MSCE in Energy Infrastructure Brief on Air Pollution

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Introduction

This brief will cover some basic air pollution concepts with a focus on ambient air pollution the U.S. It will not cover indoor air pollution or air pollution in the workplace although both of these topics are important. From an international perspective, the U.S. has relatively good air quality. Many developing countries would be in major violation of the U.S. air quality standards. The progress in cleaning the air has recently been slowed by the increasing number and magnitude of wildfires. We briefly discuss this issue, although mitigation involves the large issue of mitigating climate change.

Regulated Pollutants in the U.S.

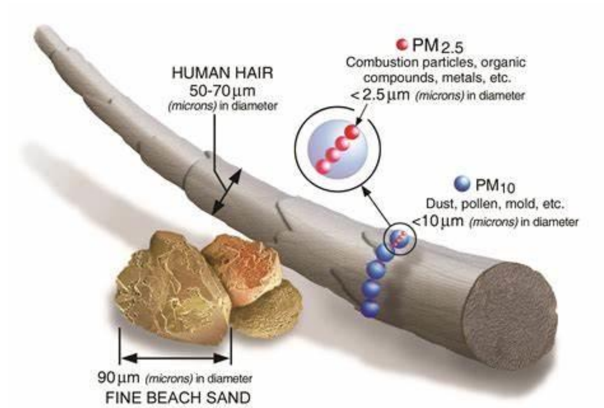
Criteria Air Pollutants

EPA has established a large ambient air quality monitoring system for six of the most common air pollutants: particulate matter, ozone, nitrogen dioxide, sulfur dioxide, lead and carbon monoxide. The EPA not only measures the atmospheric concentrations of all of the criteria pollutants at numerous monitoring sites in real time, but the Clean Air Act also requires that EPA set national ambient air quality standards (NAAQS) for each criteria pollutant based on scientifically acceptable ambient air concentrations at relevant averaging times (typically hourly, daily and/or annual average values). The EPA periodically conducts comprehensive scientific reviews of the literature every 5 years and proposes new acceptable ambient air concentrations (i.e. NAAQS) when deemed necessary based on the latest scientific information. The table below shows the NAAQS. A given standard has a concentration level, an averaging time and a statistical form. The primary standards are to protect human health, and the secondary standards are to protect the public welfare from other adverse effects (e.g. effects on soil, water, crops, vegetation). It should be noted that California has its own set of air quality standards because they were in effect prior to the passage of the federal Clean Air Act. However, California's standards cannot be less stringent than the NAAQS.

Pollutant		Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide		primary	8-hour	9 ppm	Not to be exceeded more than once per year
			1-hour	35 ppm	
Lead		primary and secondary	Rolling 3 month average	0.15 μg/m^3	Not to be exceeded
Nitrogen Dioxide		primary	1-hour	100 ppb	98th percentile, averaged over 3 years
		primary and secondary	Annual	53 ppb	Annual Mean
Ozone		primary and secondary	8-hour	0.075 ppm	Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 years
Particle Pollution	$PM_{2.5}$	primary	Annual	12 μg/m^3	annual mean, averaged over 3 years
		secondary	Annual	15 μg/m^3	annual mean, averaged over 3 years
		primary and secondary	24-hour	35 μg/m^3	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24-hour	150 μg/m^3	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide		primary	1-hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		secondary	3-hour	0.5 ppm	Not to be exceeded more than once per year

For further information see [Reviewing National Ambient Air Quality Standards (NAAQS): Scientific and Technical Information | US EPA]

EPA's recent focus has been on $PM_{2.5}$ (see figure https://www.epa.gov/pm-pollution/particulate-matter-pm-basics) as it has been related to numerous health effects. The annual average standard was revised in 2024 and lowered from 12 to 9 μg/m^3. With the advent of low-cost $PM_{2.5}$ monitors, there has been a lot of hyper-local monitoring by community members in urban areas, with increased concern for the exact location of EPA monitoring sites. The Clean Air Act does not require EPA to establish NAAQS at a zero-risk level, but rather at a level that reduces risk sufficiently to protect public health with an adequate margin of safety.



EPA reports air quality measurements to the public in terms of an 'Air Quality Index (AQI)'. A value of 100 indicates that the short-term concentration is exactly equal to the relevant air quality standard for a given pollutant. A level of 50 indicates that the value is exactly one-half of the standard. The largest AQI for that day is reported. The table below summarizes the AQI categories.

AQI Basics for Ozone and Particle Pollution

Daily AQI Color	Levels of Concern	Values of Index	Description of Air Quality
Green	Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

AQI Basics | AirNow.gov

Hazardous Air Pollutants (HAPs, also called "Air Toxics")

A set of pollutants other than the criteria air pollutants that are not found everywhere in the U.S. but are emitted by certain sources or source categories. They primarily consist of organic compounds and highly toxic compounds emitted by only a few sources. The potential emissions from relevant sources of 186 of them that have been regulated by EPA since 1990 (Hazardous Air Pollutants | US EPA). Unlike criteria pollutants, ambient concentrations of HAPs are not routinely measured (they are not found everywhere). EPA uses hazardous air pollutant emissions and ambient monitoring data to develop regulatory programs that limit their emissions from stationary sources. Enforcement is based on both emission measurements and predicted downwind ambient concentrations using air quality models. Additional compounds that are not on EPA's list are also regulated by certain states.

Gaseous concentration metrics

Air pollutant concentrations for gases are reported in units of volume fraction of pollutant gas per volume of air, typically parts per billion by volume (ppbv). However, particulate matter concentrations are reported in units of mass of particles per volume of air, typically in micrograms per cubic meter ($\mu g/m^3$). In both cases, the volume of air is standardized at 20 degrees Celcius and

1 atmosphere pressure. If needed, the following formula converts a gaseous pollutant concentration from units of ppbv to µg/m^3:

$$\text{Gas concentration in } \mu g/m^3 = \frac{(Gas\ concentration\ in\ ppbv)\ x\ (Molecular\ Weight\ of\ Gas)}{24.45}$$

where

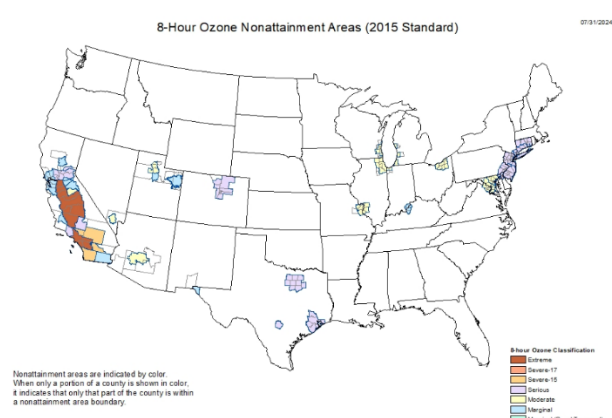
Molecular weight of pollutant gas = grams of pollutant per mole

24.45 is the volume of and ideal gas at standard conditions of 20 Celcius and one atmosphere pressure.

Locations of Regulatory Emphasis

Depending on the regulated pollutant, the relevant downwind area of impact on air quality varies considerably. Primary pollutants are defined as those directly emitted from a given source whose downwind concentrations are determined solely by atmospheric dilution. Examples are carbon monoxide whose concentrations are highest adjacent to traffic. Another example is many of the HAPs (e.g. benzene) whose downwind concentrations are highest near a given source. Reducing the atmospheric levels of primary pollutants requires reduction of those same pollutants at the emission source. In contrast, secondary pollutants are defined as those pollutants that are formed downwind by atmospheric chemical reactions. Reducing the atmospheric levels of secondary pollutants requires reduction in the emissions of 'precursor' compounds that participate in the downwind reactions. An example is ozone that is an important component of photochemical smog whose precursor emissions include both nitrogen oxides and selected reactive organic species. Perhaps the most complex pollutant in this regard is particulate matter. It can be both directly emitted as well as formed in the downwind atmosphere.

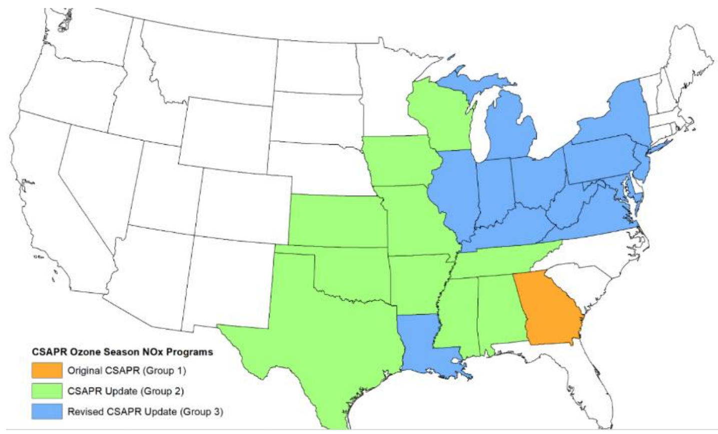
NAAQS Non-attainment areas



For those air monitors whose concentrations exceed the NAAQS, the Clean Air Act has specified an air quality modeling procedure to define a **nearby** area surrounding the monitoring site(s) that is designated as a non-attainment area. The size of the surrounding area depends on the location of nearby sources and the number of monitors exceeding the NAAQS. EPA states that these areas are as shown in the example map for ozone (8-Hour Ozone Nonattainment Areas (2015 Standard) | Green Book | US EPA). Emissions from stationary sources (e.g. industrial facilities and power plants) located in a non-attainment area are subject to stricter emission regulations than those outside the area. Emissions from transportation sources are not subject to these restrictions, but instead are regulated by EPA with national standards across all locations in the U.S.

Cross-state Air Pollution Rule

This rule regulates SO_2 and NO_x emissions from power plants to lower the concentrations of regional O_3 and $PM_{2.5}$. It recognizes the importance of secondary pollutant formation as air travels across state borders and applies only to certain states that whose precursor emissions affect ozone and $PM_{2.5}$ non-attainment areas in downwind states. The regulated states are shown in the map. Different revisions (colors) reflect updated and more stringent emission regulations (see: Revised Cross-State Air Pollution Rule Update | US EPA).



Operating Permits for Major Stationary Sources

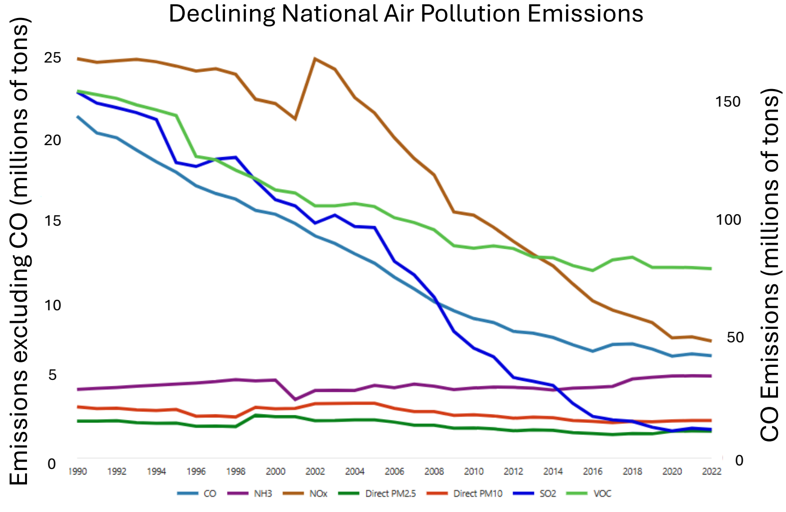
As described in Title V of the Clean Air Act, major stationary sources of air pollution (e.g power plants, industrial facilities) must obtain and maintain a Title V operating permit. As described in detail at the EPA website (Who Has to Obtain a Title V Permit? | US EPA), EPA defines a major source of air pollution as one that has actual or potential emissions at or above the major source threshold for any "air pollutant". Potential emissions are based on the source operating at full capacity. The major source emission threshold for any criteria air pollutant is 100 tons/year (this is the "default value"). Lower thresholds apply in non-attainment areas (but only for the pollutants that are in non-attainment). Major source thresholds for HAPs are 10 tons/year for a single HAP or 25 tons/year for any combination of HAPs. The EPA generally has not required non-major sources to get permits.

The purpose of an operating permit is to enable the source, State, EPA and the public to better understand the requirements to which the source is subject, and whether the source is meeting those requirements by listing all the requirements in one publicly available document. EPA also requires fees to pay the cost of the permit program, regular emission reports, and yearly compliance certifications. Operating permit contents include a facility description, a list of applicable pollution control technologies, results of air emission sampling and monitoring, and a documentation of compliance reporting.

Applicable pollution control technologies for a given major source are specified by EPA and defined by both source type and pollutant. The specific control technologies are listed in different categories that vary in stringency. Two major categories are Best Available Control Technology (BACT) and Lowest Achievable Emission Rate (LAER). LAER is required for major new or modified sources in non-attainment areas and BACT is required for these same sources in attainment areas. For more information, see: RACT/BACT/LAER Clearinghouse (RBLC) Basic Information | US EPA.

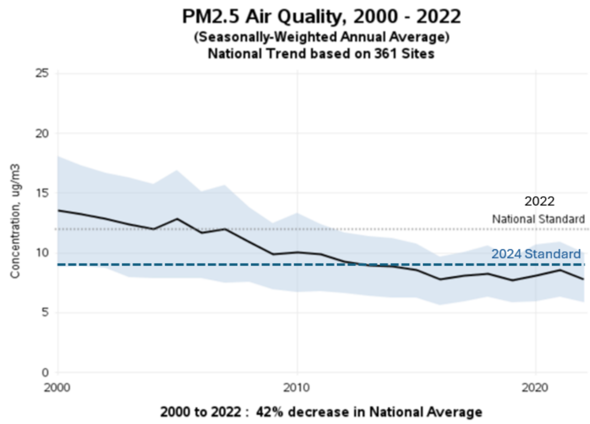
Trends in Regulated Pollution Levels

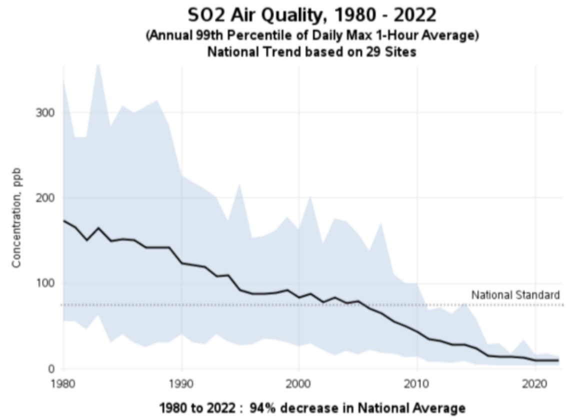
The effect of these regulations has been to reduce the total emissions of air pollutants stationary sources over time. Although not discussed here, the reductions in transportation related emissions has also been significant. The figure shows the time trends in criteria air pollutant emissions over time. Significant reductions in nitrogen oxides (NOx: the sum of nitrogen dioxide and its precursor nitric oxide), primary $PM_{2.5}$, sulfur dioxide, and volatile organic carbon (a precursor to ozone formation). The SO_2 reductions are due in part to controls on coal-fired power plants and switching from coal to natural gas plants. The NOx reductions are due in part to additional exhaust controls on power plants and exhaust treatment of transportation emissions. The latter is also responsible for significant reductions in primary $PM_{2.5}$ (from filtering diesel exhaust) and volatile organic compounds.

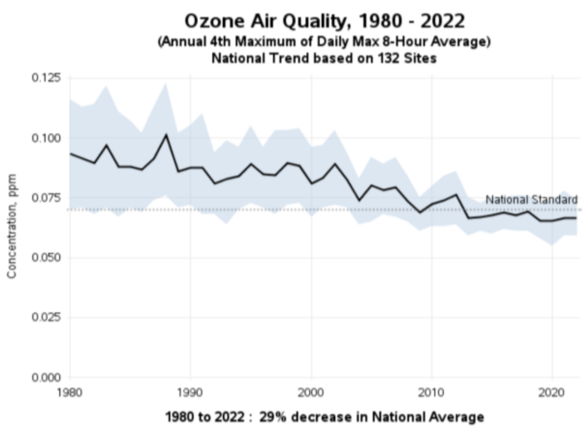


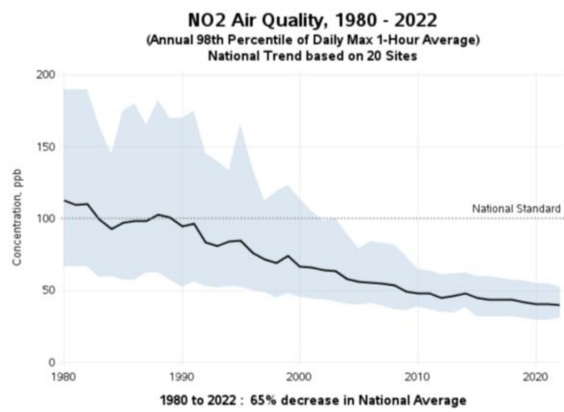
Our Nation's Air 2023 (epa.gov)

The result of these emission reductions is a reduction in atmospheric concentrations of these pollutants. Shown in the figure below are trends for four important criteria pollutants. The reductions in SO_2 and NO_2 levels are most pronounced, with less recent reductions in both $PM_{2.5}$ and ozone levels. Also included is the most recent $PM_{2.5}$ standard adopted in 2024.









National Air Quality: Status and Trends of Key Air Pollutants | US EPA

Unregulated Air Pollution: Wildfires

EPA considers smoke from wildland fires to be "natural," and therefore beyond regulation. For this reason, exceedances of the NAAQS from wildland fire smoke do not affect non-attainment status. In contrast, EPA considers the smoke from prescribed burns to be anthropogenic, i.e., a regulated pollutant. However air quality impacts from prescribed burns are much smaller than from wildland fires due in part to the ability to choose favorable meteorological conditions (high humidity, moderate wind speeds, minimum downwind exposures) and in part to on-site abatement capabilities. EPA requires permits for prescribed burns and transfers oversight authority to state agencies.

While there has been steady improvement in air quality across the U.S. over the last few decades, the recent increase in the number of wildland fires has slowed improvement for several pollutants, mainly in the Western U.S. The figure below shows the change in the number of acres per year that burned due to wildfires. It compares the monthly averages in the eastern and western states between the first half of the period of measurement (1984-2002) and the second half (2003-2021) (Climate Change Indicators: Wildfires | US EPA).

Wildfires have caused violations of the 24 hour $PM_{2.5}$ standard. Researchers have found that the total US population exposed to at least one day with a daily average of 100 mg/m^3 $PM_{2.5}$ has increased from about one hundred people for the period between 2006 and 2010 to about one million people for the period between 2016 and 2020 (Childs et al *Environ. Sci. Technol.* 2022, 56, 13607−13621). Wildfires have also recently impacted eastern U.S. air quality due to long range transport of smoke plumes from large Canadian fires. Wildfires also emit nitrogen oxides and volatile hydrocarbons that undergo downwind photochemistry to produce ozone exceedances on a regional scale. Some HAPs are also found in wildfire smoke, notably benzene, formaldehyde, acrolein, lead and copper. In addition, if the fire also passes through populated areas and ignites structures, the levels of lead in downwind air can be significant (New analysis shows spikes of metal contaminants, including lead, in 2018 Camp Fire wildfire smoke | California Air Resources Board).

Useful Websites

- AirNow.gov An EPA website (along with Canadian and Mexican partners) that provides real-time air quality data at specific locations (zip code, city or state). It reports the air quality index by location. I also has an archive of data accessible by calendar date and location.
- Nonattainment Areas for Criteria Pollutants (Green Book) | US EPA Provides detailed information on all U.S. non-attainment areas
- Air pollution (who.int) Detailed information on global air pollution and air quality standards set by the World Health Organization
- About | California Air Resources Board Information on air pollution regulations in California.
- UW MSCE Energy Infrastructure, https://www.energy-infrastructure.uw.edu/