mean annual concentration of NO$_2$ (µg/m$^3$) over Prague (year: 2010).
Figure 32. Spatial distribution of mean annual concentration of O$_3$ (µg/m$^3$) over Prague (year: 2000).

Figure 33. Spatial distribution of mean annual concentration of O$_3$ (µg/m$^3$) over Prague (year: 2010).
Figure 34. Spatial distribution of mean annual concentration of HNO$_3$ (µg/m$^3$) over Prague (year: 2000).

Figure 35. Spatial distribution of mean annual concentration of HNO$_3$ (µg/m$^3$) over Prague (year: 2010).
Figure 36. Spatial distribution of mean annual concentration of PM$_{10}$ (µg/m$^3$) over Prague (year: 2000).

Figure 37. Spatial distribution of mean annual concentration of PM$_{10}$ (µg/m$^3$) over Prague (year: 2010).
The methodology used for the estimation of the damage due to attack of air pollutants at the selected UNESCO cultural heritage sites is based on the use of the dose-response functions, first year exposure, for the multi-pollutant situation:

\[ R = 4.0 + 0.0059[SO_2]_{Rh_{60}} + 0.054Rain[H^+] + 0.078[HNO_3]_{Rh_{60}} + 0.0258PM_{10} \]

where

- \( R \) = surface recession, \( \mu m \)
- \( Rh_{60} \) = \( Rh - 60 \) when \( Rh > 60 \), 0 otherwise (\( Rh \) = relative humidity, \% - annual average)
- \( Rain \) = amount of precipitation, mm year\(^{-1}\) - annual average
- \([SO_2]\) = concentration, \( \mu g \text{ m}^{-3}\) - annual average
- \([H^+]\) = concentration, mg l\(^{-1}\) - annual average
- \([HNO_3]\) = annual average concentration, \( \mu g \text{ m}^{-3}\)
- \(PM_{10}\) = annual average concentration, \( \mu g \text{ m}^{-3}\)

The multi-pollutant dose-response function relate damage to limestone, expressed in terms of rate of surface corrosion, to a range of atmospheric pollutants: sulphur dioxide (SO\(_2\)), nitric acid (HNO\(_3\)), acidity of rainfall (H\(^+\)), and particulate matter (PM\(_{10}\)). Environmental parameters also play a role, as reflected by the presence in the dose-response function of the two terms amount of precipitation (Rain) and relative humidity (Rh).

Figure 38 and Figure 39 show the corrosion maps for limestone based on the pollution data for the city of Prague related to the year 2000 and 2010, respectively. Between 2000 and 2010 it is possible to observe a slight decrease of the recession rate for limestone in most of the city of Prague. The decrease in correspondence of the Klementinum is about 8\% (7.5 \( \mu m \text{ year}^{-1}\) in 2000 and 6.9 \( \mu m \text{ year}^{-1}\) in 2010).

Predicted soiling rate of limestone in Prague was calculated by applying the dose-response function:

\[ \Delta R/Ro = 1 - \exp(-PM_{10} \times t \times 6.5 \times 10^{-6}) \]

where \( \Delta R/Ro \) is the relative loss of reflectance, \( PM_{10} \) is the concentration of \( PM_{10} \) (\( \mu g \text{ m}^{-3}\)), \( t \) is the time (days) and 6.5 \( \times 10^{-6} \) is a soiling constant for limestone.

This dose-response function was used to predict the loss in reflectance after 5 years as a function of the ambient \( PM_{10} \) concentrations to which the material is exposed. The maps showing the predicted 5-years loss in reflectance for limestone in Prague are reported in Figure 40 and 41 for the years 2000 and 2010, respectively.

The general decrease of air concentrations of \( PM_{10} \) in Prague between 2000 and 2010 has improved the status of the stone surfaces exposed to the action of external agents of deterioration. The loss of reflectance after five years estimated for the Klementinum was approximately 35\% in 2000 and 31\% in 2010. The “tolerable soiling before action” is 35\%, which represents the threshold triggering significant adverse public reaction of what constitutes acceptable soiling. This means that within 5-6 years the effects of any restoration work performed on the Klementinum will be cancelled. For cultural heritage objects a period of 10-15 years is considered to be appropriate.
Part IV – The relationship between the environment and the artefact

Fig. 38. Limestone corrosion map ($\mu$m year$^{-1}$) for the city of Prague (year: 2000).

Fig. 39. Limestone corrosion map ($\mu$m year$^{-1}$) for the city of Prague (year: 2010).
Figure 40. Limestone soiling map (% loss in reflectance after 5 years) for Prague (year: 2000).

Figure 41. Limestone soiling map (% loss in reflectance after 5 years) for Prague (year: 2010).
3.9 References


Department of Transportation Engineering, 2013. The Yearbook of Transportation Prague 2012.


4 The Neues Museum, Berlin, Germany

4.1 Geographic and climate profile of Berlin

Berlin, the largest city and the capital of Germany, is located in the North-eastern part of Germany (52° 31’ N, 13° 24’ E) in the glacial valley of the Spree River, about 180 km south of the Baltic Sea, 190 km north of the Czech-German border, and 89 km west of Poland. The Berlin metropolitan area (approximately 38 km from north to south and 45 km from east to west) has an extent of 892 km². About 60% of the Berlin area is covered by buildings and associated spaces and transport’s infrastructure (roads, railroads, airfields). Parks, forests, rivers, lakes, and canals make up more than 30 % of its territory (Statistik Berlin-Brandenburg 2015a). Berlin is encircled by the rural State of Brandenburg. The total extension of Brandenburg is 29,482 km². Land use of Brandenburg is dominated by agriculture (49%) and forestry (35%) (Statistik Berlin-Brandenburg 2015b).

Berlin is situated in an area with a mainly flat topography. Most of the Berlin-Brandenburg region lies well under 100 meters above sea level with hills hardly reaching 200 meters. The mean elevation of Berlin is 75 metres above sea level. The highest natural elevation is Müggelberge, a hill that rises 115 metres above sea level. Teufelsberg, one of several hills constructed from the rubble left by World War II bombing, rises to 116 metres.

Berlin has a marine west coast climate that is mild with no dry season, warm summers and moderate seasonality. Due to its location, the climate in Berlin is influenced by dry continental air masses from Eastern Europe and by maritime air masses from the Atlantic. The most frequent wind direction is west (21 %), followed by southwest (16 %). West to northwest winds correspond to the oceanic component with mainly less polluted sea air. The east to southeast winds correspond to the continental component with the higher pollutant concentration in the winter.

The city’s mean annual temperature is about 9 °C. Summers are warm and sometimes humid with average temperatures of 20-22 °C while winters are relatively cold with average temperatures of -2 to 0 °C. Average precipitation is 590 mm, with a distinctive maximum during summer. About one-fifth to one-fourth of the total falls as snow (mainly from December through March).

The city of Berlin shows a mosaic of micro-scaling climates. The crucial factors are density and height of buildings, integration of open spaces, parks, forest and lakes and thermodynamic parameters of the different materials used in the city. Berlin shows strong UHI (urban heat island) effects, with night-time temperature values during summer days, on average, about 2 to 3 °C higher respect to surrounding areas. However, the “heat islands” of the several densely built-up areas form a “heat archipelago” with a complicated distribution of surface air temperatures. Mean precipitation inside of Berlin varies between 530 and 630 mm, which represents a difference of up to 100 mm over a small area with relatively little orographic influence (Endlicher and Lanfer, 2003; Scherer et al. 2013).

The flat topography of the area does not prevent air circulation. For these reasons pollutants do not accumulate in the atmosphere for long periods and the concentrations are usually moderately low. The Central German Uplands in the south rise to quite a height but they are too far away to have any air circulation reduction effect.
4.2 Population

Berlin is the second largest city in the European Union in terms of its population and is the largest city in Germany. In 2010, Berlin had a population of 3.44 million registered inhabitants, with a population density of 3,860 inhabitants per km² (Statistik Berlin-Brandenburg 2015a). The so called "Inner Rapid-Railway (S-Bahn) Circle" is above average, with a population density of 11,150 people per square kilometre. The urban area of Berlin stretches beyond the city limits and comprises about 3.7 million people. By comparison, the entire Federal State of Brandenburg has a population of 2.52 million (86 people per square kilometre).

4.3 Energy

Berlin's fuel-mix for energy production is based on non-renewable resources (Figure 42). Despite the increased climate-environmental awareness in Berlin and generous national subsidies, the share of renewable energy sources in both the total primary and the final energy consumption is still the lowest among the various energy sources. The major energy sources are fossil based (namely oil and gas), taking a share of more than 70% of the total energy consumption (Amt für Statistik Belin-Brandenburg, 2013). Over the last two decades the shares of coal and lignite, the dominant energy sources in 1990, declined strongly at the favour of gas, oil and renewable energy sources. The largest final energy consumption sectors are residential and service industries, with a share of nearly 70%, followed by the transport sector (24.6%) and mining (6.3%).

![Energy Composition Diagram](image-url)

Figure 42. Composition of Berlin's primary energy consumption by energy carriers in 2010. Source: Amt für Statistik Belin-Brandenburg (2013).
Berlin has managed to reduce its primary energy consumption and also its CO₂ emissions, from 356,208 terajoule (TJ) in 1990 to 306,372 TJ in 2010. Currently, both the City of Berlin and the surrounding State of Brandenburg have ambitious targets for reducing and “greening” energy consumption. Berlin set the goal to decrease consumption of 9.8 percent in 2020 vis-à-vis 2005 (Energy Plan 2020). A change in fuel-mix composition is a crucial step in order to reach the climate neutrality goal (Senate Department for Urban Development and the Environment, 2014).

4.4 Industry

Reunification in 1990 had a vast effect on Berlin’s ecological footprint, because the shutdown of most of East Berlin’s industrial operations and the modernization of a large proportion of buildings since then has cut pollutant emissions substantially.

Currently, the economic structure of the city is dominated by the commerce, trade and services (CTS) sector with about 90% of added value and employment. Tourism and the creative industries are among the branches with growing importance. The tourist industry is experiencing higher growth rates than any of the city’s other business sectors, with a number of overnight stays recorded at more than 22 million in 2011 by the Berlin’s Statistics Office.

The industrial structure of Berlin nowadays consists of about 736 companies. The metals and electronics industry plays an important role and mechanical and automotive engineering have a long tradition in Berlin. Additional core sectors are the chemical-pharmaceutical, biotechnology, environmental and information technology, as well as the increasingly important tertiary sector. This economic characteristic forms a typical pattern with the tertiary sector mainly based in the centre of Berlin, while 95% of industrial land is allocated along or outside the S-Bahnring (suburban railway ring), which encloses the city centre. Figure 43 shows the location of the facilities in Berlin and surroundings inscribed in the E-PRTR register.

Figure 43. Distribution of E-PRTR (The European Pollutant Release and Transfer Register) facilities in Berlin and surroundings in 2011.
4.5 Transport and infrastructures

Berlin has one of the most modern and efficient transportation infrastructures in Europe and the city aims at promoting public transport and increasing its modal share. Berlin's transport infrastructure is highly complex, with trains, metro, trams and buses providing a diverse range of urban mobility. Long-distance rail lines connect Berlin with all of the major cities of Germany and with several international destinations. Regional rail lines provide access to the surrounding regions of Brandenburg and to the Baltic Sea. Deutsche Bahn also runs an airport express rail service.

The Berlin underground (U-Bahn) together with the S-Bahn urban rail service form the backbone of public transport network in Berlin. With 25 lines, 305 stations and an extension of 476 km, this urban rail system transports more than 850 million passengers per year. The tram network has a length of 192 kilometres, transports 167 million passenger per year and operates predominantly in eastern boroughs while the bus network (1,656 km) operate extensive services in all boroughs (382 million passenger per years). The network is completed by 197 km of inner-city waterways and 5,334 km of roads, of which 73 km are motorways ("Autobahn").

Public-private-partnerships and cooperation schemes involving the urban logistics stakeholders contribute to reducing congestion in the inner city. In one such public-private-partnership, the Traffic Management Center (Verkehrsmanagementzentrale - VMZ) provides travellers and transportation providers with real-time traffic data. The Berlin Traffic Map (Figure 44) shows where traffic flows smoothly (green) and where traffic problems (yellow) or traffic jam (red) exists. Closures on the main road network are marked in black. Through a menu it is possible to select further information such as construction sites, parking lots or bus stops, which will be shown on the map.

Figure 44. Screenshot of the Berlin Traffic Map (http://www.viz-info.de/en/web/guest/home).
Berlin has two commercial airports. Berlin Tegel Airport (TXL), which lies within the city limits, and Schönefeld Airport (SXF), which is situated just outside Berlin's south-eastern border in the state of Brandenburg and services mainly low-cost airlines. Both airports together handled 24 million passengers in 2011. Berlin Brandenburg Airport (BER) will replace Tegel and Schönefeld as single commercial airport of Berlin. Originally planned to be opened in 2011, the new airport has been delayed several times. The latest projected opening date is 2017.

Berlin is accessible by way of navigable rivers. Container traffic is conducted from Berlin to the Port of Hamburg and vice versa via the Elbe-Spree inland waterway. For many goods, shipping by inland waterway is an ecologically and economically sensible alternative to rail or road.

In 2012, Berlin counted around 1.35 million registered vehicles, of which 1.15 million were cars that ran mainly on petrol or diesel (Table 7). With 342 cars per 1000 residents in 2012 (570/1000 in Germany), Berlin has one of the lowest numbers of cars per capita in Europe.

<table>
<thead>
<tr>
<th>Number of registered vehicles</th>
<th>1 354 881</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>1 150 191</td>
</tr>
<tr>
<td>Motorbikes</td>
<td>99 099</td>
</tr>
<tr>
<td>Buses</td>
<td>2 126</td>
</tr>
<tr>
<td>Lorries</td>
<td>83 415</td>
</tr>
<tr>
<td>Tractor trucks</td>
<td>5 186</td>
</tr>
<tr>
<td>Self-propelled machines</td>
<td>3 589</td>
</tr>
<tr>
<td>Other</td>
<td>11 275</td>
</tr>
</tbody>
</table>


With its urban traffic planning strategy, Berlin has developed a very comprehensive set of measures aiming at reducing car use in the city but also promoting cycling and walking as well as public transport. In Berlin, the general speed limit is 55 km/h on main roads, but about 75% of Berlin's roadways are designated as 30 km/h zones. The city promotes and speeds up public transport and also creates measures for mobility management for companies, as well as for commuters, for schools and for elderly people. In that past decade, Berlin has experienced a long trend towards more cycling and walking by improving the infrastructure for bikes. It is estimated that in 2011 Berlin had 721 bicycles per 1000 residents. Cyclists have access to 620 km of bicycle paths. Around 500,000 daily bike riders accounted for 13% of total traffic in 2009.

In 2008 Berlin implemented a low emission zone (LEZ) covering a central city area of 88 km² with more than 1.1 million residents (Figure 45). The scheme is based on coloured stickers categorising vehicles according to their emission group. Since 1 January 2010 only vehicles with Euro 4 or retrofitted Euro 3 vehicles are allowed to enter the LEZ. The implementation of the Berlin LEZ has led to an accelerated modernisation of the vehicle fleet, with >98% of the passenger cars and 85% for duty vehicles now having a “green sticker”.

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Apart from reducing emissions with improved vehicle technologies, the city is also concentrating on traffic planning measures, such as optimizing traffic lights to ensure a more efficient traffic flow. The parking policy coordinated at regional level intends to progressively reduce car use to the benefit of public transport, cycling and walking. A reform of the parking management was launched in 2011 and the feasibility of reducing on-road parking spaces by 16% by 2018 is currently assessed.

Berlin is among the largest car sharing cities in the world (McGrane, 2013). Car sharing is promoted by dedicated parking spaces, and several measures promote multimodal interconnectivity. Several operators of car sharing are active, whose fleet is largely constituted by fully electric or partially electric vehicles for a total of 2475 vehicles in 2012 (Senate Department for Urban Development and the Environment of the State of Berlin, 2014).

Currently, alternative motors do not play a significant role in private passenger transport, but they have developed dynamically in the past few years. Since 2010, the number of vehicles with liquid gas motors has increased from around 9,000 to 14,000 in 2013, while the number of hybrid vehicles doubled between 2009 and 2013 to approximately 4,300 in Berlin. The number of electric vehicles has increased manifold during that time, so that Berlin can be seen as a nationwide showcase of electric mobility.

The German federal government is aiming to have at least one million electric vehicles driving on German roads by 2020. Electric vehicles could provide an ecologically, technically and economically viable alternative for the urban commercial traffic. Around one third of the traffic in cities consists of trade contractors and suppliers. Until now, this commercial traffic has mostly relied on diesel power. A research group led by the Technical University Berlin is now investigating how electric vehicles could be sensibly used in the urban distribution networks.
4.6 Emission inventories

The City of Berlin has implemented since 1989 an emission register. The emission inventory is based on a bottom-up approach and report annual emission data within its administrative boundaries (in a grid of 1x1 km) for the following polluter groups:

- plants requiring a permit (industrial plants);
- heating systems not requiring a permit (domestic heating);
- other plants not requiring a permit (small business);
- motor vehicle traffic;
- other traffic (rail, ship and air traffic);
- other sources.

Table 8 shows emission sources included in the emission inventories for the year 2009 (Senate Department for Urban Development and the Environment, 2015a).

<table>
<thead>
<tr>
<th>Source</th>
<th>NOx (as NO\textsubscript{2})</th>
<th>PM</th>
<th>SO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg</td>
<td>%</td>
<td>Mg</td>
</tr>
<tr>
<td>Industrial plants</td>
<td>6594</td>
<td>35.4</td>
<td>153</td>
</tr>
<tr>
<td>Domestic heating</td>
<td>2807</td>
<td>15.1</td>
<td>95</td>
</tr>
<tr>
<td>Small business</td>
<td>127</td>
<td>0.7</td>
<td>258</td>
</tr>
<tr>
<td>Motor vehicles traffic</td>
<td>7510</td>
<td>40.3</td>
<td>225</td>
</tr>
<tr>
<td>Other traffic</td>
<td>641</td>
<td>3.4</td>
<td>669</td>
</tr>
<tr>
<td>Other sources</td>
<td>940</td>
<td>5.0</td>
<td>119</td>
</tr>
<tr>
<td>Total</td>
<td>18619</td>
<td></td>
<td>3125</td>
</tr>
</tbody>
</table>

According to the emission register, all emissions have been greatly reduced since 1989, with reductions of between 73% for NOX and 95% for SO\textsubscript{2}. SO\textsubscript{2} has for years stagnated at a low level, and its significance is no longer great. The particulate emissions from the exhaust of motor vehicles have decreased by more than 80% between 1989 and 2009. However, since emissions from tyre abrasion and turbulence have been reduced by only 43%, motor vehicle traffic remains the second most important source of particulate emissions in Berlin, surpassed only by the category "other traffic sources".

In the area of domestic heating an impressive decrease in emissions has been achieved, thanks to an increase in pipeline-based energy sources, instead of the formerly predominant brown coal. Motor vehicle traffic is the main cause of several pollutants, such as PM\textsubscript{10} and NOX. In 2009, road traffic accounted for more than 40% of the nitric oxide emissions in Berlin, while industrial plants caused less than 35% of the total of these emissions. Since the pollution emitted by road traffic enters the atmosphere close to the ground, it contributes to a much greater degree to air pollution than do pollutants from high smokestacks.

Data from the Berlin emission inventory do not contradict gridded emission data used for modelling purposes on the 50 km x 50 km EMEP grid and the new gridding system at a resolution of 0.1° × 0.1° longitude-latitude in the WGS84 geographic coordinate system covering the Neues Museum.
and based on officially reported emissions under CLRTAP, although the relative weight of the different sources of emission changes as a function of the extension of the areas considered.

4.7 Air Quality - Ground level air pollutants

The atmospheric pollution load in Berlin is monitored with the aid of the Berlin Air Quality Monitoring Network of the Senate Department of Urban Development and Environment. Currently, the network consists of 16 fixed measurement stations for air pollutant monitoring. Of the 16 stations, six are along heavily travelled streets, five are in inner-city areas (both residential and commercial), and five are at the periphery of the city or in forest areas. The city provides online information on air quality.

Compared with the ‘70s and ‘80s, the atmospheric burden of most air pollutants has been reduced substantially. Sulphur dioxide air concentrations have been reduced by >90%. With regard to PM$_{10}$, the situation has improved significantly: the annual mean concentrations at the stations were in the suburbs at 18-19 µg/m$^3$, in inner-city areas at 22-23 µg/m$^3$ and along heavily travelled streets at 24-29 µg/m$^3$. In areas with road influences NO$_2$ concentrations were between 43 and 66 µg/m$^3$ in 2012 while the average NO$_2$ concentration in Berlin was 27 µg/m$^3$. Near-ground ozone concentrations frequently exceed the EU long-term 8-hour target at several sites during the summer months. Pollutants show a seasonal pattern, with maxima values of PM$_{10}$ and O$_3$ in winter and summer, respectively. In Berlin, autumn and spring are the more stable and dryer seasons, favouring a moderate pollution accumulation.

Figure 46 shows the trends of the annual mean of the main pollutants measured at the monitoring station DEBE065, a traffic station situated approximately 5.0 km from the Neues Museum.

![Figure 46. Temporal trend of main atmospheric pollutants measured at station DEBE065, Berlin.](image-url)
Improvements of the air quality in Berlin depends on many components: the de-industrialization of the city, the modernization of existing facilities, cleaner vehicles and fuels, the changeover to low-emission fuels, the increase of power/heat cogeneration, the promotion of energy saving and the growth of renewable energy sources. Since the LEZ implementation, PM$_{10}$ emissions from transport decreased by 40% and NOx by 19%. Ambient PM$_{10}$ pollution was reduced by 3% compared to pollution scenarios without a LEZ (baseline scenario). Decrease in PM$_{10}$ was larger for traffic stations inside the LEZs than those outside, although PM$_{10}$ does not decrease at all in background areas away from major roads (Wolff, 2014). Long-term trend of NO$_2$ in Berlin shows only a limited improvement (7-12% lower) despite a decrease of NOx emissions.

Particulate matter and nitrogen dioxide are still a problem for the air quality in Berlin. These problems are mainly linked to the high contribution from traffic and other small sources but also to the input of pollutants arising from sources outside Berlin, including the contribution by long-range transport of particulate matter from coal power plants and small combustion systems of eastern neighbours. This long-range transport was modelled in Berlin and it was found that the main sources for secondary sulphate aerosol imported into the Berlin area coincides with the industrialised region in Southern Poland and in Slovakia while the high nitrate levels in Berlin come from the high traffic volume in Germany and the subsequent nitrogen oxide emissions (Senate Department for Urban Development and the Environment, 2015b).

Studies on source apportionment analysis demonstrate that in Berlin, about 50% of the urban background PM$_{10}$ concentration level is due to long range transport, mainly secondary aerosols (ammonium nitrate and ammonium sulphate) and natural sources (Lenschow et al., 2001). John and Kuhlbusch (2004) show a large share of regional background PM in the Berlin city centre (about 50%). At kerbside sites the major contribution sources are traffic (including exhaust and abrasion products), which accounts for 35–55% of PM$_{10}$, and industry, accounting for 15–25% of PM$_{10}$. Half of the PM$_{10}$ traffic contribution can be attributed to non-exhaust emissions such as re-suspension and abrasion, which cannot be addressed by focusing exclusively on vehicle emissions control technology (Querol et al., 2004).

Despite the reduction of domestic charcoal burning in the past years in Germany, wood burning is still an important aerosol source in Berlin (Wagener et al, 2012). PM$_{10}$ from wood burning is an important winter source with a contribution to the daily PM$_{10}$ concentrations reaching 13 µg m$^{-3}$ in suburban Berlin (Fuller et al., 2013). With a projected 57-110% increase in biomass burning between 2010 and 2020 at the European level (Wagner et al., 2010), as a result of the commitment to obtain 20% energy from renewable sources, an increase of urban wood combustion could increase the domestic contribution to PM$_{10}$ concentrations in Berlin.
4.8 Implications on the UNESCO Cultural Heritage Site: The Neues Museum

The Neues Museum (Figure 47) is part of the Berlin’s Museum Island (Museumsinsel) in the River Spree, a small island that is home to five world-class museums (the Neues Museum, the Altes Museum, the Pergamon Museum, the Bode Museum, and the Alte Nationalgalerie). The Neues Museum houses the archaeological collections of the Egyptian Museum and Papyrus Collection, the Museum of Pre- and Early History, as well as works from the Collection of Classical Antiquities.

The museum was originally built between 1843 and 1859. Near the end of World War II, the museum was severely damaged by bombing and was left abandoned until 1999. Only then did the reconstruction work begin, which ended up lasting for ten years. The Neues Museum reopened in 2009. The renovation of the building is part of a general restoration of the entire Museum Island, which runs until 2015.

Despite the wartime damage and the long series of conservation interventions that followed, the Museumsinsel has retained a high degree of authenticity in its historic buildings, in their functions, in their design, and in their context. It was awarded UNESCO World Heritage Status in 1999. The World Heritage site extends over an area of 8.6 ha and is surrounded by a buffer zone of 30.4 ha, which includes associated areas already protected as historic monument-groups. About 1000 inhabitants live within the property/buffer zone.

Being located in the heart of the city (Figure 48), the Neues Museum is subject to the environmental pressure caused by air pollution from the metropolis. All of the improvements in air quality are automatically reflected in a decrease of the environmental damage on the surfaces of historical buildings and monuments exposed outdoors. For instance, the renewal and electrification of the S-
Bahn (elevated railway) line running through the Berlin’s Museum Island area completed in 1998 has led to a reduction in noise and pollution compared to the past situation (steam/diesel engines). The pollution and environmental damage to roofs and facades and the decoration on the museum building are expected to be removed in the course of the general maintenance process in a manner compatible with conservation.

The spatial distribution of air pollutants in Berlin for the years 2000 and 2010 was derived from air pollutants data collected by the local network of monitoring stations and reported to the European Environmental Agency (AirBase, 2014).

Figures 49 and 50 show the spatial distribution of mean annual concentration of $\text{SO}_2$ over Berlin for the years 2000 and 2010, respectively. A decrease in concentrations within ten years of the order of about 50% is clearly observable on the whole metropolitan area (red line) and in particular in correspondence of the LEZ (blue line). Mean annual concentration of $\text{NO}_2$ (Figures 51 and 52) and of $\text{PM}_{10}$ (Figures 53 and 54) appear generally stagnant during the period investigated, with only minor improvements. The annual mean ground-level ozone concentration in 2010 (Figure 56) appears higher than those of 2000 (Figure 55), with the highest values in peripheral areas.

In consequence of the higher levels of ozone in 2010 and stagnant levels of $\text{NO}_2$, calculated nitric acid ($\text{HNO}_3$) concentrations also appear, on average, higher in 2010 (Figure 58) than in 2000 (Figure 57). Nitric acid is not measured by the Berlin Air Quality Monitoring Network, so atmospheric nitric acid concentrations were calculated from $\text{NO}_2$, $\text{O}_3$, relative humidity (Rh) and temperature (T) by using the following empirical function derived within the MULTI-ASSESS project (MULTI-ASSESS, 2005):
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Part IV – The relationship between the environment and the artefact

\[
HNO_3 = 516 \times e^{3400/(T+273)} \times ([NO_2] \times [O_3] \times Rh)^{0.5}
\]

where

- \([HNO_3]\) = annual average concentration, \(\mu g \, m^{-3}\)
- \([NO_2]\) = concentration, \(\mu g \, m^{-3}\) - annual average
- \([O_3]\) = concentration, \(\mu g \, m^{-3}\) - annual average
- \(T\) = temperature, °C – annual average
- \(Rh\) = relative humidity, % - annual average
Figure 49. Spatial distribution of mean annual concentration of SO$_2$ ($\mu$g/m$^3$) over Berlin (year: 2000).

Figure 50. Spatial distribution of mean annual concentration of SO$_2$ ($\mu$g/m$^3$) over Berlin (year: 2010).
Figure 51. Spatial distribution of mean annual concentration of NO\textsubscript{2} (µg/m\textsuperscript{3}) over Berlin (year: 2000).

Figure 52. Spatial distribution of mean annual concentration of NO\textsubscript{2} (µg/m\textsuperscript{3}) over Berlin (year: 2010).
Part IV – The relationship between the environment and the artefact

Figure 53. Spatial distribution of mean annual concentration of PM$_{10}$ (µg/m$^3$) over Berlin (year: 2000).

Figure 54. Spatial distribution of mean annual concentration of PM$_{10}$ (µg/m$^3$) over Berlin (year: 2010).
Figure 55. Spatial distribution of mean annual concentration of O₃ (µg/m³) over Berlin (year: 2000).

Figure 56. Spatial distribution of mean annual concentration of O₃ (µg/m³) over Berlin (year: 2010).
Figure 57. Spatial distribution of mean annual concentration of HNO$_3$ (µg/m$^3$) over Berlin (year: 2000).

Figure 58. Spatial distribution of mean annual concentration of HNO$_3$ (µg/m$^3$) over Berlin (year: 2010).
The methodology used for the estimation of the damage due to attack of atmospheric pollutants at the selected UNESCO cultural heritage sites is based on the use of the dose-response functions, first year exposure, for the multi-pollutant situation:

\[
R = 4.0 + 0.0059[SO_2]Rh_{60} + 0.054Rain[H^+] + 0.078[HNO_3]Rh_{60} + 0.0258PM_{10}
\]

where

- \( R \) = surface recession, \( \mu \text{m} \)
- \( Rh_{60} \) = \( Rh - 60 \) when \( Rh > 60 \), 0 otherwise (\( Rh \) = relative humidity, \% - annual average)
- \( Rain \) = amount of precipitation, \( \text{mm year}^{-1} \) - annual average
- \([SO_2]\) = concentration, \( \mu \text{g m}^{-3} \) - annual average
- \([H^+]\) = concentration, \( \text{mg l}^{-1} \) - annual average
- \([HNO_3]\) = annual average concentration, \( \mu \text{g m}^{-3} \)
- \( PM_{10} \) = annual average concentration, \( \mu \text{g m}^{-3} \)

The multi-pollutant dose-response function relate damage to limestone, expressed in terms of rate of surface corrosion, to a range of atmospheric pollutants: sulphur dioxide (\( SO_2 \)), nitric acid (\( HNO_3 \)), total acidity of rainfall (\( H^+ \)), and particulate matter (\( PM_{10} \)). Environmental parameters also play a role, as reflected by the presence in the dose-response function of the two terms amount of precipitation (\( Rain \)) and relative humidity (\( Rh \)).

Figure 59 and Figure 60 show the corrosion maps for limestone based on the pollution data for the city of Berlin related to the year 2000 and 2010, respectively. A slight decrease of the recession rate for limestone in most of the city of Berlin has been observed between 2000 and 2010. The decrease in correspondence of the Neues Museum is about 5% (6.8 \( \mu \text{m year}^{-1} \) in 2000 and 6.5 \( \mu \text{m year}^{-1} \) in 2010).

Predicted soiling rate of limestone in Berlin was calculated by applying the dose-response function:

\[
\frac{\Delta R}{R_0} = 1 - \exp(-PM_{10} \times t \times 6.5 \times 10^6)
\]

where \( \Delta R/R_0 \) is the relative loss of reflectance, \( PM_{10} \) is the concentration of \( PM_{10} \) (\( \mu \text{g m}^{-3} \)), \( t \) is the time (days) and \( 6.5 \times 10^6 \) is a soiling constant for limestone.

This dose-response function was used to predict the loss in reflectance after 5 years as a function of the ambient \( PM_{10} \) concentrations to which the material is exposed. The maps showing the predicted 5-years loss in reflectance for limestone in Berlin are reported in Figure 61 and 62 for the years 2000 and 2010, respectively.

The modest decrease of air concentrations of \( PM_{10} \) in Berlin between 2000 and 2010 has slightly improved the status of the stone surfaces exposed to the action of external agents of deterioration. The loss of reflectance after five years estimated for the Neues Museum was approximately 31% in 2000 and 29% in 2010. The “tolerable soiling before action”, representing the threshold triggering significant adverse public reaction of what constitutes acceptable soiling, is generally set at 35%. At current \( PM_{10} \) concentrations, this threshold will be reached for the Neues Museum within 6-7 years after any restoration work. For cultural heritage objects a period of 10-15 years is considered to be appropriate.
Fig. 59. Limestone corrosion map ($\mu$m year$^{-1}$) for the city of Berlin (year: 2000).

Fig. 60. Limestone corrosion map ($\mu$m year$^{-1}$) for the city of Berlin (year: 2010)
Figure 61. Limestone soiling map (% loss in reflectance after 5 years) for Berlin (year: 2000).

Figure 62. Limestone soiling map (% loss in reflectance after 5 years) for Berlin (year: 2010).
4.9 References


5 Concluding remarks

In this study we used publicly available air quality information and meteorological data in order to better understand the role of anthropogenic activities on the levels of air pollutants in three cities with different climatic, topographic and emission-related characteristics and to assess the damage on stone materials due to air pollution at three UNESCO sites: the Parthenon, Athens, Greece; the Klementinum, Prague, Czech Republic; and the Neues Museum, Berlin, Germany.

In a previous report in this series, HNO$_3$ (produced from oxidation of atmospheric nitric oxides) and PM$_{10}$ were identified as the main factors responsible for the corrosion of the stone materials these historical artefacts are built with. SO$_2$ contributes to a lesser extent to the recession rate while current pH values of the rain have only a small impact. Road traffic is a predominant source for NO$_2$ and PM$_{10}$. Nitrogen and sulphur oxides are also PM precursors and contribute to PM concentrations and related materials damage. Therefore, the most effective strategies for reducing the damage of the stone material due to the air pollution and for reducing the economic cost of maintenance of cultural heritage buildings should focus on the transport sector.

Older vehicles are responsible for the major part of the automotive pollutants. Accelerated improvement of the total vehicle fleet by replacing older by new vehicles with lower emissions should aim at reducing air pollution in metropolitan areas and thus the damage to built cultural heritage that they host. Structural measures oriented at reducing transportation needs, local traffic management, incentives for public transport use, car-sharing schemes, development of less emitting, or even non emitting, means of transportation (electric vehicles), should help to avoid a significant amount of pollutants from internal combustion engines. The experience performed in Berlin and other European cities suggests that a Low Emission Zone (LEZ), where the oldest and most polluting vehicles are banned, is one of the most effective single measures to achieve air quality improvements since it does not significantly impact traffic volumes but rather drive changes in the overall fleet composition. However, LEZ alone are not sufficient to improve air quality in areas away from major roads and additional measures will be necessary for the control of background levels.

On the whole, literature data provided evidence that non-exhaust sources (tyre-wear, break-lining, road abrasion, etc.) together with re-suspension of dust load, already deposited on the surface, contribute substantially to primary PM$_{10}$ from road traffic in all three cities. PM$_{10}$ is involved in the corrosion processes of the marble/limestone of the monument studied and is crucial to soiling, a visual nuisance resulting from the darkening of exposed surfaces by deposition of atmospheric particles. Unlike the traffic exhaust emissions, this coarse part of the PM load cannot be tackled by improving vehicles emissions. The effectiveness of measures addressing soil and road-dust re-suspension, such as street sweeping/ water flushing treatments, should also be examined to mitigate PM$_{10}$ concentrations and to reduce deterioration of historical stone monuments. Fleet electrification would improve urban air quality but would have a limited impact with respect to particulate matter emissions, which are not significantly reduced by electric vehicles due to the high weight of non-exhaust emissions.

Inside the main residential areas, incomplete biomass combustion for heat production, e.g. in domestic boilers, wood stoves and fireplaces can be an important PM$_{10}$ emission source on specific months during winter. The adverse impact of domestic biomass combustion on PM mass concentration is pronounced, because the combustion in domestic heating appliances is often incomplete and such emissions are mostly unregulated. Moreover, the release height of the emissions is low and the air mixing can be poor during the winter season, which both amplify the
local air quality impact and increase the risk of deterioration of the studied monuments made of marble/limestone.

Although road transport is the main emission source in urban areas, further emission reductions should be considered for the other sources. In some cases, the weights of harbour and industry activities play important roles in air quality levels. Further diffusion of best available techniques (BAT) and increased controls on emissions together with enlargement of natural gas penetration, increased use of renewable energy sources and energy saving measures could reduce the risks that threaten our cultural heritage.

High O$_3$ levels can be attributed to elevated background of O$_3$ and to the primary pollutant emissions in the metropolitan areas. Ozone precursors such as nitrogen oxides and volatile organic compounds originate mainly from traffic fossil-fuel combustion. In urban areas, O$_3$ reacts with NO to produce NO$_2$ that further competes with NMVOC for reaction with OH radicals decreasing photochemical O$_3$ build-up and producing HNO$_3$ downwind. Atmospheric nitric acid does not only contribute to acidification and eutrophication but is also an important parameter for the corrosion and surface degradation of the materials of cultural heritage.

In addition to pollution caused by local industries and the metropolitan areas, literature data indicate that the three cities and the UNESCO sites that they host are affected from regional and long-range transboundary pollution transport. Since the deterioration of monuments is also linked to sources outside of the city or even outside the country, the improvement of air quality and the reduction of the damage to the studied monuments require coordinated efforts.

In conclusion, this series of reports on the “Pilot study on inventory and condition of stock of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO) cultural heritage sites” may provide some answers to some policy-oriented questions:

**What is the current situation of the predicted corrosion and soiling due to air pollution of the limestone material at the studied cultural monuments?**

The dose-response function used to calculate the recession rate of the limestone material at the studied UNESCO sites after one year of exposure indicates that for the Parthenon in Athens, the Klementinum in Prague and the Neues Museum in Berlin the estimated recession rate after one year of exposure is well above the background corrosion rate (3.2 µm year$^{-1}$) and generally close to the target for the year 2050 (6.4 µm year$^{-1}$) or even at the Neues Museum close to the target for 2020 (8.0 µm year$^{-1}$).

At current PM$_{10}$ concentrations, predicted soiling rate of limestone for the three monuments indicate that the “tolerable soiling before action”, representing the threshold triggering significant adverse public reaction of what constitutes acceptable soiling, will be reached within 4-7 years after any restoration work. For cultural heritage objects a period of 10-15 years is considered to be appropriate.

**What is the cost of damage to materials due to air pollution of these works of art and historic buildings?**

Estimation of corrosion costs at five UNESCO sites performed in a previous report of this series showed that actual corrosion due to air pollution would result in material deterioration costs ranging
from € 9.2 per square metre per year (m² year⁻¹) to € 43.8 m² year⁻¹, depending on the status of the material, the pollution level and the climatic conditions. These costs add to the cost in background areas, estimated from € 14 m² year⁻¹ to € 28 m² year⁻¹. Cost estimates are, however, subject to uncertainty due to the assumption in estimating lifetimes of materials and the cost of the interventions.

**What are the main pollutants responsible for the predicted corrosion and soiling of limestone material of the studied cultural monuments?**

At current low concentrations, SO₂ is still an important deteriorating agent for limestone but not more the dominant factor. In a multi-pollutant scenario, nitric acid (produced from atmospheric nitric oxides) and particulate matter seem to play a prominent role in determining damage of limestone. Nitric acid and particulate matter concentrations are higher in cities, where most of our cultural heritage is situated. The acidity of precipitation, expressed by the pH value, seems to have a little impact on corrosion in the current situation. PM₁₀ dominates for soiling of materials.

**What improvements in the predicted corrosion and soiling of limestone materials of the studied cultural monuments can be estimated?**

The improvement of air quality between 2000 and 2010 in the three cities that host the studied UNESCO sites has produced a small but quantifiable decrease in the recession rate for limestone, first year exposure, which includes practically most of the metropolitan areas. The corresponding decrease in recession rate of limestone located at the studied UNESCO sites is about 5-8%. It is generally agreed that relative change of degradation rates is more representative than absolute values. The estimated decrease in the recession rate for limestone is mainly attributable to a significant reduction of air concentration of SO₂, which has nearly halved in the time period investigated. By contrast, air concentrations of NO₂, HNO₃, O₃ were basically stagnant, with small increases or decreases depending on the particular site, and therefore with limited effects on the overall recession rate.

The modest decrease in atmospheric concentrations of PM₁₀ in the vicinity of the three UNESCO sites between 2000 and 2010 has anyway slightly improved the environmental conditions by reducing the loss of reflectance after five years of a few percentage points.

**What is the role of the anthropogenic activities in cities in determining the levels of pollutants affecting the studied UNESCO sites and thus the damage of the materials these objects are built with?**

The studied UNESCO sites are located in the heart of European capitals. In these urban areas, several air quality problems are present, mainly related to NO₂ and PM₁₀, two pollutants that currently seem to play a prominent role in determining damage of limestone.

Road traffic is an important source for both pollutants. Road transport was the most important sector for urban emissions of NO₄ in all three cities and is among the top three sectors for emissions of PM₁₀ in these metropolitan areas. Additional large sources are energy production and distribution, incomplete biomass combustion for heat production, e.g. in domestic boilers, wood stoves and fireplaces and, in some case, industry production and harbour activities.
In addition to the local origin, the levels of pollutants, with a negative impact on materials used in objects of cultural heritage, are significantly affected by sources outside the city or even outside the country. High PM$_{10}$ concentrations may be due to natural sources, too. This is the case with the Parthenon and the Greek city of Athens, where elevated background PM$_{10}$ levels can be explained by intrusion of Saharan dust, thus indicating an important geographical difference between North and South Europe.

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