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THE HEALTH IMPACTS OF NITROGEN DIOXIDE (NO_2) POLLUTION

Review of the science commissioned by the Health and Environment Alliance (HEAL)

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01. INTRODUCTION

NITROGEN DIOXIDE IN ATMOSPHERIC AIR AND ITS SOURCES

NITROGEN DIOXIDE (NO_2) IS A REDDISH-BROWN GAS WITH A CHARACTERISTIC PUNGENT ODOUR.

NO_2 in the atmospheric air poses a health hazard and has an adverse environmental impact because:

- it absorbs visible solar radiation reducing air transparency and contributing to atmospheric warming,
- as a strongly reactive gas, it participates in the generation of oxidising gases in the atmosphere,
- determines ozone concentration in the troposphere as a key factor in ozone-forming reactions.

Chemical reactions in the atmosphere, occurring with NO_2 participation, lead to the formation of nitric acid and other secondary substances, including nitrates, present in the particulate matter (PM2.5).

NO_2 in the troposphere originates both from natural sources (flow from the stratosphere, emissions from bacteria and volcanoes and atmospheric discharges) and anthropogenic emissions. Still, the natural emissions are distributed all over the Earth's surface, and the resulting background concentration is very low. Human activity-related emissions, which are related to human presence in a particular area dominate for the impact on human exposure. Combustion processes (for heat or electricity generation purposes or in combustion engines) are the primary source of the emissions above. During the processes, atmospheric nitrogen bonds with oxygen, forming nitrogen oxide that is quickly oxidised to NO_2.

THE PRIMARY SOURCES OF NITROGEN OXIDE EMISSIONS IN THE EUROPEAN UNION INCLUDE:

(EEA 2022a)

ROAD TRANSPORT	37%
AGRICULTURE	19%
INDUSTRY	15%
ENERGY GENERATION	14%
UTILITY SERVICES	9%

In 2019, nitrogen oxide emissions in 27 member states constituted only

58%

(in the pandemic year 2020, they amounted to 52%) of those reported in 2005.

THE PRIMARY SOURCES OF NITROGEN OXIDES IN POLAND INCLUDE:

(EEA 2021)

ROAD TRANSPORT	35%
ENERGY GENERATION	21%
AGRICULTURE	20%
INDUSTRY	11%
UTILITY SERVICES	11%

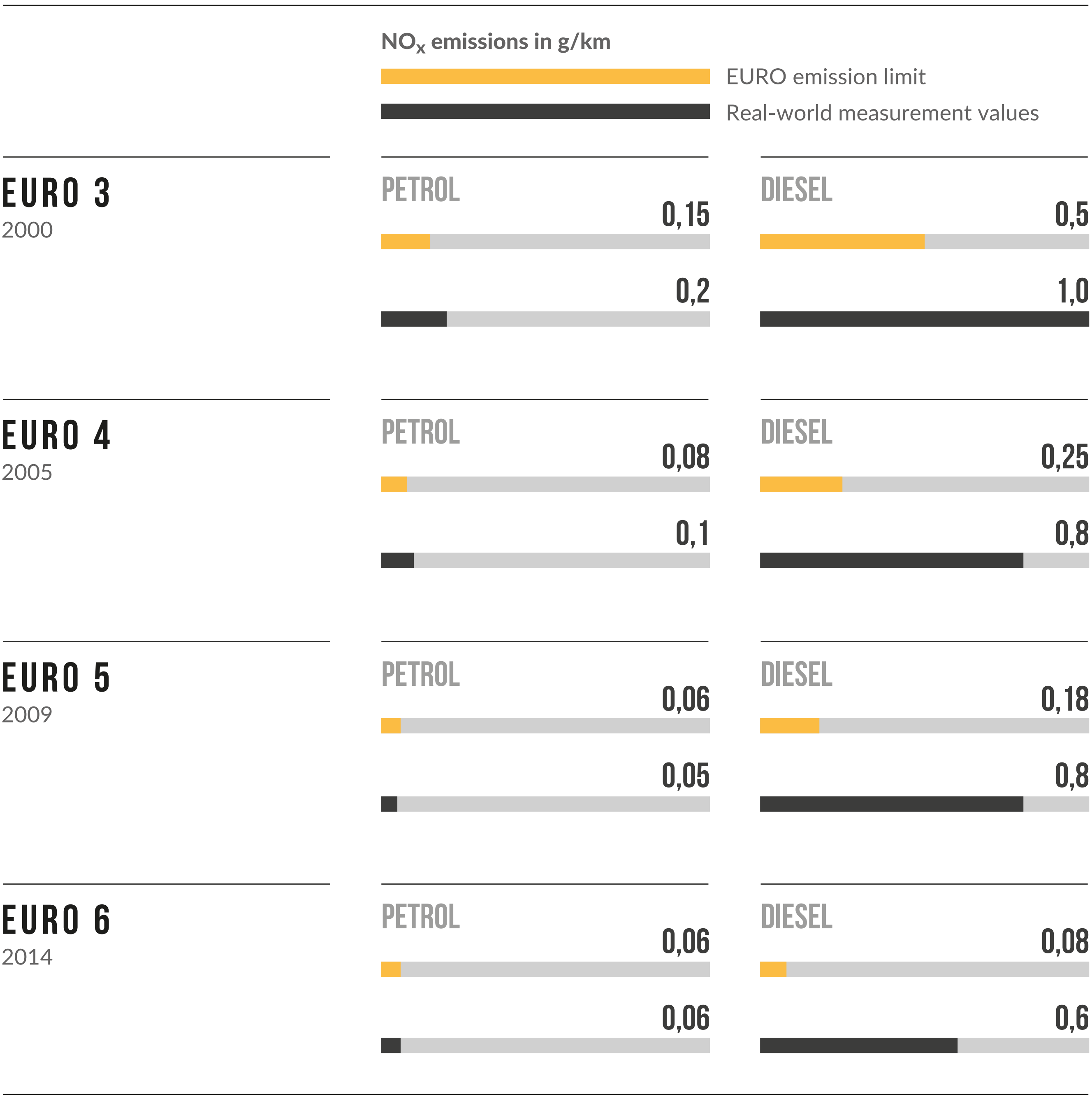
In 2019 in Poland, emissions constituted

78%

of those reported in 2010 and dropped to 68% in 2020.

In addition to the number of vehicles and traffic intensity, the engine type, quality and age of vehicles travelling on roads determine the nitrogen oxide emissions from transport. More stringent European standards forced significant reductions in emissions from vehicles in recent decades. Compared to EURO 3, effective since 2000, EURO 6 in force since 2014 expects a 2.5 fold reduction in nitrogen oxide emissions from petrol engines and a 7.5 fold reduction for Diesel engines in newly registered vehicles (Fig. 1). According to EURO 3–EURO 5, the permitted emissions from Diesel engines can be three times higher than those from petrol engines; only EURO 6 reduces the difference to 25%. Still, measurements of Diesel engine emissions in real operation conditions reveal that they are two-three times higher for the EURO 3–EURO 5 engines and up to 7.5 times higher for the newest EURO 6 engines than stated in the standard. The observed deviation from the standard is much lower for petrol engines.

Figure 1. Comparing nitrogen oxide emission standards for various EURO standards (https://www.eea.europa.eu/media/infographics/comparison-of-nox-emission-standards/view)



HEALTH IMPACT OF NO_2 EXPOSURE – SOURCES OF KNOWLEDGE

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Research on the health impacts of NO_2 exposure has been carried out since the 1970s. The research included clinical trials on small groups of people in whom changes in physiological indices were observed (e.g. pulmonary ventilation efficiency) at a strictly controlled exposure level change and epidemiological studies on large populations varying for the exposure levels. The research aimed to identify the relationship between selected health parameters (such as the frequency of disease occurrence or mortality rate) and exposure. The research results revealing a higher prevalence of respiratory diseases among children exposed to elevated indoor NO_2 concentrations turned out significant. Gas boilers used for heating water were the main NO_2 sources in the research. Clinical trials revealed, e.g. enhanced bronchial responses even at a short-time exposure to elevated NO_2 concentrations, especially among people with asthma. In the 1990s, research emerged linking the daily respiratory and cardiovascular mortality rates with 24h NO_2 concentration in the atmospheric air. The data available back then did not allow for excluding the impact of air pollution other than NO_2, strongly correlated with NO_2, on the relationship. Some study results revealed the relationship between the daily number of ambulatory or hospital admissions due to asthma and respiratory diseases among children and adults, and the daily NO_2 levels. The results of scientific research helped the World Health Organisation develop in 2005 air quality guidelines for NO_2 and determine the limit values for NO_2 concentration in the EU's air quality standards which are in force until now.

CLINICAL TRIALS REVEALED, E.G. ENHANCED BRONCHIAL RESPONSES EVEN AT A SHORT-TIME EXPOSURE TO ELEVATED NO_2 CONCENTRATIONS.

More numerous and accurate scientific research published in the following decade strengthened the conclusions on the NO_2 health impact. Their summary is included in the "Integrated Assessment of the Knowledge of nitrogen oxides health effects" published by the United States Environmental Protection Agency in 2016 (USEPA 2016). The conclusions are based on a holistic, systematic and critical review of toxicological, clinical and epidemiological studies and on specific assessment rules for the available scientific evidence. According to the assessment, short-term (lasting from several minutes up to a month) exposure to NO_2 negatively affects the respiratory system. Epidemiological studies are the main source of this knowledge. They analyse the association of the changes in the population health indices, including but not limited to the daily number of hospital admissions or the daily death rates, with the daily levels of the population's exposure to NO_2, with simultaneous control of other, time-variable risk factors. A negative impact of long-term (months or years) exposure on the respiratory tract is also likely. The available data suggested the impact on the cardiovascular system as well as its contribution to many other health effects, including mortality (Table 1). For most of the analysed health effects, the scientific evidence available for the 2016 assessment was stronger than for a similar evaluation in 2008.

Table 1. Summary of causes of the relationship between health and NO_2 exposure by US EPA (US EPA 2016)

HEALTH IMPACT	RELATIONSHIP*	ASSESSMENT CHANGE SINCE 2008**
SHORT–TERM EXPOSURE		
Respiratory diseases	Causal	+
Cardiovascular diseases	Suggested	+
Deaths – all-cause	Suggested	0
LONG–TERM EXPOSURE		
Respiratory diseases	Likely	+
Cardiovascular diseases and diabetes	Suggested	+
Birth rates and reproduction		
fertility and gestation	Insufficient	0
infant health	Suggested	+
child development	Insufficient	0
Deaths – all-cause	Suggested	+
Cancers	Suggested	+

* Relationship power category:
» causal – scientific evidence is sufficient to declare a causal relationship,

» likely – scientific evidence suggests a likelihood of a causal relationship,

» suggested – scientific evidence suggests a possible causal relationship but is not sufficient to infer it,

» insufficient – scientific evidence is insufficient to infer a presence or absence of a causal effect.

**
+ – stronger evidence,
0 – no change in the relationship power assessment.

This report summarises primarily the conclusions from research on the health effects of NO_2 exposure on the respiratory system. The better-known exposure impact on different diseases in this group is described in detail in the following sections. Still, further research suggests a more substantial impact than presented in the US EPA assessment of NO_2 exposure on some other diseases. Therefore they are also discussed below. The summary is primarily based on recent systematic literature reviews and pooled analyses of available data. The impact of air pollution, including but not limited to NO_2, on many other diseases and health issues not presented in this study is a subject of numerous studies. However, their results do not allow for clear conclusions on the existence and power of the investigated relationships.

02. EFFECTS OF LONG-TERM EXPOSURE TO NITROGEN DIOXIDE POLLUTED AIR

AVAILABLE STUDIES SUGGEST THAT LONG-TERM (MONTHS OR YEARS) EXPOSURE TO NO_2 IS MORE SIGNIFICANT FOR HEALTH THAN SHORT-TERM EXPOSURE. THIS SECTION DESCRIBES THE BEST-KNOWN EXPOSURE EFFECTS.

CHILDREN

ASTHMA INCIDENCE

The relationship between the likelihood of asthma onset and long-term exposure to NO_2 was the subject of many cohort studies carried out in various parts of the world. The impact was investigated of exposure in different periods of the child's life – from birth up to twenty years of age. The last two systematic literature assessments and meta-analyses of the available study results suggest a ca. 5–10% increase in the asthma incidence in the population per 10 µg/m^3 rise in long-term NO_2 exposure (Khreis et al., 2017; HEI 2022). The relative risk calculated in the analysis performed by Kheris et al. 2017, covering seven cohort studies, amounted to 1.10 (95% CI: 1.01–1.21) per 10 µg/m^3, while in a successive HEI analysis covering twelve studies, it was 1.05 (95% CI: 0.99––1.12). A high variability was observed between the study results. According to the HEI analysis, exposure in the child's early life was more significant.

ACUTE INFECTIONS OF THE AIRWAYS

Several epidemiological studies concerned the relationship between the frequency of acute lower respiratory infections (bronchitis, bronchiolitis, and pneumonia) among children and long-term NO_2 exposure (HEI 2022). The studies, primarily of a cohort design, were conducted in North American, European and Asian countries. A systematic assessment of eleven studies indicate a statistically significantly, by ca. 9%, increased incidence related to long-term exposure to NO_2 higher by 10 µg/m^3 (RR = 1.09, 95% CI: 1.03–1.16). The increase in the respiratory infection risk did not depend on the age of children's exposure.

NERVOUS SYSTEM DEVELOPMENT DISORDERS

The relationship between cognitive and psychomotor development disorders in children and air pollution became the subject of research only in the last ten years. Most of the research evaluated the impact of exposure to fine particulate matter, indicating a significant relationship between the risk of autism development and exposure to PM2.5 at the early life stages (Lin LZ et al., 2022). However, studies on exposure to NO_2 are less common and less explicit. A systematic review of the studies identified ten publications that could be included in a meta-analysis (Shang et al. 2020). Five of them originated from Europe, the other ones from Asia. The analysis suggests a relationship between a child's poorer psychomotor development with prenatal exposure to NO_2. No relationship was, however, detected between the child's cognitive and speech development and exposure rate. The results concerning the relationship between the child's attention, behaviour, emotions and IQ and exposure to NO_2 are not clear and suggest the need for future research.

ADULTS

ASTHMA INCIDENCE

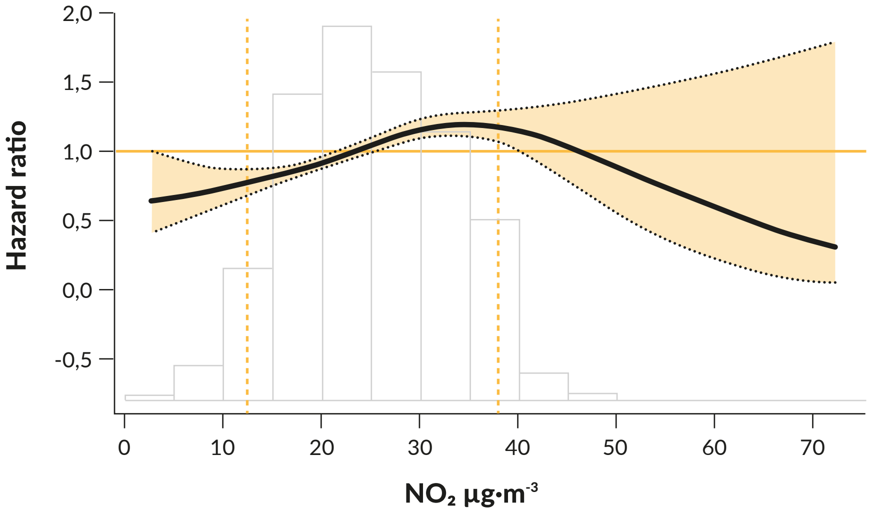
The relationship between the likelihood of developing asthma and NO_2 exposure was the subject of several cohort studies carried out in Europe, Australia and Canada. A systematic review of the studies and a meta-analysis of seven study results reveals a ca. 10% increase in the risk of asthma incidence per 10 µg/m³ rise in the population's long-term exposure to NO_2 (RR = 1.10, 95% CI: 1.01–1.21) (HEI 2022). The results of a recent large European study (ELAPSE) published after the HEI analysis (2022) are consistent with the systematic review's conclusions (Liu et al. 2021a). In three cohorts covering over 98,000 adult inhabitants of Denmark and Sweden, observed for over sixteen years on average, the risk of asthma incidence rose by ca. 17% per 10 µg/m³ increase in NO_2 exposure (RR = 1.17, 95% CI: 1.10–1.25). The increase in the risk was reported for nearly the whole NO_2 concentration range observed in the study. However, it was slower at the highest exposure (when the relatively low number of studied subjects reduced the estimated risk's accuracy) (Fig. 2). It should be pointed out that nearly all studied subjects lived in areas where NO_2 concentrations did not exceed the limit values of the current EU pollution standards (40 µg/m³). However, for over 80% of the subjects, the exposure exceeded the WHO's 2021 guideline values (10 µg/m³).

Figure 2. The risk of asthma rise in the long-term exposure to NO_2 (Liu at al. 2021)

black line – estimated risk value,

dotted line – 95% CI estimation limits,

histogram – the distribution of NO_2 exposure in the study group



INCIDENCE OF CHRONIC OBSTRUCTIVE PULMONARY DISEASE (COPD)

The HEI (2022) report contains the latest systematic review of studies on the relationship between the incidence of COPD and the NO_2 exposure. The literature review identified seven studies on this topic published before 2019. The studies were carried out in Europe, Canada and Australia. Their results differed significantly, and the risk increase estimated in the meta-analysis amounted to ca. 3% per 10 µg/m^3 of NO_2; it was not statistically significant (RR = 1.03, 95% CI: 0.94–1.13). A meta--analysis of five studies that could consider the impact of tobacco smoking revealed no relationship between COPD incidence and NO_2 exposure.

The ELAPSE study mentioned before considered also COPD incidence in the cohorts including inhabitants of Denmark and Sweden (Liu et al. 2021 b). A statistically significant risk increase, amounting to 11% per 10 µg/m^3 NO_2 exposure (RR = 1.11, 95% CI: 1.06–1.16) was observed. The authors think that the difference between their analysis results and previous observations can be attributed to the COPD case definition based on the first hospitalisation due to such diagnosis record and the data suggesting the disease's more advanced stage during the hospitalisation. Still, the differences between the results of studies on the relationship between COPD incidence and NO_2 exposure indicate weak scientific evidence on this relationship.

DIABETES INCIDENCE

The scientific evidence on the relationship between diabetes mellitus (type 2) incidence and morbidity rate and NO_2 exposure is moderately strong, according to the HEI review (2022) assessment. Combined results from seven studies published between 2014 and 2019 reveal a ca. 9% higher diabetes prevalence in a population with 10 µg/m^3 higher NO_2 exposure (RR = 1.09, 95% CI: 1.02–1.17). However, a pooled analysis of seven studies on diabetes incidence suggests a statistically insignificant (ca. 4%) incidence increase at a 10 µg/m^3 higher exposure (RR = 1.04, 95% CI: 0.96–1.13). On the other hand, the results of a large cohort studies carried out in Denmark (Andersen et al. 2012) and Canada (Bai et al., 2018), showing a monotonic increase in the incidence with the exposure, suggest a positive relationship between incidence and exposure. A recently published study using data on more than 41 million Americans over 65 also confirms the relationship between diabetes incidence and exposure to air pollution (Sade et al. 2003). It suggests a ca. 6% risk increase per 10 µg/m^3 NO_2 (RR = 1.059, 95% CI: 1.053–1.064). The increase was observed from the lowest NO_2 concentrations (below 5 µg/m^3) up to ca. 68 µg/m^3, but the relationship disappeared in a relatively small group of persons exposed to higher concentrations. The latest studies, published after USEPA classified scientific evidence linking the risk of diabetes incidence with NO_2 exposure as "suggestive", support a stronger conclusion on the relationship.

DEATHS

A systematic literature review concerning the relationship between all-cause mortality and respiratory mortality with long-term exposure to NO_2, informing the process of WHO guidelines development, identified forty-one cohort studies with the results published before September 2018 (Huangfu and Atkinson, 2020). A pooled analysis of the study results indicates that long-term exposure to

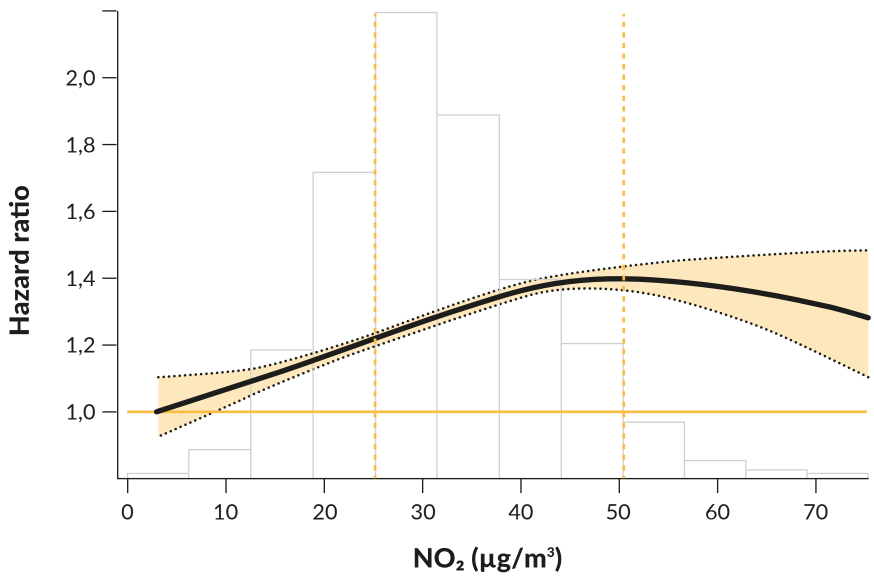
NO_2 higher by 10 μg/m^3 is related to a ca. 2% increase in the all-cause death risk, a 3% increase in the risk of death due to respiratory diseases, including but not limited to COPD, and a 6% higher death rate due to bronchitis or pneumonia (respectively RR = 1.02 (95% CI: 1.01–1.04); 1,03 (1.01–1.05); 1,03 (1.01–1.04); 1.06 (1.02–1.10)). The results of many studies published after 2018 are consistent with the meta-analysis results.

Among the latest studies, the results of the European ELAPSE study are particularly important. A part of the study using data about over 325,000 subjects from six countries (Sweden, Denmark, France the Netherlands, Germany, and Austria), observed for 19.5 years on average, reveals a significant increase in the all-cause mortality as well as respiratory and cardiovascular mortality, with the NO_2 exposure already at its concentrations lower than 10 μg/m^3 (Strak et al. 2021) (Fig. 3). The risk coefficients were higher than those in Huangfu and Atkinson's analysis (2020). For the all-cause, respiratory and cardiovascular mortality, they amounted to 1.09 (95% CI: 1.07–1.10); 1.10 (1.0–1.17) and 1.09 (1.05–1.15), respectively. The coefficients did not change significantly in an analysis considering other air pollution types, including but not limited to PM2.5, suggesting the significance of NO_2 as a risk factor independent of other pollutants. Similar relationships and risk increase were identified from the lowest observed NO_2 levels in an analysis of data from administrative data bases about over 29 million people from six countries (Norway, Denmark, England, the Netherlands, Belgium, Switzerland) and the city of Rome covered by the ELAPSE study (Stafoggia et al. 2022). In another large, recently published American study on a thirteen million cohort of people over 65 (Qian et al. 2021) and in a study on all inhabitants of New Zealand over 30 years of age (Hales et al. 2021), similar relationships were observed between mortality and exposure to NO_2. Similarly to ELAPSE study, the relationships were independent of the interfering impact of PM2.5, and a risk increase was observed at a very low NO_2 concentration (less than 10 μg/m^3). In another American study covering nearly 50 million people over 65 years of age, similar relationships were observed between all-cause, respiratory and cardiovascular mortality and NO_2, also considering exposure to fine dust and black carbon (which is an indicator of pollution from combustion, similarly to NO_2) (Eum et al. 2021).

Figure 3. The risk of deaths in the long-term exposure to NO_2 (Strak et al. 2021)

black line – all-cause mortality,

histogram – the distribution of NO_2 exposure in the study group



ONSET AND PROGRESS OF RESPIRATORY AND CARDIOVASCULAR DISEASES

Data collected in the UK Biobank's cohort study on 55,000 adults in twenty-two health care centres in England, Scotland and Wales between 2006 and 2010 were used in several interesting analyses on the onset and progress of chronic diseases, and the impact of different risk factors, including but not limited to air pollution exposure, on the process. The incidence of one or more chronic respiratory diseases (asthma, COPD or lung cancer) and all-cause and cause-specific mortality was investigated in over 265,000 subjects with no respiratory tract diseases in an initial study (Wang et al., 2023). The risk of respiratory health deterioration was higher due to increased exposure to NO_2 (Table 2). Among the subjects with respiratory diseases, exposure to NO_2 contributed more significantly to a higher risk of further health deterioration and death. Similar and even stronger relationships were observed for exposure to particulate matter pollution (especially PM2.5).

Table 2. Risk of developing chronic respiratory disease and death depending on long-term exposure to NO_2 in the UK Biobank's cohort (wg Wang et al. 2023)

HEALTH CONDITION CHANGE	RELATIVE RISK*	95% CI*
Healthy → falling ill with a chronic respiratory disease	1,04	1,02–1,06
New chronic respiratory disease → many chronic respiratory diseases	1,10	1,02–1,17
Healthy → death	1,04	1,02–1,06
New chronic respiratory disease → death	1,06	1,00–1,06
Many chronic respiratory diseases → death	1,23	1,08–1,39

* per 10 $\mu g/m^3$ NO_2. The RR was calculated after adjustment for potential confounding factors.

A similar analysis of UK Biobank's data for over 168,000 subjects with no arterial hypertension at the beginning of the study revealed a significant relation to exposure to NO_2 and particulate matter pollution of hypertension occurrence, the incidence of cardiovascular diseases as well as of the risk of gradual progress to more acute cardiovascular disease stages and deaths (Zhang et al. 2023).

03. EFFECTS OF SHORT-TERM EXPOSURE TO NO_2 AIR POLLUTION

AMBULATORY ADMISSIONS AND HOSPITALISATIONS

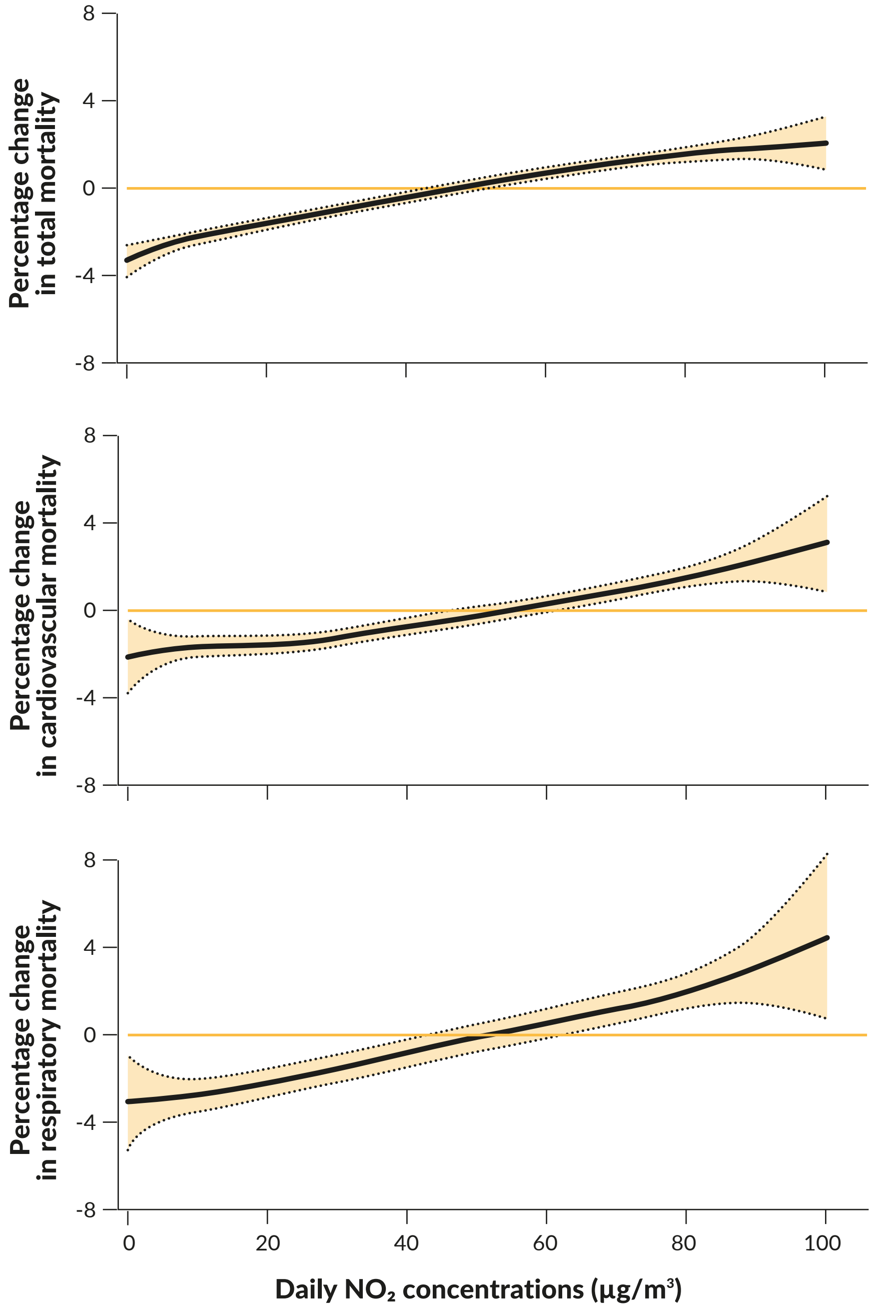
The relationship between the daily number of ambulatory admissions and hospitalisations due to the respiratory disease exacerbations, and the daily air pollution levels, including but not limited to NO_2, has been studied since the 1990s. The results from fifteen studies carried out in thirty-two cities worldwide were available already at the beginning of the previous decade; the quality of the results was good enough to include them in a pooled analysis (Mills et al. 2015). According to the meta-analysis, the mean increase in the risk is ca. 0.6% per 10 $\mu g/m^3$ of the daily NO_2 concentration (RR = 1.0057, 95% CI: 1.0033–1.0082).

A newer literature review focusing on ambulatory admissions and hospitalisations due to exacerbated asthma identified twenty-one publications on the relationship between asthma exacerbation and 24h NO_2 concentration (Zheng et al. 2021). Most studies originated from Europe, the USA and Canada, but some were carried out in Asia, Australia and Latin America. The overall risk coefficient, calculated for all the studies, goes up 1.4% per 10 $\mu g/m^3$ of the 24h NO_2 concentration (RR = 1.014, 95% CI: 1.008–1.020). Such an increase was observed in all age groups, although the relationships were more evident among children and elderly people. The quality of scientific evidence on the relationship between asthma exacerbation requiring an ambulatory admission or hospitalisation and NO_2 exposure was assessed as high.

DEATHS

A systematic literature review on the relationship between the daily number of deaths and the 24h mean NO_2 concentration covered fifty-four results of analyses performed in different parts of the world, including those using data from many areas (Orellano et al. 2020). The review suggests a 0.7% increase in the death risk on (or after) the day with NO_2 concentration higher by 10 $\mu g/m^3$ (RR = 1.0072; 95% CI: 1.0059–1.0085). The results are confirmed by a pooled analysis of data from 398 cities in twenty-two countries representing various economic development levels, covering over 62 million deaths between 1973 and 2018 (Meng et al., 2021). According to the analysis, an increase in the daily NO_2 concentration by 10 $\mu g/m^3$ was related to a rise in all-cause, cardiovascular and respiratory mortality by ca. 0.5%, 0.4% and 0.5%, respectively. The relationships did not change after considering the simultaneous impact of particulate matter, ozone, sulphur dioxide and carbon oxide pollution. The mortality risk increased nearly linearly as the exposure rose even from the lowest observable NO_2 concentrations (Fig. 4).

Figure 4. Daily mortality and short-term exposure to NO_2 – results of a pooled analysis of data from 398 cities in twenty--two countries (Meng et al. 2021)



04. WHO GUIDELINES FOR NO_2 – SCIENTIFIC BASIS

T

The WHO guidelines for NO_2 concentration in the air, published in 2006, recommended maintaining a mean annual exposure below 40 µg/m^3 and short-term exposure at the one-hour average not exceeding 200 µg/m^3 (WHO 2006). Although the results of clinical experimental studies with strictly controlled NO_2 exposure conditions and levels could be used for determining the guidelines for short-term exposure, the scientific basis for establishing a long-term guideline was quite uncertain. A high correlation between exposure to NO_2 and other types of air pollution, including but not limited to fine particulate matter, and a lack of sufficiently detailed long-term studies that could separate the impact of NO_2 from the interfering effect of other pollutants were the leading cause for the uncertainty. The guidelines for long-term exposure to NO_2 were thus determined using studies showing the increase in the respiratory symptoms frequency among children exposed to NO_2 from gas boilers at home. This evidence served as the basis for the WHO's 2000 guidelines for Europe (WHO 2000). The limit value (annual mean: 40 µg/m^3) applicable in Poland (and other EU member states) is based on the WHO's recommendations issued in 2000.

THE LIMIT VALUE (ANNUAL MEAN 40 µG/M^3) APPLICABLE IN POLAND IS BASED ON THE WHO'S RECOM-MENDATIONS ISSUED IN 2000.

Significant progress in epidemiological studies on the health effects of air pollution (including NO_2) within more than a decade after announcing the WHO 2006 guidelines (WHO 2006) enabled their use when formulating the WHO guidelines in 2021. The results of studies on the relationship between mortality and long-term exposure, including a systematic literature review conducted by Huangfu and Atkinson for WHO (2020), whose results are described in the report's previous section, were the main source of evidence. Since the collected data did not suggest the existence of health effects "threshold", i.e. NO_2 concentration below which no mortality risk increase was observed at rising exposure, it was agreed that the mean from the lowest NO_2 concentrations (determined by the distribution's fifth centile) from five studies with the lowest NO_2 concentrations should be taken to identify the guidelines' recommended level. After rejecting two studies with the lowest NO_2 values but with uncertain results because of the method used in the analysis, the mean of the following five "lowest" concentrations amounted to 8.8 µg/m³. A positive relationship was observed between all-cause mortality and NO_2 exposure in all five studies, suggesting the guideline level not exceeding 10 µg/m³. An analysis of the results concerning mortality due to COPD and acute respiratory infections, as well as the latest studies not included in the pooled analysis (mentioned in the report's previous section), also confirmed the guideline's selected level.

In addition to the recommended NO_2 guideline level, the WHO defined three "interim targets" at 40 µg/m³ (the guideline level of 2006), 30 µg/m³ and 20 µg/m³ as the mean annual values of NO_2 exposure, whose reaching within specific time shall bring measurable health results.

Numerous time-series studies published after 2006, as well as identifying the relationship between health and the 24h NO_2 exposure, also after adjustment for other pollutants, indicated the need to determine new guidelines for the daily NO_2 concentrations. Considering that, similarly to long-term exposure, no health effects "threshold" was observed, and long-term exposure significantly contributes to the health condition, short-term guidelines were determined in connection with the guidelines for the annual mean NO_2 concentrations. The data on the 24h NO_2 concentration distribution throughout a year from many cities in the world indicate that the 24h values exceeding 25 µg/m³ occur for only a few days a year in areas where the mean annual NO_2 concentration amounts to 10 µg/m³ (i.e. at the annual mean guideline level). Therefore, although the short-term NO_2 exposure will impact health in such places, it will be relatively low and acceptable. Hence, the guideline level for the mean 24h NO_2 concentration was determined as 25 µg/m³, whereby it should not be exceeded more often than three times a year (corresponding to the 99th centile of the 24h mean distribution in a year). The concentration value of 120 µg/m³ was assumed as the highest interim target; the concentration corresponded to approximately one-hour NO_2 mean of 200 µg/m³, recommended as the short-term guideline level in 2006. The guideline levels and interim targets for NO_2, recommended by the WHO in 2021, are summarised in Table 3.

Table 3. WHO guideline levels and interim targets for NO_2 (µg/m³) (WHO 2021)

RECOMMENDATION	ANNUAL AVERAGE	24H AVERAGE*
Interim target 1	40	120
Interim target 2	30	50
Interim target 3	20	–
WHO guideline level	**10**	**25**

* exceeded on max. three days a year

05. NO_2 LEVELS IN POLAND AND ESTIMATED HEALTH EFFECTS OF EXPOSURE

In 2020, the mean annual NO_2 concentration was less than 14 µg/m³ in half of the measuring points in Poland; it was less than 10 µg/m³ (i.e. below the WHO's guideline levels) in a quarter of the points and over 18 µg/m³ also in a quarter of them. The highest concentrations (49 µg/m³) were measured in Krakow. The NO_2 median level in Poland was higher than in twelve other European countries for which the data are available at the European Environmental Agency.

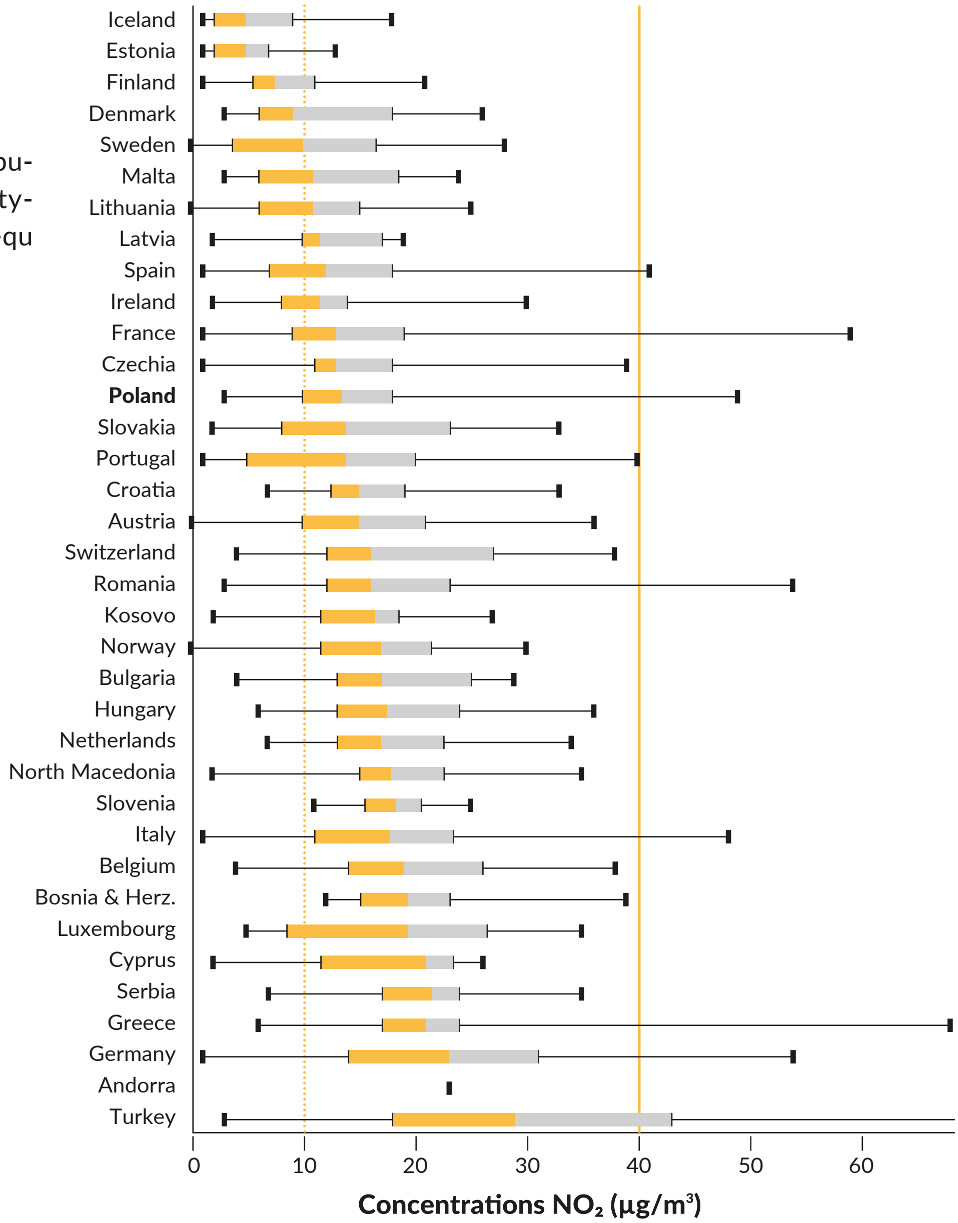
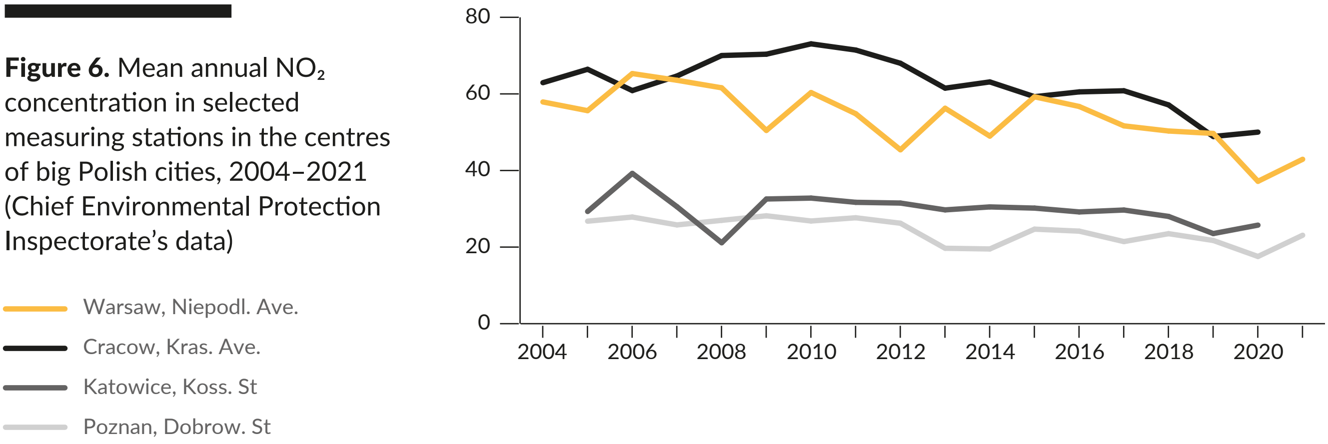


Figure 5. Mean annual NO_2 concentrations measured in European countries in 2020 (https://www.eea.europa.eu/publications/status-of-air-quality-in-Europe-2022/europes-air-quality-status-2022)

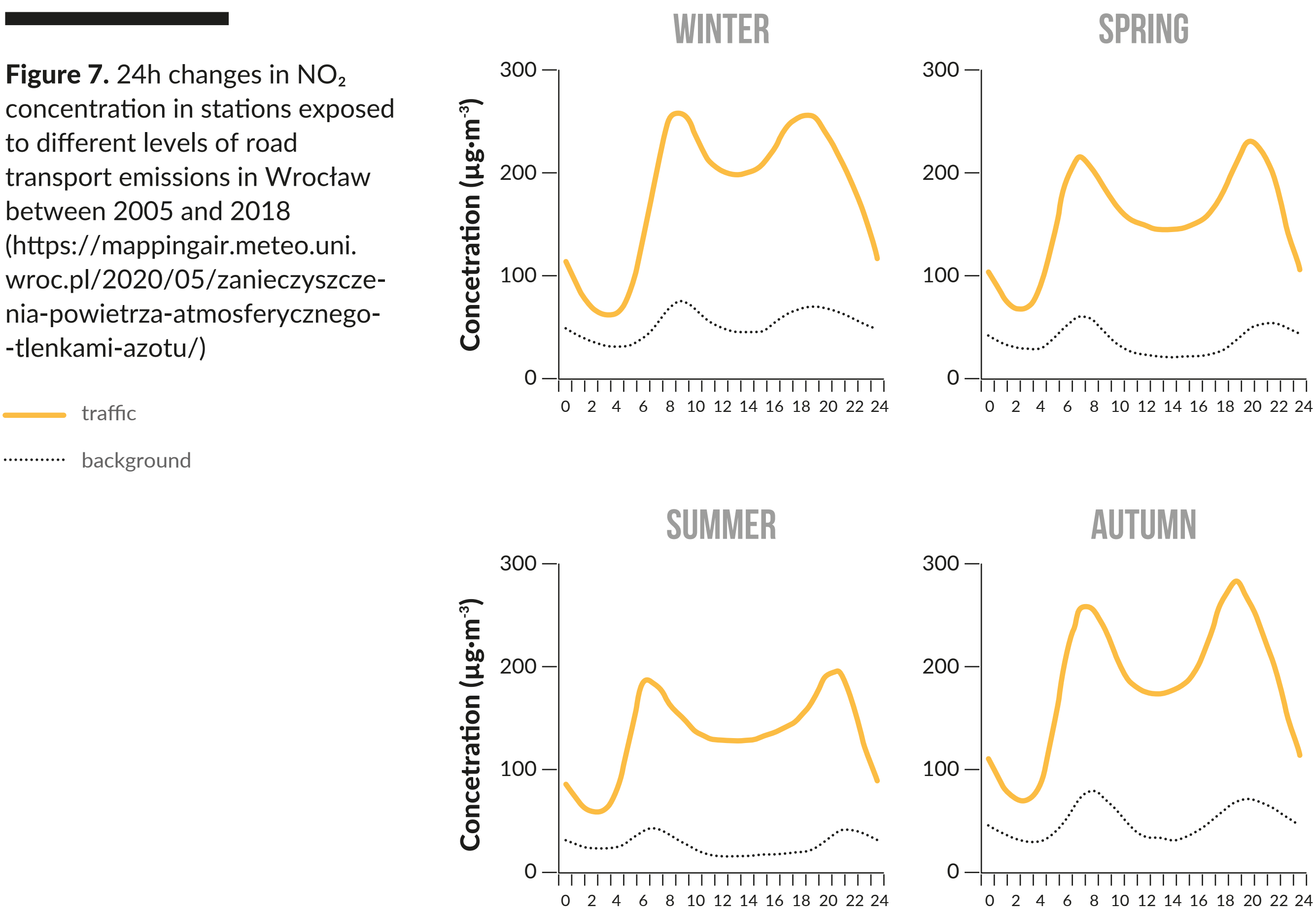
A slight decrease was observed between 2004 and 2021 in measuring stations in big city centres in Poland (including those with the highest NO_2 concentrations) (Fig. 6).

Figure 6. Mean annual NO_2 concentration in selected measuring stations in the centres of big Polish cities, 2004–2021 (Chief Environmental Protection Inspectorate's data)



The location of a measuring station within a city is of key importance for the measured NO_2 levels. Since NO_2 concentration drops quickly with the distance to the source of nitrogen oxide emissions, the highest concentrations are observed in stations located near streets with heavy vehicle traffic. It is illustrated by data from Wrocław, where NO_2 concentrations in a station exposed to close traffic emissions were several times higher than in a station located farther from thoroughfares (Fig. 7). A significant increase in NO_2 concentration was observed during peak vehicle traffic hours, especially in the "traffic" station.

Figure 7. 24h changes in NO_2 concentration in stations exposed to different levels of road transport emissions in Wrocław between 2005 and 2018 (https://mappingair.meteo.uni.wroc.pl/2020/05/zanieczyszczenia-powietrza-atmosferycznego--tlenkami-azotu/)



Based on NO_2 exposure distribution in the population, mortality data and considering the relationship between the mortality and exposure indicated by epidemiological studies, health effects attributed to the exposure in the given population can be calculated. Such calculations carried out by the European Environmental Agency reveal that 3,400 deaths and 38,500 lost years of life in 2020 could be attributed to NO_2 exposure levels exceeding the WHO's guidelines in Poland (EEA 2022b). Based on the mean NO_2 exposure in Poland (13.1 μg/m³ according to EEA 2022b) and risk coefficients presented in the report's previous sections, one can calculate the percentage of incidences attributable to exposure exceeding the WHO's guideline level in Poland (Table 4). The percentage is relatively low (2-5%). The non-uniform exposure levels result in the percentage being significantly higher, e.g. exceeding 7.3% (in children) and 11.8% (adults) for asthma, in a quarter of the Polish population exposed to higher NO_2 concentrations (over 18 μg/m³).

Table 4. Percentage of selected disease incidences attributed to NO_2 exposure exceeding the WHO guideline level in Poland

INCIDENCE OF:	% RELATED-ATTRIBUTED TO NO_2 (ON AVERAGE IN POLAND)	MINIMUM % ATTRIBUTED TO NO_2 IN A QUARTER OF THE POPULATION EXPOSED TO THE HIGHEST NO_2 LEVELS
Asthma (children)	2,9 (0,3–5,7)	7,3 (0,8–14,1)
Acute respiratory tract infections (children)	2,6 (0,9–5,5)	6,7 (2,3–11,2)
Asthma (adults) (acc. to Liu et al. 2021 a)	4,8 (2,9–6,7)	11,8 (7,3–16,4)
Chronic obstructive pulmonary diseases (acc. to Liu et al. 2021 b)	3,2 (1,8–4,5)	8,0 (4,6–11,2)
Diabetes (over 65 years old) (acc. to Sade et al. 2023)	1,8 (1,6–1,9)	4,5 (4,1–4,8)

06. SUMMARY

The knowledge of the health effects of air pollution with nitrogen dioxide increased significantly over the last ten-fifteen years. It confirmed previous observations on the harmful impact of exposure on the respiratory tract and suggested a likely relationship between diabetes incidence and exposure. Extensive studies covering millions of subjects confirmed the relationship between respiratory and circulatory mortality and exposure. Moreover, they revealed that harmful health impact occurs even at very low NO_2 concentrations. Determining the relationship's independence from the effects of other air pollutions (including but not limited to PM2.5) is a significant conclusion from the new studies. The recently developed knowledge highlighted the need to significantly reduce the WHO's guidelines on the NO_2 levels in atmospheric air. Nearly three-quarters of the Polish population dwells in areas with exceeded guideline levels. The inhabitants of big cities' central districts, especially those living close to main roads, are exposed to NO_2 levels over twice higher than those recommended by the WHO. A significant part of respiratory diseases in these groups can be attributed to NO_2 exposure and road traffic in cities, as it predominantly results from car engine emissions.

A SIGNIFICANT PART OF RESPIRATORY DISEASES CAN BE ATTRIBUTED TO NO_2 EXPOSURE AND ROAD TRAFFIC IN CITIES, AS IT PREDOMINANTLY RESULTS FROM CAR ENGINE EMISSIONS.

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