The INGAA Foundation, Inc.

Potential Impacts of the Ozone and Particulate Matter NAAQS on Retrofit NOx Control for Natural Gas Transmission and Storage Compressor Drivers

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December 2017

INGAA Foundation Report
Report No. 2016-6

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EXECUTIVE SUMMARY

The Clean Air Act requires EPA to establish National Ambient Air Quality Standards (NAAQS) for criteria pollutants, including ozone and fine particulate ($PM_{2.5}$). NOx emissions can react in the atmosphere to form ozone or $PM_{2.5}$ (i.e., nitrates) so NOx is regulated as a "precursor." To address NAAQS nonattainment, the Clean Air Act requires states to reduce NOx emissions from existing equipment. Emission inventories indicate that natural gas-fired reciprocating internal combustion engines and combustion turbines that drive natural gas compressors are a relatively significant contributor to the stationary source NOx inventory.

Based on several potential regulatory scenarios selected by the project team, this report assesses the potential impact of the ozone NAAQS on existing natural gas-fired compressor drivers based on three regulatory scenarios. The ozone NAAQS is the primary driver for NOx controls, but implications of the $PM_{2.5}$ NAAQS are also discussed in this report. In 2015, EPA lowered the ozone NAAQS to 70 parts per billion (ppb). This new standard will require additional NOx reduction unless EPA revisits the standard.

This study assessed transmission and storage (T&S) sources at risk of regulation, as determined by the geographical coverage of selected regulatory scenarios, cross-referenced with units in the INGAA engine-turbine database (ETDB) that do not include NOx control. The ETDB includes approximately 4,350 reciprocating engines and 1,120 combustion turbines that drive natural gas compressors. The number of these sources that fall within each scenario are shown in Table 1 and general cost estimates are shown in Table 2. Within the scenarios considered and constraints of this study, the estimate of potentially affected unit counts and cost highlights include:

- An upper bound estimate of affected units nationwide indicates up to 2,633 engines and 375 turbines could require retrofit control, with a cost estimate of $3.5 billion. The potentially affected units comprise approximately 60% of engines and 33% of turbines.
- A lower bound estimate, based on counties with ambient ozone monitoring data similar to the 2015 ozone NAAQS (i.e., 70 ppbv based on an 8-hour average) and adjacent counties indicates 417 engines and 101 turbines may require retrofit control, with a cost estimate of $573 million. (Nearly 10% of engines and approximately 9 % of turbines).
- The mid-range estimate of unit counts is based on the lower bound scenario with *statewide* NOx RACT included for 13 states (see list in Table 1). Under this scenario, the study estimated that 1,631 engines and 271 turbines will be impacted. A detailed cost estimate was not conducted for this scenario, but the total costs would be approximately $2 billion. (Approximately 37% of engines and 24% of turbines).
- An overriding source of uncertainty in the cost estimates is that site-specific costs associated with peripheral systems, facility modification, and installation can significantly affect control costs, and those costs can be similar in magnitude to emissions control technology costs. These costs vary for each site.

These costs estimates are based on the scenarios described below, and a presumption that additional NOx reductions are required in response to the revised October 2015 ozone NAAQS, which lowered the standard to 70 ppb. The implementation schedule, as prescribed by the Clean Air Act, required states to recommend nonattainment areas in the fall of 2016. EPA was required to complete the designation process by October 2017, but can delay designations in some cases. State implementation plan (SIP) deadlines are tied to the designation dates, and SIPs are expected in 2020 or the following years. In some cases, states may take earlier action, such as updating NOx Reasonably Available Control Technology (RACT) regulations, which are a principle mechanism for NOx reductions in affected states.

Based on experience with previous ozone NAAQS and $PM_{2.5}$ NAAQS actions and to target the analysis for this project, three regulatory scenarios were selected:

- A nationwide requirement represents the upper bound of affected units and costs. This upper bound financial impact is unlikely, but also provides an understanding of long-term cost implications associated with addressing legacy units that do not include NOx emission controls. A unit size threshold of 1,000 horsepower (HP) for engines and 5,000 HP for turbines was applied to the upper bound scenario.
- The middle-ground analysis uses the lower bound scenario as the starting point and adds a number of states where “statewide RACT” is possible based on previous rulemakings.
- The lower bound estimate contains counties and adjacent counties where the three year average of monitoring data from the EPA ambient monitoring network is greater than 69 ppbv. Note that upcoming EPA designations will clarify how the geographical coverage from this scenario compares to the official designations. Subsequent implementation activity (e.g., SIPs to address NOx transport) will likely impact counties other than those designated as ozone nonattainment. For the lower bound scenario, unit counts and costs are cataloged by engine HP into three size ranges: 500 – 999 HP, ≥ 1,000 HP, and ≥ 2,400 HP. The large size category was included because it was the cut-point for “large engines” that EPA included in the 1990s NOx SIP Call Phase 2 Rule.

The number of units within each scenario is shown in Table 1. For cost estimates, units were categorized to consider significant cost implications (e.g., whether a turbocharger or turbocharger upgrade was needed), and costs were applied, by category, to determine a “rolled up” cost estimate for the upper bound and lower bound scenarios. A precise breakdown of costs for each engine type was not within the scope of this project. Cost information was provided by technology service providers and manufacturers, and all noted that facility-specific modifications can significantly impact retrofit costs. Thus, the cost estimates are reasonable to assess total cost risk for the industry, but facility-specific review would be necessary to determine costs for a particular unit or facility. An example of cost differences for retrofit of two different models of two-stroke lean burn engines is discussed in Section 3.3.

Rolled up cost estimates are shown in Table 2. The most expensive component-level cost is for lean burn engine retrofits that require installation of turbochargers and cooling system upgrades. Other related alterations (e.g., other upgrades to air handling systems, engine controls, etc.) and facility modifications can cause a single engine retrofit to cost up to 4 million dollars. Likewise, for turbine retrofits. Non-standard retrofits and associated upgrades and facility modifications can result in the upper end of turbine retrofits to cost between 1.5 and 3 million dollars.

Table 1. Quantity of "affected" engines and turbines

Scenario	Geographical Area	Unit Type	Reciprocating Engines			Turbines
			500 – 999 HP	≥1,000 HP[A]	≥2,400 HP	≥ 5000 HP
A	**Nationwide** (45 states in INGAA ETDB with compressor drivers) *Total Uncontrolled Engines: 2,633* *Total Uncontrolled Turbines: 375*	Lean burn:	161	2121	668	
		Rich burn:	209	148	3	
		Turbines:				375
B[B]	**Counties with ozone monitoring data >69 ppb; plus the adjacent counties; plus statewide controls for select states:** NY, PA, IL, AZ, MS, LA, AL, GA, NC, VA, TN, WV, OH. *Total Uncontrolled Engines: 1,631* *Total Uncontrolled Turbines: 271*	Lean burn:	96	1408	430	
		Rich burn:	80	47	2	
		Turbines:				271
C[B]	**Counties with ozone monitoring data >69 ppb; plus the adjacent counties** *Total Uncontrolled Engines: 417* *Total Uncontrolled Turbines: 101*	Lean burn:	23	345	99	
		Rich burn:	44	5	None	
		Turbines:				101

[A] Count for ≥ 1,000 HP includes ≥2,400 HP engines

[B] Appendix 3 lists counties by state with monitoring data >69 ppb (and adjacent counties).

Table 2. Cost of Retrofit

Scenario	Geographical Area	Unit Type	Reciprocating Engines ≥1000 HP*			Turbines ≥ 5000 HP
A (upper bound)	Nationwide (45 states in INGAA ETDB with compressor drivers)	Lean burn Engine	$3.34 billion			
		Rich burn Engine	$43.2 million			
		Turbines				$150 million
Engine size ranges for Scenario C:			**500 – 999 HP**	**≥1000 HP***	**≥2400 HP**	
C (lower bound)	Counties with ozone monitoring data >69 ppb plus the adjacent counties	Lean burn Engine	$35 million	$531 million	$159 million	
		Rich burn Engine	$13.2 million	$1.5 million	Not applicable	
		Turbines				$40.4 million

*Note: >1000 HP count includes >2400 HP engines

1. INTRODUCTION AND BACKGROUND

The National Ambient Air Quality Standards (NAAQS) are standards established by the United States Environmental Protection Agency (EPA) under authority of the Clean Air Act. NAAQS must be set for six criteria pollutants: particulate matter, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. The NAAQS primary standards are designed to protect human health, including an adequate margin of safety for sensitive populations such as children, the elderly, and individuals suffering from respiratory diseases. Secondary standards are designed to protect public welfare (e.g., vegetation and crops) from any known or anticipated adverse effects of a pollutant. The Clean Air Act requires a review of each NAAQS every five years. Delays in EPA conducting this review often result in lawsuits that frequently culminate in a consent decree schedule for completing the review. During its review, EPA can conclude that the current NAAQS is protective and propose to retain the existing standards. However, in recent reviews of the ozone and particulate matter NAAQS, EPA has adopted lower standards, with the latter focusing on fine particulate matter ($PM_{2.5}$).

NOx emissions are regulated in conjunction with the ozone and $PM_{2.5}$ NAAQS because NOx can react in the atmosphere to form ozone or $PM_{2.5}$ (i.e., “nitrates”). Thus, NOx is regulated because it is a “precursor” to ozone and $PM_{2.5}$. NOx emissions are a product of combustion processes, and can be formed from nitrogen and oxygen in the combustion air, regardless of the fuel composition. Natural gas-fired reciprocating engines and combustion turbines used to drive natural gas compressors at transmission compressor stations and underground storage facilities emit NOx. Ambient monitors are primarily located in or near urban areas, as well as protected areas such as national parks or wilderness areas. If monitors within a state include locations that fail to meet (i.e., “attain”) the NAAQS (i.e., “nonattainment areas”), or state emissions cause or contribute to downwind nonattainment through NOx transport, states are obligated to implement emission reductions through an EPA approved State Implementation Plan (SIP). States with ozone and $PM_{2.5}$ NAAQS nonattainment areas are typically required to implement NOx reductions from *existing* emission sources, such as implementation of NOx “reasonably available control technology” (RACT) for existing equipment.

The two most recent ozone NAAQS and $PM_{2.5}$ NAAQS reviews have resulted in EPA taking the following actions:

- In March 2008, the ozone NAAQS was revised from 0.08 parts per million (ppm), which equates to 84 parts per billion (ppb), to 75 ppb, based on an 8-hour averaging time.
- Following another proposal in 2010, delays from litigation, and deferral on the decision, in October 2015 the ozone NAAQS was revised from 75 ppb to 70 ppb (8-hour averaging time).
- In 2006, the *24-hour* $PM_{2.5}$ NAAQS was decreased to 35 micrograms per cubic meter ($\mu g/m^3$).
- In 2013, the *annual* $PM_{2.5}$ NAAQS decreased to 12 $\mu g/m^3$.

In response to the 2015 revised ozone NAAQS, as well as recent revisions to the $PM_{2.5}$ NAAQS, there will be pressure to reduce NOx emissions from existing equipment. However, with the recent change in the Administration, EPA is reviewing the 2015 ozone NAAQS. Several lawsuits have been filed challenging the 2015 ozone NAAQS and that litigation has been held in abeyance while EPA reviews the 2015 rule to determine whether the 70 ppb standard should be maintained, modified, or reconsidered. Meanwhile, the deadline for EPA to complete designations was

October 1, 2017. In early November,[1] EPA released designations of "attainment / unclassifiable" for most areas of the U.S. including Indian country, addressing about 85 percent of U.S. counties. Nonattainment designation is more likely for the remaining counties, and the Clean Air Act includes provisions to delay designations by one year. EPA has not extended the time allowed under the Clean Air Act to complete the remaining designations, but has indicated its intent to address the remaining areas in a separate future action.[2] Although there is some uncertainty regarding the 2015 ozone NAAQS, this study was conducted considering scenarios with geographical coverage for a 70 ppb standard.

Whenever EPA revises a NAAQS, it must undertake a five to ten year process during which nonattainment areas are determined, states develop SIPs for EPA review and approval, and states develop and implement regulations that require emissions reductions. This process can include federal actions to develop *regional* rules that require reductions from multiple states to address emissions transport. Appendix 4 provides a tabular summary of the federal NAAQS, as well as related implementation timelines and review schedules from a recent EPA presentation. For completeness and to show how averaging times and statistical forms of NAAQS differ, pollutants other than ozone and $PM_{2.5}$ are included.

Earlier ozone NAAQS (e.g., the 2008 ozone NAAQS revision) have still not yet been completely implemented. For example, litigation has slowed EPA regional actions for electric utilities (i.e., the federal Cross State Air Pollution Rule or "CSPAR"). Furthermore, the ozone NAAQS and $PM_{2.5}$ NAAQS have both been lowered over the last two decades, meaning that emission reductions have already been implemented for many sources, especially larger sources such as electric utilities and those sources in urban locations which are more likely to be designated as nonattainment areas. Thus, emissions reductions that will need to be taken to achieve attainment with the 2015 ozone NAAQS are more likely to impact broader geographical areas (e.g., more rural areas) and combustion sources unaffected by previous actions. EPA background material associated with recent ozone NAAQS reviews identified existing stationary reciprocating engines and combustion turbines as primary contributors to the current NOx emission inventory.[3] Similarly, the Ozone Transport Commission (OTC), a coalition of northeast states, recently identified NOx emissions from "pipeline transportation of natural gas" as the largest stationary source emitter other than electric utilities in the eastern U.S. states covered by the CSAPR.[4] OTC has released a draft "model rule" for control of existing reciprocating engines and turbines, and recommends reductions in the OTC as well as eastern states that contribute to ozone nonattainment in the northeast from NOx transport. Appendix 2 presents counts of potentially impacted units for a scenario that requires reductions from reciprocating engines and turbines in CSAPR states.

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[1] On November 6, 2017, EPA released a pre-publication Federal Register Notice of the 2015 ozone NAAQS designations, a Fact Sheet, and related background information. *See* https://www.epa.gov/ozone-designations/designations-2015-ozone-standards.

[2] Several environmental groups filed a complaint for declaratory and injunctive relief on December 4, 2017 in the United States District Court for the Northern District of California, requesting that the court order EPA to promulgate designations for the remaining areas of the country. *Am. Lung Ass'n v. Pruitt*, No. 3:17-cv-06900 (filed Dec. 4, 2017, N.D. Ca.).

[3] EPA-452/P-14-006, "Regulatory Impact Analysis of the Proposed Revisions to the National Ambient Air Quality Standards for Ground-Level Ozone," (Nov. 2014).

[4] Ozone Transport Commission/MANE-VU Committees' Meeting, Stationary and Area Source Committee / Control Measures Work Group Presentation, Washington DC (Sept. 7, 2017).

Background documents included in the administrative record[5,6] for recent EPA regulations also include examples of "scenario analysis" of NOx reductions needed to attain the NAAQS based on current NOx emission inventories. These documents include NOx inventories for different categories of sources, such as electric generating units (EGUs), non-EGU stationary sources, area (i.e., disperse) sources, and mobile sources. The category of non-EGU stationary sources includes natural gas-fired reciprocating engines and combustion turbines, and the EPA documents indicate:

- Reciprocating engines and turbines are key NOx emission sources that comprise a large percentage of the available of NOx emissions inventory in the United States, especially the eastern U.S., and include many units without NOx controls;
- Reciprocating engines and turbines are NOx emission sources with technologically available controls such as low emissions combustion (LEC) for lean burn reciprocating engines, non-selective catalytic reduction (NSCR) for rich burn engines, and lean premixed combustion burners for combustion turbines; and,
- The available NOx controls are cost effective for these sources.

Thus, assuming that EPA retains the 70 ppb ozone NAAQS, compressor drivers at transmission compressor stations and storage facilities are at risk of requiring retrofit NOx emission controls. To a lesser extent, the $PM_{2.5}$ NAAQS may also result in emission reduction requirements or serve as further motivation to achieve reductions for the ozone NAAQS. For example:

- Co-benefits for the $PM_{2.5}$ NAAQS may further support state and EPA decisions to reduce NOx for ozone nonattainment.
- Since ozone nonattainment is primarily a warm weather phenomenon (due to atmospheric chemistry), some NOx RACT regulations have limited applicability to the ozone season (typically late spring through early fall). Atmospheric formation of $PM_{2.5}$ from nitrates is not limited to warmer months, so $PM_{2.5}$ NAAQS related reductions support annual applicability of NOx RACT.

There are over 4,000 reciprocating engines and over 1,000 turbines in the natural gas transmission and storage industry. Most are "legacy" units (e.g., installed prior to 1970) and the majority of those units have not implemented NOx controls or possibly added minimal controls (e.g., a reduction of 50% or less). There are NOx control options available for most legacy engines that will achieve a reduction of 80% or higher, and the emission controls are technically and economically feasible in most cases. This study assessed the status of existing units based on an available engine-turbine database (ETDB). The ETDB was originally developed by the Gas Research Institute (GRI) and Pipeline Research Council International (PRCI), but is currently administered by INGAA and was updated by INGAA members in 2015 – 2016. The ETDB was used to identify potentially affected units for the scenarios that identify locations (i.e., counties or states) with potential regulations to reduce NOx emissions. Sections 3.2 and 3.4 of this report present a summary of unit counts affected under each scenario for reciprocating

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[5] Regulatory Impact Analysis of the Proposed Revisions to the National Ambient Air Quality Standards for Ground-Level Ozone. EPA-452/P-14-006 (Nov. 2014).

[6] Technical Support Document for the Cross-State Air Pollution Rule for the 2008 Ozone NAAQS: Assessment of Non-EGU NOx Emission Controls, Cost of Controls, and Time for Compliance. Docket ID No. EPA-HQ-OAR-2015-0500. U.S. EPA Office of Air and Radiation (Nov. 2015).

engines and turbines, respectively. However, state- or county-level, or site-specific related detail that could identify a particular unit or facility is not divulged. This report is also sensitive to concerns about divulging vendor information on control costs. Vendors that provided cost estimates for emission controls were concerned about the public availability or potential misuse of "detailed" information, because site-specific factors contribute significantly to retrofit control costs, and analysis of site-specific costs is beyond the scope of this study.

In addition to this introductory section, this report provides a discussion of the regulatory scenarios in Section 2. The analysis and results of unit counts for each scenario are detailed in Section 3, along with a discussion of technologies and unit-level cost considerations. Section 4 discusses the rolled-up cost estimates for the three scenarios. Section 5 includes discussion and uncertainties. Appendices contain a tabular summary of the three regulatory scenarios reviewed, a list by state of counties included in Scenario C, and EPA tabular summaries of the federal NAAQS and related implementation timelines and review schedules.

2. REGULATORY SCENARIO DISCUSSION

Multiple regulatory scenarios were discussed with the project team. The candidate scenarios were based on experience with state and federal actions since the 1990s regarding NOx RACT or similar NOx control rules that affect existing compressors drivers. An initial overview of implications (e.g., approximate number of affected units) was formulated by data collection and analysis from EPA ozone monitors, background documents from EPA actions such as Regional NOx Rule or the 2015 ozone NAAQS. A brief presentation of these scenarios follows in Sections 2.1 and 2.2. The scenarios selected by the steering committee are described in Section 2.3.

2.1. Compilation of Ozone Monitoring Data

Monitor data recorded for each state were gathered from the EPA Monitor Values Report[7] where criteria pollutant summary data are displayed for individual monitoring sites**.** These monitoring data were compiled for each state from 2012 – 2016. Note that the 2016 data was incomplete at the time of analysis and will be officially released sometime in 2017. Examples of a portion of the report output are shown in Table 3 for the state of New Jersey during 2015. In this example, the details of the monitor location are listed as well as the fourth maximum 8-hour average for the specific monitor in 2015 (i.e., the "4th highest high" is the statistic used for the ozone NAAQS). The monitors with average readings greater than 0.069 ppm are highlighted in pink. For each series of three years, 2012-2014, 2013-2015, and 2014-2016, the three year 8-hour averages were calculated. States and counties where either the 2013-2015 or the 2014-2016 three year 8-hour average was greater than 0.69 ppm were noted and utilized as one of the "affected counties" within the regulatory scenarios. All effected counties, and adjacent counties are represented in the map in Figure 1 and listed in Appendix 3.

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[7] https://www.epa.gov/outdoor-air-quality-data/monitor-values-report.

Table 3. Fourth Maximum Monitor Data for New Jersey for 2015

County	City	CBSA	Address	fourth_max_8hr
Atlantic	Galloway (Township of)	Atlantic City-Hammonton, NJ	Edwin B. Forsythe National Wildlife Refu	0.068
Bergen	Leonia	New York-Newark-Jersey City, N	Overpeck Park, 40 Fort Lee Road	0.076
Camden	Camden	Philadelphia-Camden-Wilmingt	266 Spruce Street	0.079
Camden	Winslow (Township of)	Philadelphia-Camden-Wilmingt	Ancora State Hospital, 202 Spring Garde	0.072
Cumberland	Vineland	Vineland-Bridgeton, NJ	Lincoln Avenue And Route 55, Northeast	0.068
Essex	Newark	New York-Newark-Jersey City, N	360 Clinton Avenue	0.072
Gloucester	East Greenwich (Township	Philadelphia-Camden-Wilmingt	Clarksboro Shady Rest Home, Shady Lan	0.076
Hudson	Bayonne	New York-Newark-Jersey City, N	Veterans Park On Newark Bay, 25th Stre	0.077
Hunterdon	Raritan (Township of)	New York-Newark-Jersey City, N	Raritan Township Municipal Utilities Aut	0.073
Mercer	Lawrence (Township of)	Trenton, NJ	Athletic Fields, Route 206 South	0.073
Mercer	Not in a City	Trenton, NJ	Washington Crossing State Park, Titusvil	0.075
Middlesex	East Brunswick	New York-Newark-Jersey City, N	Horticultural Farm #3, Off Ryder'S Lane	0.077
Monmouth	West Long Branch	New York-Newark-Jersey City, N	Edison Science Building, 400 Cedar Aven	0.077
Morris	Chester	New York-Newark-Jersey City, N	Building #1, Department Of Public Works	0.07
Ocean	Jackson (Township of)	New York-Newark-Jersey City, N	Colliers Mills Wildlife Management Area	0.075
Passaic	Wanaque (Wanaque-Midv	New York-Newark-Jersey City, N	Ramapo Mountain State Forest, Access	0.071
Warren	Knowlton (Township of)	Allentown-Bethlehem-Easton, P	Columbia Wildlife Management Area, D	0.066

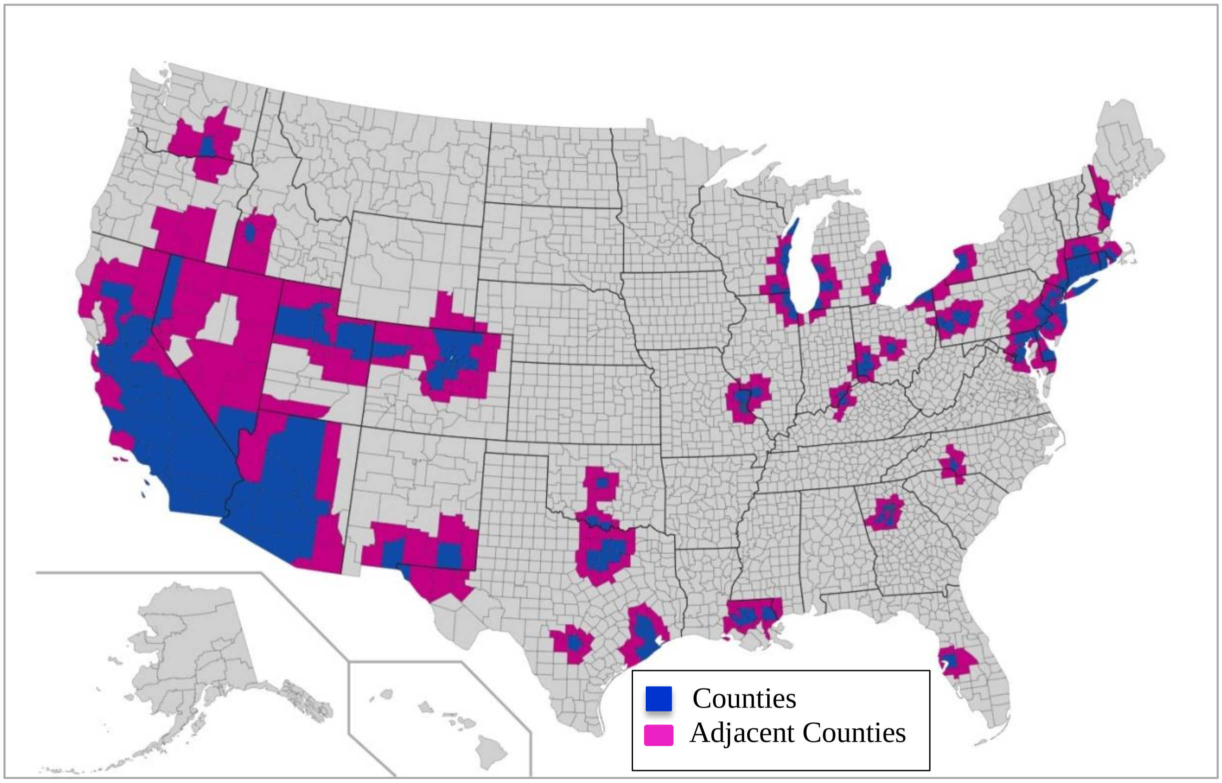


Figure 1. Counties and Counties Adjacent to Counties with Monitor Readings > 69 ppb.

2.2. Scenario Descriptions by Geographic Region

Scenarios were presented to the project team including geographical coverage for regional rules such as the NOx SIP Call (Figure 2) and the CSAPR (Figure 3).

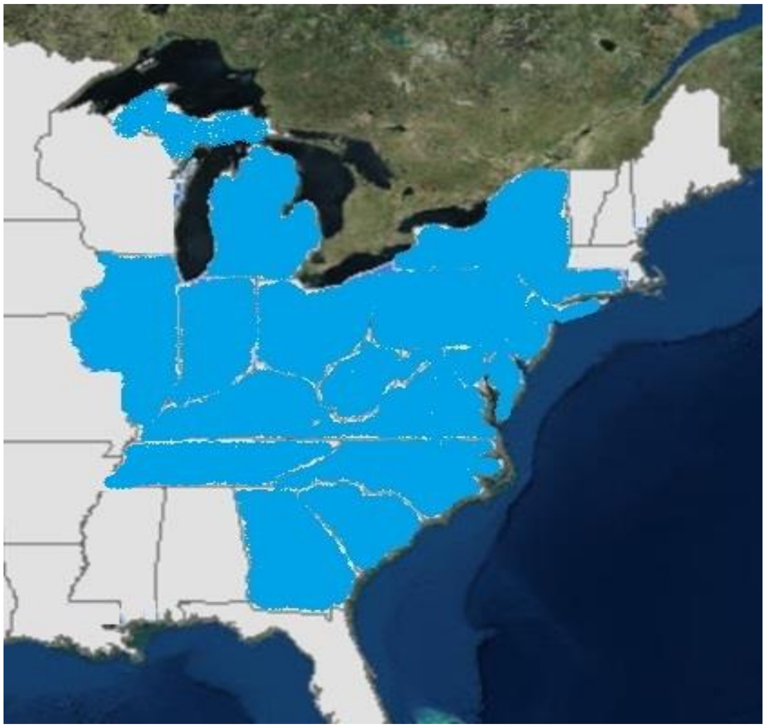


Figure 2. NOx SIP Call Region

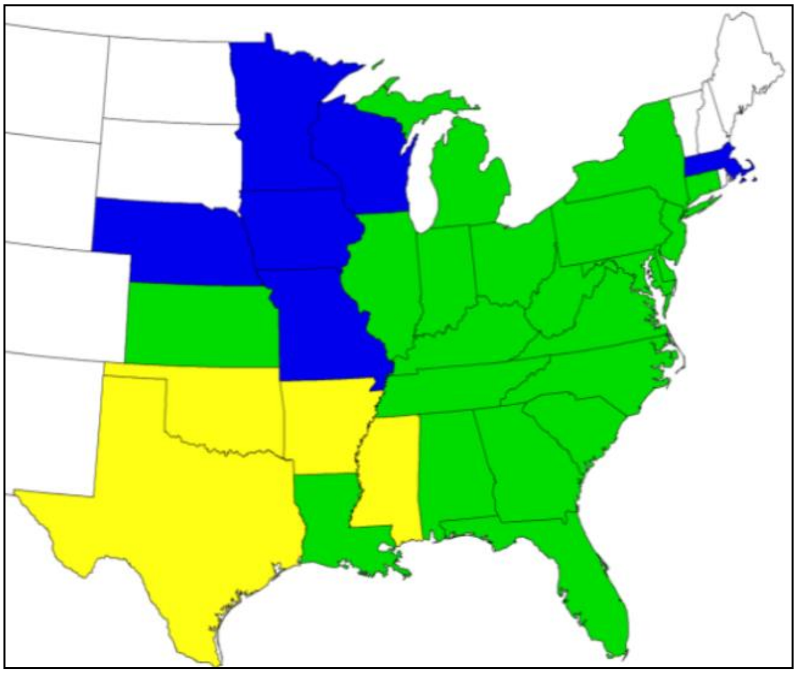


Figure 3. CSAPR States

In Fall 2016, states wrote letters to EPA recommending counties to designate as nonattainment (Figure 4). Finally, several eastern states have recommended broad non-attainment due to NOx transport that affects eastern U.S. air quality. Potential scenarios were discussed, including Delaware's recommendation for a large eastern U.S. nonattainment area shown in Figure 5, and Connecticut's request (Figure 6) to include upwind states that affect its air quality.

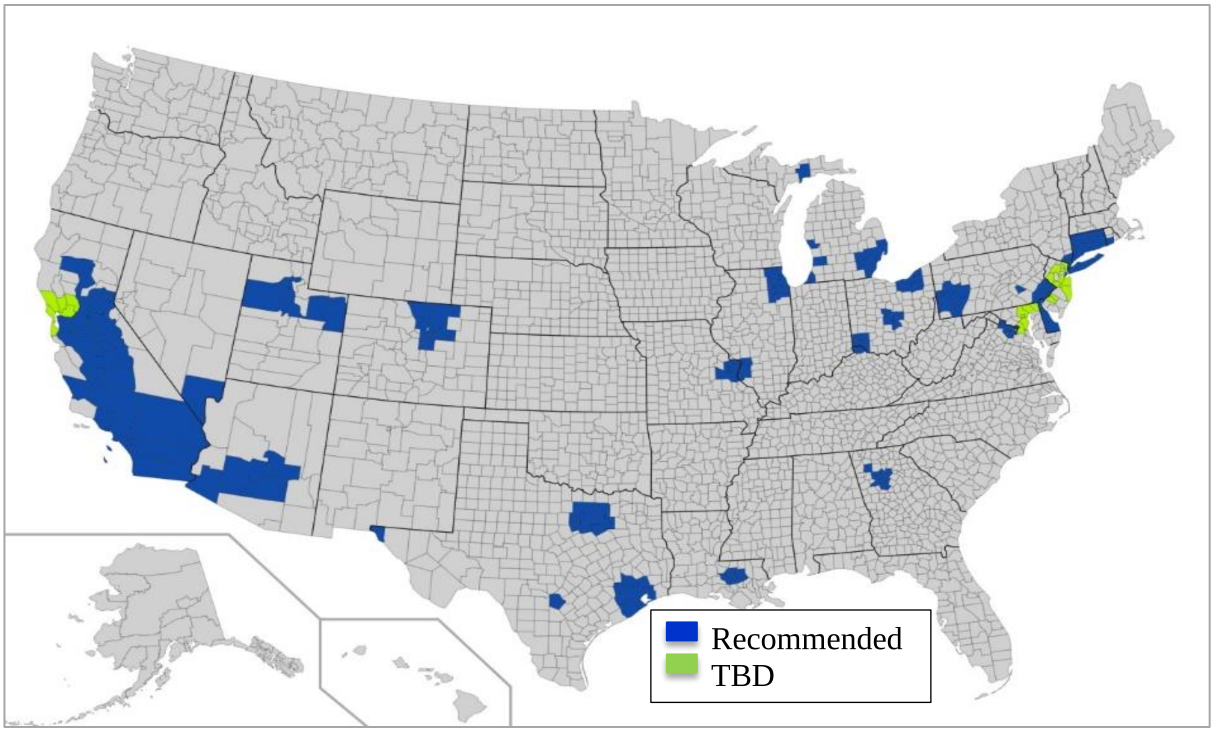


Figure 4. Fall 2016 State Letters to the EPA – Recommended Nonattainment Areas

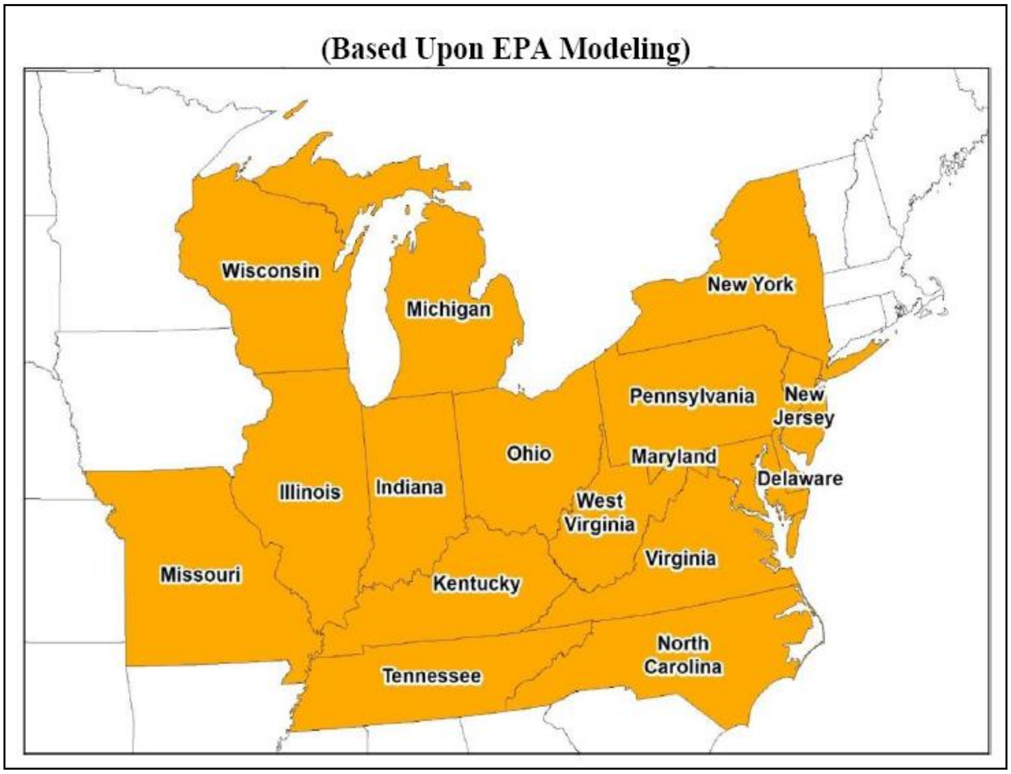
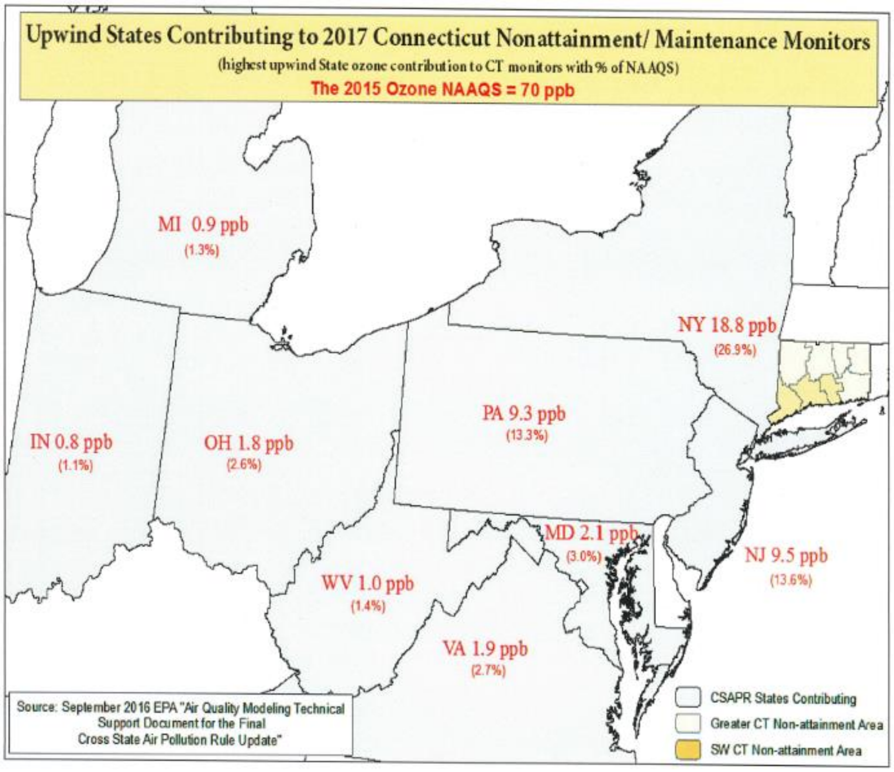


Figure 5. Delaware's Recommended Eastern U.S. Non-Attainment Area


Upwind States Contributing to 2017 Connecticut Nonattainment/ Maintenance Monitors
(highest upwind State ozone contribution to CT monitors with % of NAAQS)
The 2015 Ozone NAAQS = 70 ppb

Source: September 2016 EPA "Air Quality Modeling Technical Support Document for the Final Cross State Air Pollution Rule Update"

Figure 6. Connecticut's Request for Upwind State Controls showing Each State's Contribution to Connecticut Ozone

2.3. Results of Project Team Decision on Regulatory Scenarios

In December 2016, the project team selected the following three scenarios to provide an upper bound, middle ground, and lower bound for the analysis. The upper bound, a nationwide requirement, represents the greatest potential financial impact. It is very unlikely but provides a high-end cost estimate (in current $) while also indicating long-term implications that consider legacy units without NOx control. The middle-ground analysis uses the lower bound scenario as the starting point and adds a number of states as "statewide RACT" candidates. The lower bound contains only counties and adjacent counties where the three year average of EPA monitored values are greater than 0.069 ppm. Further descriptions of the three scenarios follow below and are summarized in Appendix 1:

(A) Upper bound (Scenario A): All uncontrolled engines and turbines in the database are included in the upper bound analysis. This nationwide scenario includes a single controlled emission level and horsepower (HP) threshold for rich burn (NOx = 2 g/bhp-hr; 1,000 HP) and lean burn engines (3 g/bhp-hr; 1,000 HP) and turbines (42 ppm; 5,000 HP). This report identifies the number of additional units that would be added at lower HP thresholds, but does not assess the incremental costs for retrofit control.

(B) Middle ground (Scenario B): Beginning with the map from the lower bound analysis (Scenario C below), and adding "state-wide RACT controls" for the following states: NY, PA, IL, AZ, MS, LA, AL, GA, NC, VA, TN, WV, OH. This scenario contains counts for multiple HP ranges for engines of 500-900 HP, greater than 1,000 HP, and greater than 2,400

HP. The initial goal was to assess this scenario for two emission thresholds, but cost information from service providers indicated great uncertainty in providing generic estimates because of complications associated with site-specific costs. Therefore, for legacy *uncontrolled* engines, a differentiation of cost estimates is not provided for a 3 g/bhp-hr target versus a lower target, because the incremental cost is within the uncertainty of a multi-billion dollar cost "rolled up" estimate. In some instances (e.g., for some Caterpillar lean burn engines), current emissions meet 3 g/bhp-hr, and incremental costs can be included for retrofit to achieve a lower NOx target. This is discussed further below.

Assessing facility-level or unit-level costs is beyond the scope of this study. Cost calculations were "rolled up" for a population of engines, but incremental cost associated with an incremental reduction (e.g., for a NOx end point of 3 versus 1 g/bhp-hr for lean burn engines) is within the uncertainty associated with variations in site-specific installation / upgrade costs. Thus, the rolled up costs provided in this report are consistent with an end point that achieves 80-90% NOx reduction for reciprocating engines (i.e., 1 to 3 g/bhp-hr for lean burn engines) and 42 to 25 ppm for turbines. Additional site- and/or company-specific information, which generally requires a site visit to assess site attributes, peripherals, and operational controls, is necessary to provide a more refined cost estimate.

(C) Lower bound (Scenario C): The map in Figure 1 is based on counties with ozone monitoring data >69 ppb plus the adjacent counties that may also be affected as states pursue reductions outside of urban core areas. This scenario contains counts and costs for multiple HP thresholds for engines of 500-900 HP, greater than 1000 HP, and greater than 2400 HP. As noted for Scenario B, complications associated with site-specific cost variations resulted in a single cost estimate rather than attempting to discern incremental costs for two different NOx end points.

3. SCENARIO ANALYSIS – TECHNOLOGY REVIEW AND UNIT COUNTS

3.1. Overview of INGAA Reciprocating Engine and Turbine Data Base

The review of the Engine Turbine Data Base (ETDB) included additions and modifications to address data gaps, including corrections to issues such as mismatch in the specificity of the engine makes and models. To identify the "affected units" for each scenario, the database of approximately 4350 engines and approximately 1120 turbines was sorted by horsepower, NOx emissions control, and geography. This was overlaid with the scenarios described in Section 2.3 to define the count and distribution of uncontrolled sources for each scenario, as shown above in Table 1.

3.2. Engines – General Discussion of Control Technology and Unit-Level Costs

3.2.1. Overview of LEC for Lean Burn Engines

"Low emission combustion" (LEC) technology for lean burn engine NOx control includes a combination of turbocharging (to increase the air fuel ratio or "AFR") / intercooling (IC), enhanced mixing (e.g., high pressure fuel injection), and increased ignition energy. NOx from lean burn engine combustion is reduced by increasing the AFR because the leaner operation results in lower peak temperatures and decreased NOx emissions; however, as the AFR is increased, the charge becomes leaner, which effects "light-off" and combustion stability. Thus, higher energy ignition or pre-combustion chambers (PCC) are used. A PCC is a small chamber upstream of the engine cylinder used to ignite a small amount of fuel in a less lean environment. The flame from this chamber ignites the leaner mixture in the cylinder.

In recent years, retrofit technology to reduce NOx from lean burn engines has included enhanced mixing approaches – primarily through the use of higher pressure fuel injectors. Physical contours, such as the piston crown shape can also impact mixing. For pipeline compressor engines, high and intermediate fuel injection that takes advantage of pipeline gas pressures readily available at the facilities has proven to be an effective method to reduce emissions and provide improved combustion stability. By using injection pressures up to 400 or 500 psia, the homogeneity of the cylinder charge is enhanced. Experience has shown that this offers positive emission and operational benefits. For new engines, LEC equipped lean burn engines typically achieve NOx of approximately 0.5 to 0.7 g/bhp-hr. For existing units with LEC retrofit, this level of performance is not typically achievable – and NOx permit limits for LEC retrofit typically range from 1.5 to 3 g/bhp-hr. For lean burn engines, achieving lower levels for either new or retrofit LEC, which is commensurate with aggressive regulatory requirements in certain locations, currently requires the application of post-combustion controls (i.e., selective catalytic reduction).

3.2.2. Overview of NSCR for Rich Burn Engines

Rich burn engines, due to the oxygen deficiency in the combustion by-products, can be controlled using Non-Selective Catalytic Reduction (NSCR). NSCR is analogous to “Three-Way Catalysts” used for gasoline powered vehicles. NSCR catalysts reduce carbon monoxide (CO) and hydrocarbon (HC) exhaust emissions via oxidation reactions, while also converting nitrogen oxides (NOx) via reduction reactions (i.e., oxygen in NOx molecules serve as an oxidant and NOx is reduced to N_2). Proper NSCR function that controls CO, HC, and NOx emissions requires the AFR to be controlled over a narrow range, and the engine requires an exhaust sensor (typically for oxygen), a catalyst, and an AFR controller. The AFR range for a rich burn engine with NSCR versus a comparable 4-stroke lean burn engine is shown in Figure 7.

For rich burn retrofit design and efficient function of the 3-way catalyst, the engine-out emissions are typically constrained by a NOx target, which is more highly regulated than CO or hydrocarbon emissions. The performance of retrofit aftermarket catalysts is dependent on case-specific inputs. Therefore, to improve the target emissions level, from 2 g/bhp-hr to 0.5 g/bhp-hr, for example, is not simply a matter of using larger or more expensive catalyst, or a higher performance AFR controller. Engine (make and model), tradeoffs between NOx emissions and CO/hydrocarbon emissions, and other site-specific factors need to be considered in NSCR system design.

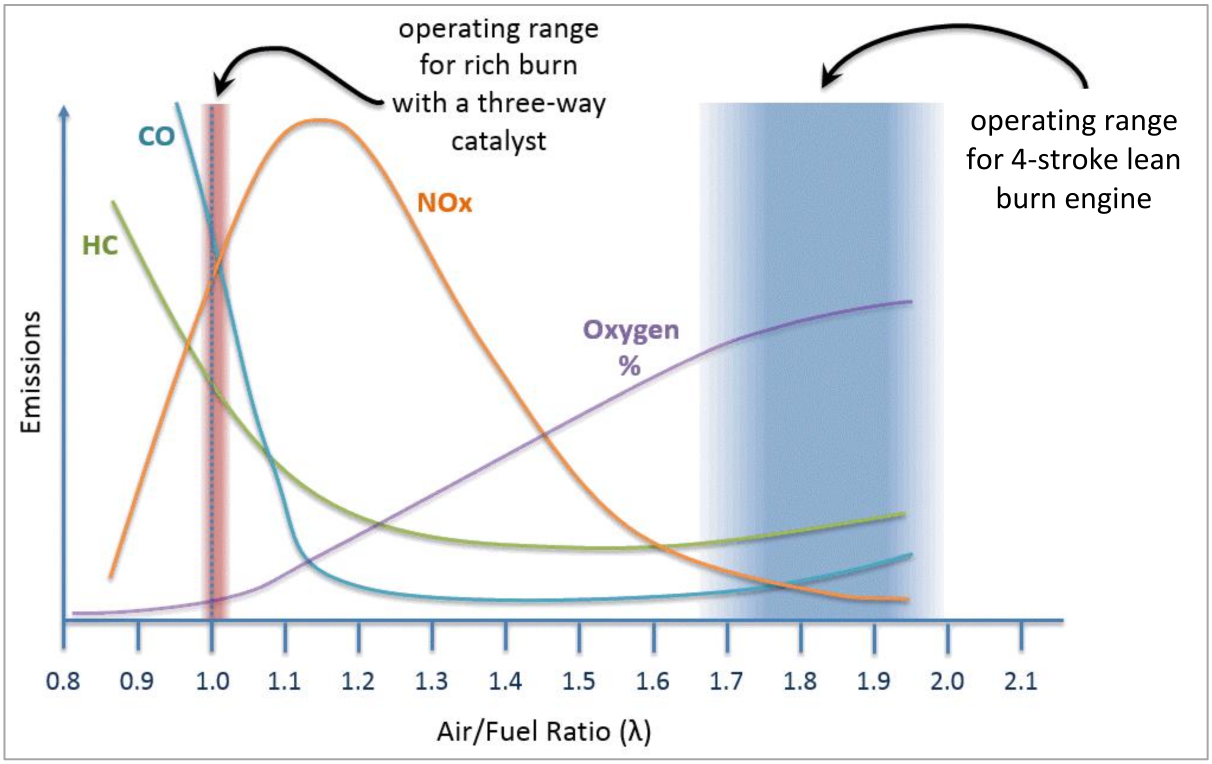


Figure 7. Visual representation of approximate AFR range for 4-stroke rich- or lean-burn engines.[8]

3.2.3. General Comments on Specific Engine Counts, Controls, and Costs

Section 4 discusses the methodology and rolled up costs for the three scenarios, but this section includes initial discussion of cost considerations for different engine makes and models. Several companies and manufacturers that are the principle providers of retrofit LEC control for lean burn engines or NSCR for rich burn engines provided the information used in this study. LEC costs dominate the total cost risk associated with potential NOx controls. In general, it is difficult to provide precise cost estimates for LEC retrofit because site-specific factors contribute significantly to unit-specific costs. However, technology providers provided component level costs or cost ranges , the engines from the ETDB were sorted based on configuration (e.g., whether or not turbocharged), and then costs were assigned based on that categorization.

3.2.3.1. Caterpillar, Lean Burn – Within the boundaries of this study, all Caterpillar engine models in the families GCM34, G3600A4, G3600 and G3500B are rated at or below 1 g/bhp-hr and therefore no additional control is required. For this report, incremental control is considered for some 3500 series engines. For engines greater than or equal to 1000 HP in Scenario A, there are 124 G3500 model engines, the vast majority being G3516 TALE (Turbocharged, Aftercooled, Low Emission). Engine emissions are less than 3 g/bhp-hr (assumption for Scenario A). This quantity decreases to 65 engines for Scenario B, and 44 engines for Scenario C. The G3516 TALE estimated upgrade cost is included in Scenario B and C only, where emission targets lower than 3 as the current emissions level of the engine is less than 3 g/bhp-hr. A generic cost for a retrofit is on the order of $100,000 with additional costs for installation and site or source specific modifications.

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[8] Caterpillar

3.2.3.2. Clark, Lean Burn – The quantity of 2-stroke Clark engines with 1000 HP or larger in Scenario A is 638. Based on different engine attributes (e.g., scavenging, air handling, ignition, etc.) associated with different model numbers, this quantity can be subdivided into 20 or more separate categories for assessing retrofit/upgrades and costing. As an example, and to demonstrate model-specific differences and categorization for cost roll-up, retrofit upgrades are systematically compared and tabulated in Section 3.3 for two engine models, a Clark BA 8 cylinder, 1600 HP unit and a Clark TLA 8 cylinder, 2700 HP unit. These units were selected to demonstrate the cost range for two popular models in the ETDB that also bound engine types that are older and more costly to retrofit versus model with lower costs (e.g., where turbocharger upgrades are not required or minimal). The number of Clark engines ≥1000 HP or larger in Scenario B is reduced to 486 and in Scenario C to 113. The discussion provided in Section 3.3 includes more details, but the cost range varies widely for 2-stroke integral engines – e.g., a range on the order of $500,000 to $4 million.

3.2.3.3. Cooper, Lean Burn – The number of 2-stroke Cooper engines ≥ 1000 HP in Scenario A is 933. This quantity can be subdivided into 20 or more separate categories for retrofits/upgrades and costing. However, in general, the largest differentiation in the cost of a retrofit is the presence or absence of a turbocharger. The number of Cooper engines ≥1000 HP in Scenario B is reduced to 615 and in Scenario C to 113. The cost range is similar to the range noted above for Clark engines.

3.2.3.4. Ingersoll Rand, Lean or Rich Burn – Of the 283 Ingersoll Rand engines ≥1000 HP in Scenario A, 163 are lean burn and 120 are rich burn. The lean burn engines are turbocharged, and depending on the upgrades required, a retrofit cost ranges from $1 million to $2 million. The number of Ingersoll Rand engines ≥1000 HP in Scenario B is reduced to 119 lean burn and 39 rich burn and in Scenario C to 31 lean burn. Price quotes for rich burn engine NSCR can be $20,000 or lower, but these costs address primary equipment and not a turnkey installation. Considering auxiliary and installation costs, an estimate of $300,000 per engine was utilized for NSCR.

Table 4. Engine Quantity ≥ 1000 HP by Manufacturer for Scenario A, B, and C

Manufacturer	**Combustion Cycle / AFR**	**Quantity**		
		Scenario A:	**Scenario B:**	**Scenario C:**
Caterpillar 3500	4SLB	124	65	44
Clark	2SLB	638	486	113
Cooper	2SLB	933	615	113
Cummins	4SRB	5	1	0
Delaval	4SLB	1	1	1
F-M	2SLB	6	3	1
IR	Mixed	283	158	31
Superior	Mixed	66	25	13
Waukesha	Mixed	7	2	0
Worthington	2SLB	200	99	34

Table 5. Engine Quantity from 500 to 900 HP by Manufacturer for Scenario A, B, and C[1]

Manufacturer	Combustion Cycle / AFR	Quantity		
		Scenario A:	**Scenario B:**	**Scenario C:**
Ajax	2SLB	14	5	1
Caterpillar	Mixed	59	23	13
Clark	2SLB	24	12	4
Cooper	2SLB	82	54	6
Cummins	4SRB	14	11	7
IR	4SRB	37	17	6
LeRoi	4SRB	13	7	6
Superior	Mixed	43	12	6
Waukesha	4SRB	65	22	8
Worthington	2SLB	18	12	10
Unknown		1	1	0

[1] Many of these are emergency engines that may be excluded from NOx regulations. The engines are primarily 4-stroke rich burn units that would use NSCR for control. NSCR cost implications are minor compared to lean combustion controls, so the units and costs were retained in the analysis.

3.3. Engines – Cost Comparison Example for Clark BA and Clark TLA Engines

Rolled up cost estimates are provided in Section 4. The majority of costs for retrofit NOx control is associated with LEC retrofit to 2-stroke or 4-stroke legacy integral engines. This section provides a discussion of component-level cost estimates for LEC for two Clark engine models prevalent in the ETDB. Costs for LEC were approximated for the following two examples: a Clark BA 8 cylinder, 1600 HP unit and a Clark TLA 8 cylinder, 2700 HP unit. Costs are summarized in Table 6, which indicated cost ranges for component level requirements by using the following labels:

$ – Less than $100,000
$$ – $100, 000 to $500,000
$$$ – $500,000 to $1,000,000
$$$$ – More than $1,000,000

Total costs (range) and cost per horsepower are also shown in the table for these two engine types. The other prevalent manufacturer of integral engines is Cooper Bessemer, and similar technology differences and retrofit cost implications apply to that fleet of engines.

Table 6. Cost Example for Clark BA and Clark TLA

	Component / Modification	**Clark BA**	**Clark TLA**
General Information	Number of Cylinders	5, 6, 8, 10	5, 6, 8, 10
	Horsepower/Cylinder	200	340
	Base Model # of Cylinders	8	8
	Base Model Rated Power	1600	2720
Scavenging System	Stock	Piston	Single Turbo
	Add Turbocharger	$$$	
	Upgrade Turbo (Frame OK)		$$
	Upgrade Turbo and Frame		$$$
Intercooler System	Stock	n/a	IC
	Add Intercooler	$$	
	Upgrade Intercooler		Per Cylinder $$
Fuel System	Stock	Low Pressure Direct	Low Pressure Direct
	Medium Pressure Fuel Injection and controls	Base + per cylinder $$	
	High Pressure Fuel Injection and controls		Base + per cylinder $$$
	Upgrade Control System	Base + per cylinder $$	Base + per cylinder $
Engine Components	New Heads, Pistons & Liners	Base + per cylinder $$$	
Additional System Upgrades	On Engine (Modify External Air Intake, Dry Exhaust)	$$	
	Off Engine (Modify Filter and Silencer)	$$$	
	Auxiliary Cooling	$$	
Total Cost		$2 - 4 million	$800,000 - $1.6 million
Per HP Cost		$1250-$2500	$300 – 600

3.4. Turbines – Discussion of Control Technology, Counts, and Unit-Level Costs

The general principle for NOx control technology for turbines is similar to LEC for lean burn engines – reduce NOx by manipulating air and fuel mixing to reduce peak combustion temperatures. The combustion process for older (uncontrolled) turbines use “diffusion flame” combustors which result in higher temperatures, while low NOx technology is referred to as “lean premixed combustion” (LPM) where air/fuel mixing and combustion is staged in multiple zones.

Retrofit LEC for lean burn engines is provided by after-market service providers as well as manufacturers. For turbines, the manufacturers provide LPM technology, and retrofit control is not available for all models. Thus, there is a potential risk for introduction of unproven controls or stranded horsepower when retrofit LPM combustion is not available.

Ideally, this would be addressed through proper consideration of "technological" or "economic" feasibility which would preclude controls according to standard NOx RACT principles. For example, NOx rules often include "alternative RACT" as a regulatory option, which allows the operator to assess technical feasibility and cost effectiveness of control options. If future rules appropriately consider NOx RACT criteria for technological and economic feasibility, this may not be an issue. However, where LPM combustion control is not available, agencies may presume that other NOx control technology can be applied, such as water/steam injection or SCR. This results in more expensive development, engineering, and installation costs. Or, if controls are not available or are cost prohibitive, existing units could be at risk of becoming stranded capacity (i.e., replacement is required). This report does not assess control costs associated with technology other than LPM retrofit and assumes alternative RACT options would preclude the need for turbine replacement.

As with reciprocating engine retrofit control, the leading turbine manufacturers noted that where retrofit control is available, site attributes can significantly impact costs. The additional costs could be associated with facility, package, or control system modifications necessary to support retrofit, and could vary from several hundred thousand to several million dollars. The cost estimates in this report are best estimates based on a typical site.

Table 6 lists the turbine counts by manufacturer for the three scenarios. The highest counts are for General Electric and Solar Turbines, which collectively comprise about 80% of all counts across all scenarios. Due to this prevalence and less retrofit control availability for other units, the cost estimate focused on these two manufacturers.

Table 7. Quantity of Turbines ≥ 5000 HP

Manufacturer	Scenario A:	Scenario B:	Scenario C:
Allison	**10**	**7**	**3**
Dresser Clark	**11**	**11**	**5**
GE	**168**	**134**	**50**
Pratt & Whitney	**14**	**8**	**1**
Rolls Royce	**42**	**8**	**3**
Solar	**121**	**95**	**32**
Westinghouse	**7**	**7**	**6**
Unknown	**2**	**1**	**1**
Total	**375**	**271**	**101**

3.4.1. Turbines – Retrofit Control Emissions Levels

Emissions retrofit options range from 42 to 15 ppm NOx @ 15% oxygen depending upon the make/model and rating of the turbine. For example, the majority of the 32 Solar Turbines in Scenario C are either Centaur 50s that can meet 38 or 25 ppm NOx or Taurus 70s that can meet 28, 25 or 15 ppm NOx (depending on rating). The majority of the 50 GE turbines are either M3712

RA units that can meet 42 ppm NOx or MS3002 units that can meet 35 or 42 ppm NOx. In some instances, the manufacturer indicated retrofit packages are readily available, while other instances may require additional development (and thus higher costs).

3.4.2. Turbines – Unit Level Retrofit Control Costs

The total costs associated with the retrofit options, whether available or requiring development, will require incurring additional costs for any facility, package, and control system modifications necessary to support the retrofit. An example of costs for different NOx emission targets is shown in Table 8.

The cost estimate for a gas turbine retrofit will range from approximately $250,000 to $3.4 million depending on the model/rating, retrofit package status, and emissions target. Additional costs may be incurred for any necessary package and control system modifications. In some cases, those costs could exceed the "package" costs in Table 8.

Table 8. Turbine Costs

Make	Model	To 42 ppm	To 35 ppm	To 25 ppm
GE Heavy Duty MS3002 Family	MS3002F	$500k – $1M	$$$$	n/a
GE Heavy Duty MS5000 Family	MS5001 L-R	$500k – $1M	n/a	>$1M
Solar	Various	n/a	$250k – $500k	$250k – $500k

4. COST ESTIMATE SUMMARY BY SCENARIO

Rolled up costs for the upper bound and lower bound cost estimates are shown in Table 2. The costs estimates were developed as follows:

- For each scenario, affected equipment from the ETDB was sorted into multiple categories, based on model numbers that indicate the status of component-level technology that significantly impacts retrofit costs (e.g., turbocharged, etc.).
- NOx control costs were acquired from technology providers and manufacturers to develop costs estimates for the equipment / manufacturer categories. This included costs for LEC (lean burn engines), NSCR (rich burn engines) and LPM combustion (turbines). For the upper bound and lower bound scenarios, apply the appropriate technology cost, by category, to the unit counts for that scenario.
- Sum total costs for primary categories (e.g., by engine size range) and total costs for all equipment for the scenario.

The rolled up cost estimates include:

- An upper bound estimate of affected units nationwide indicates up to 2,633 engines and 375 turbines could require retrofit control, with a cost estimate of $3.5 billion.

- A lower bound estimate, based on units in counties with ambient ozone levels similar to the 2015 ozone NAAQS (i.e., 70 ppbv based on an 8-hour average) and adjacent counties indicates 417 engines and 101 turbines may require retrofit control, with a cost estimate of $573 million.
- The mid-range scenario is based on the lower bound scenario with *statewide* NOx RACT included for 13 states. This scenario indicates 1,631 affected engines and 271 affected turbines. A detailed cost estimate was not conducted for this scenario, but the total costs would be approximately $2 billion.

An overriding source of uncertainty in the cost estimates is that site-specific costs associated with peripheral systems, site modifications, and installation can significantly affect control costs. These costs vary for each site.

Scenarios A and C are labelled upper or lower bound estimates, but costs could be higher or lower. For example, the lower bound scenario assumes nonattainment based on 3-year averages that could be updated (and lower) depending on EPA’s final designations. Additionally, it is possible that EPA could conclude that the 2015 (70 ppb) ozone NAAQS should not be retained. If that happens, the analysis herein would still be relevant if EPA lowers the ozone NAAQS to 70 ppb during a subsequent review. If individual states choose to take action (e.g., revise existing NOx RACT rules to achieve attainment or provide margin relative to the previous 75 ppb ozone NAAQS), or litigation causes action (e.g., a lawsuit filed by one or more northeast states forces upwind states to reduce emissions to address NOx transport), the analysis could be fine-tuned to assess the affected geographical area from evolving regulatory requirements. Costs could also be higher if affected facilities require significant upgrades (e.g., for cooling, air handling, operational control, other facility modifications) beyond expectations for a typical facility based on retrofit control installations completed to date.

5. DISCUSSION AND UNCERTAINTIES

As discussed above, regulatory scenarios were selected to define reasonable boundaries and assess likely cases based on experience with previous state and federal actions to address ozone and $PM_{2.5}$ NAAQS nonattainment. The affected engine and turbine populations will surely differ from the scenarios analyzed, but the three scenarios analyzed in this study provide a means to assess a range of implications. In any case, assuming the 70 ppb ozone NAAQS is retained and implemented, industrywide implications will likely be more significant than the response to the NOx SIP Call Phase 2 rule, with hundreds of compressor drivers affected and costs exceeding $500 million.

EPA and state analyses continue to identify engines and turbines as a primary contributor to the national NOx inventory, and cost-effective controls are available to reduce NOx from these sources. Many states have already adopted NOx RACT rules for more urban areas, and states in the northeast are challenging upwind states to mitigate NOx transport, so statewide RACT or regional actions will likely be required to address nonattainment with the 70 ppb ozone NAAQS. The number of affected units and costs would likely require controls beyond geographical areas in proximity to nonattainment areas (e.g., statewide control is some cases). This implies a likely outcome would surpass the Scenario C lower bound estimate – with many hundreds to over 1000 affected units and costs exceeding $1 billion.

This analysis includes uncertainties associated with the roll-up of costs from the list of affected units. Retrofit costs can be significantly impacted by site-specific issues. Thus, the cost estimates are reasonable for industrywide cost implications, but site-specific surveys would be needed to more accurately understand unit-level or facility-level costs. In addition, the schedule for implementing controls could impact costs. For example, the specific timing, stringency, and implementation schedule for state NOx regulations in response to the ozone NAAQS cannot be accurately forecast due to the current status of the regulatory process. Unknown factors will arise due to political, economic, and environmental factors at the state, regional, and federal level. If schedules are compressed, or a significant number of state regulations (or a regional rule) result in the need for retrofit of many units within a several year timeframe, there would be resource challenges associated with the availability of control technology service providers. This would likely impact costs.

Finally, there is the potential for environmental or energy co-benefits (or dis-benefits) to affect schedules, regulatory requirements, and costs. For example, some technologies that reduce NOx (e.g., high pressure fuel injection as a component of LEC on lean burn engines) can improve engine efficiency. Thus, greenhouse gas emissions could marginally improve (e.g., decrease CO_2 and exhaust methane per bhp-hr). Such factors have generally been beyond the scope of NOx RACT regulations to date, but could be highlighted as the regulatory focus on environmental end points evolves. This could result in regulations that constrain technology options so that NOx emissions are achieved along with other environmental goals.

6. APPENDICES

Appendix 1. Three Regulatory Scenarios Selected by the Project Team

Scenario	Geographical Area	Emission Level	Size Cut-off
A (upper bound)	Nationwide (45 states in INGAA ETDB with compressor drivers)	*Single Level* Lean burn: 3.0 g/bhp-hr Rich burn: 2.0 g/bhp-hr Turbines 42 ppmv (at 15% O_2)	Single Threshold Recips: 1000 HP Turbines: 5000 HP
B	Scenario C (Counties plus adjacent >69 ppb) plus state-wide RACT for NY, PA, IL, AZ, MS, LA, AL, GA, NC, VA, TN, WV, OH	*Two Levels*[1] Lean burn: 3.0 and 1.0 g/bhp-hr Rich burn: 2.0 and 0.5 g/bhp-hr Turbines 42 and 25 ppmv (at 15% O_2)	Multiple level Threshold Recips: 500, 1000, 2400 HP Turbines: 5000 HP
C (lower bound)	Counties with ozone monitoring data >69 ppb plus the adjacent counties.	*Two Levels*[1] Lean burn: 3.0 and 1.0 g/bhp-hr Rich burn: 2.0 and 0.5 g/bhp-hr Turbines 42 and 25 ppmv (at 15% O_2)	Multiple level Threshold Recips: 500, 1000, 2400 HP Turbines: 5000 HP

[1] Estimating incremental costs for two NOx targets was planned. However, feedback from NOx retrofit control service providers and manufacturers indicated that, for most cases, incremental costs would be more than offset by site-specific cost variability. Those site-specific costs are associated with auxiliary and peripheral system requirements, operational control systems, installation costs, other facility / site modifications, etc. Thus, rolled up costs were estimated for the upper and lower bound scenarios, and approximated for Scenario B. Cost uncertainties are discussed.

Appendix 2. Additional Regulatory Scenario – Reciprocating Engine and Turbine Counts in Non-OTR States Subject to the Cross State Air Pollution Rule (CSAPR)[A]

State[B]	Reciprocating Engines		Turbines
	Lean Burn	Rich Burn	
Alabama	61	3	15
Arkansas	80	25	2
Illinois	50	16	8
Indiana	44	0	0
Iowa	28	15	3
Kansas	68	36	10
Kentucky	145	10	16
Louisiana	261	13	55
Michigan	49	18	21
Mississippi	237	6	32
Missouri	38	20	2
Ohio	105	15	12
Oklahoma	108	56	0
Tennessee	102	7	14
Texas	199	24	22
Virginia[C]	36	2	4
West Virginia	149	3	6
Wisconsin	7	0	5
Total:	1,767	269	227

[A] The Ozone Transport Commission (OTC) has developed a model rule for compressor station engines and turbines. An OTC Work Group has recommended that the model rule be adopted in the ozone transport region (i.e., OTR, which is comprised of 11 northeast states and Washington DC) and, to address NOx transport, in upwind states covered by CSAPR.

[B] OTR states are not shown because very few uncontrolled units remain in those states. Nearly all units have been controlled or have been permitted with "alternative" NOx RACT limits.

[C] A portion of Virginia is in the OTR but most of the state is not.

Appendix 3. Affected Counties and Adjacent Counties with 3-year ozone average >69 ppb

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
NO AFFECTED COUNTIES FOR THE FOLLOWING STATES: **Alabama, Alaska, Arkansas, Hawaii, Idaho, Iowa, Kansas, Minnesota, Mississippi, Montana, Nebraska, New Hampshire, North Dakota, Oregon, South Carolina, South Dakota, Tennessee, Vermont, West Virginia, Wyoming**			
Arizona	Coconino	Mohave	CA - San Bernardino
	Gila	Navaho	CA -Riverside
	La Paz	Grahm	CA - Imperial
	Maricopa	Cochise	UT - Kane
	Pima	Santa Cruz	UT - San Juan
	Pinal		
	Yavapai		
	Yuma		
California	Alameda	Mono	NV -Clark
	Amador	Alpine	NV -Nye
	Butte	Sierra	NV -Esmerelda
	Calaveras	Yuba	NV -Douglas
	Contra Costa	Plumas	NV -Carson City
	El Dorado	Shasta	NV -Washoe
	Fresno	Trinity	AZ - Mohave
	Imperial	Mendocino	AZ - La Paz
	Inyo	Glenn	
	Kern	Colusa	
	Kings	Yolo	
	Los Angeles	Solano	
	Madera	San Mateo	
	Mariposa	Santa Cruz	
	Merced	San Benito	
	Nevada	Monterey	
	Orange	Santa Barbara	
	Placer		
	Riverside		
	Sacramento		
	San Bernardino		
	San Diego		
	San Joaquin		
	San Luis Obispo		
	Santa Clara		
	Stanislaus		
	Sutter		
	Tehama		
	Tulare		
	Tuolumne		
	Ventura		

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Colorado	Adams	Broomfield	UT - Uintah
	Arapahoe	Moffat	WY - Albany
	Denver	Routt	WY - Laramie
	Douglas	Garfield	NE - Kimball
	Jefferson	Jackson	
	Larimer	Grand	
	Park	Boulder	
	Rio Blanco	Logan	
	Weld	Morgan	
		Washington	
		Lincoln	
		Elbert	
		El Paso	
		Teller	
		Fremont	
		Chaffee	
		Lake	
		Summit	
		Clear Creek	
		Gilpin	
Connecticut	Fairfield		RI -Washington
	Hartford		RI -Kent
	Litchfield		RI -Providence
	Middlesex		MA - Worcester
	New Haven		MA -Hampden
	New London		MA -Berkshire
	Tolland		NY - Columbia
	Windham		NY - Dutchess
			NY - Putnam
			NY - Westchester
Delaware	New Castle	Kent	MD - Worcester
	Sussex		MD - Wicomico
			MD - Dorchester
			MD - Caroline
			MD - Kent
			MD - Cecil
			PA - Chester
			PA - Delaware
			NJ - Gloucester
			NJ - Salem
Florida	Hillsborough	Pinellas	
		Pasco	
		Polk	
		Hardee	
		Manatee	

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Georgia	Fulton	DeKalb	
	Gwinnett	Cherokee	
	Henry	Cobb	
	Rockdale	Douglas	
		Carroll	
		Cowetta	
		Fayette	
		Clayton	
		Spalding	
		Butts	
		Newton	
		Walton	
		Barrow	
		Hall	
		Jackson	
		Forsyth	
Illinois	Cook	McHenry	MO -St. Charles
	Lake	Kane	MO -St. Louis
	Madison	DuPage	MO -St. Louis County
		Will	IN -Lake
		Macoupin	WI -Kenosha
		Montgomery	
		Bond	
		Clinton	
		St. Clair	
		Jersey	
Indiana	Clark	Floyd	KY -Jefferson
		Washington	KY -Oldham
		Scott	KY -Trimble
		Jefferson	
Kentucky	Jefferson	Hardin	IN -Clark
		Bullitt	IN -Harrison
		Shelby	IN -Floyd
		Oldham	
		Spencer	
Louisiana	Ascension	West Baton Rouge	MS -Pearl River
	East Baton Rouge	Point Coupee	MS -Hancock
	Iberville	West Feliciana	
	Livingston	East Feliciana	
	St. Tammany	St. Helena	
		Tangipahoa	

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Louisiana (continued)		Washington	
		Orleans	
		Jefferson	
		St. Charles	
		St. John the Baptist	
		St. James	
		Assumption	
		Iberia	
		St. Martin	
Maine	York	Cumberland	NH -Carroll
		Oxford	NH -Rockingham
			NH - Strafford
Maryland	Anne Arundel	Caroll	Washington DC
	Baltimore	Howard	PA - York
	Cecil	Montgomery	PA - Lancaster
	Harford	Charles	PA - Chester
	Prince George's	St. Mary's	DE - New Castle
		Calvert	
		Kent	
Massachusetts	Bristol	Plymouth	RI -Providence
	Hampden	Norfolk	CT -Tolland
	Hampshire	Worcester	CT -Hartford
		Berkshire	
		Franklin	
Michigan	Allegan	Oceana	IN -La Porte
	Berrien	Newaygo	IN -St. Joseph
	Macomb	Kent	
	Muskegon	Ottawa	
	St. Clair	Barry	
	Wayne	Kalamazoo	
		Van Buren	
		Cass	
		Sanilac	
		Lapeer	
		Oakland	
		Washtenaw	
		Monroe	
Missouri	Jefferson	Lincoln	IL - Calhoun
	St. Charles	Warren	IL -Jersey
	St. Louis County	Franklin	IL -Madison
		Washington	IL -Monroe
		St. Francois	
		Sainte Genevieve	
		St. Louis City	

Three year ozone average >69 ppb

State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Nevada	Clark	Nye	CA - Modoc
	Washoe	Lincoln	CA -Lassen
		Carson City	CA -Sierra
		Humbolt	CA - Placer
		Pershing	CA -Nevada
		Churchill	OR - Lake
		Storey	OR -Harney
			AZ - Mojave
			CA -San Bernardino
			CA -Inyo
New Jersey	Bergen	Passaic	PA - Bucks
	Camden	Sussex	PA - Philadelphia
	Essex	Warren	NY - Rockland
	Gloucester	Cumberland	NY - Bronx
	Hudson	Atlantic	NY - New York
	Hunterdon	Burlington	
	Mercer	Somerset	
	Middlesex	Union	
	Monmouth	Richmond	
	Morris		
	Ocean		
New Mexico	Dona Ana	Luna	TX - El Paso
	Eddy	Sierra	TX -Culbertson
		Otero	TX - Reeves
		Chaves	TX - Loving
		Lea	
New York	Bronx	Orange	CT - Fairfield
	Richmond	Putnam	NJ - Bergen
	Rockland	New York	
	Suffolk	Queens	
	Westchester	Nassau	
	Erie	Niagra	
		Orleans	
		Genessee	
		Wyoming	
		Cattaraugus	
		Chautauqua	
North Carolina	Mecklenburg	Union	SC -York
		Cabarras	SC -Lancaster
		Iredell	
		Lincoln	
		Gaston	

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Ohio	Ashtabula	Trumbull	PA - Erie
	Butler	Portage	PA -Crawford
	Clermont	Summit	KY -Bracken
	Clinton	Medina	KY -Pendelton
	Cuyahoga	Lorain	KY - Campbell
	Franklin	Preble	KY - Kenton
	Geauga	Darke	KY - Boone
	Hamilton	Miami	IN - Dearborn
	Lake	Clark	IN - Franklin
	Montgomery	Greene	IN - Union
	Warren	Fayette	
		Highland	
		Brown	
		Madison	
		Union	
		Delaware	
		Licking	
		Fairfield	
		Pickaway	
Oklahoma	Jefferson	Kingfisher	TX - Clay
	Love	Canadian	TX - Cooke
	Oklahoma	Cleveland	TX - Montague
		Pottawatomie	TX - Grayson
		Lincoln	
		Logan	
		Cotton	
		Stephens	
		Carter	
		Marshall	
Pennsylvania	Allegheny	Lawrence	WV - Hancock
	Armstrong	Butler	OH - Columbiana
	Beaver	Clarion	DE - Newcastle
	Bucks	Jefferson	NJ - Gloucester
	Delaware	Clearfield	NJ - Camden
	Indiana	Cambria	NJ - Burlington
	Lebanon	Westmoreland	NJ - Mercer
	Montgomery	Washington	NJ - Hunterdon
	Philadelphia	Dauphin	
		Lancaster	
		Schuylkill	
		Berks	
		Lehigh	
		Northampton	
		Chester	

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Rhode Island	Kent	Bristol	MA - Bristol
	Providence		MA - Norfolk
	Washington		MA - Worcester
			CT - Windham
			CT - New London
Texas	Bexar	Hudspeth	NM - Dona Ana
	Brazoria	Medina	NM - Otero
	Collin	Atascosa	
	Dallas	Wilson	
	Denton	Guadalupe	
	El Paso	Comal	
	Galveston	Kendall	
	Harris	Bandera	
	Hood	Hill	
	Johnson	Ellis	
	Montgomery	Kaufman	
	Parker	Hunt	
	Rockwall	Fannin	
	Tarrant	Grayson	
		Cooke	
		Wise	
		Palo Pinto	
		Jack	
		Erath	
		Somervell	
		Bosque	
		Chambers	
		Liberty	
		San Jacinto	
		Walker	
		Grimes	
		Waller	
		Fort Bend	
		Matagorda	
		Wharton	
Utah	Davis	Box Elder	NV - Elko
	Duchesne	Cache	NV - White Pine
	Salt Lake	Rich	CO - Moffat
	Tooele	Morgan	CO - Rio Blanco
	Uintah	Summit	CO - Garfield
	Utah	Daggett	
	Weber	Wasatch	
		Juab	
		Sanpete	
		Carbon	
		Grand	

Three year ozone average >69 ppb			
State	**County**	**Adjacent County (in state)**	**Adjacent County (out of state)**
Virginia	Arlington	Fairfax County	
Washington	Benton	Kickitat	OR - Morrow
		Yakima	OR - Umatilla
		Grant	
		Franklin	
		Walla Walla	
Wisconsin	Door	Kewaunee	IL - Boone
	Kenosha	Brown	IL - McHenry
	Manitowoc	Calumet	
	Ozaukee	Fond du Lac	
	Sheboygan	Washington	
	Walworth	Milwaukee	
		Rock	
		Jefferson	
		Waukesha	
		Racine	
		Kenosha	
Washington D.C.	yes		

Appendix 4. EPA Tabular Summaries Related to NAAQS Program

- Current NAAQS, including form of the standard (excludes lead NAAQS)[9]
- NAAQS Implementation Milestones[10]
- NAAQS Review Schedule[7]

Pollutant [with link to historical tables of NAAQS reviews]		Primary / Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO)		primary	8 hours	9 ppm	Not to be exceeded more than once per year
			1 hour	35 ppm	
Nitrogen Dioxide (NO_2)		primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		primary and secondary	1 year	53 ppb (1)	Annual Mean
Ozone (O_3)		primary and secondary	8 hours	0.070 ppm (2)	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particulate Matter (PM)	$PM_{2.5}$	primary	1 year	12.0 μg/m^3	annual mean, averaged over 3 years
		secondary	1 year	15.0 μg/m^3	annual mean, averaged over 3 years
		primary and secondary	24 hours	35 μg/m^3	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24 hours	150 μg/m^3	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide (SO_2)		primary	1 hour	75 ppb (3)	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

(1) The level of the annual NO_2 standard is 0.053 ppm. It is shown here in terms of ppb for the purposes of clearer comparison to the 1-hour standard level.

(2) Final rule signed October 1, 2015, and effective December 28, 2015. The previous (2008) O_3 standards additionally remain in effect in some areas. Revocation of the previous (2008) O_3 standards and transitioning to the current (2015) standards will be addressed in the implementation rule for the current standards.

(3) The previous SO_2 standards (0.14 ppm 24-hour and 0.03 ppm annual) will additionally remain in effect in certain areas: (1) any area for which it is not yet 1 year since the effective date of designation under the current (2010) standards, and (2) any area for which an implementation plan providing for attainment of the current (2010) standard has not been submitted and approved and which is designated nonattainment under the previous SO_2 standards or is not meeting the requirements of a SIP call under the previous SO_2 standards (40 CFR 50.4(3)). A SIP call is an EPA action requiring a state to resubmit all or part of its State Implementation Plan to demonstrate attainment of the required NAAQS.

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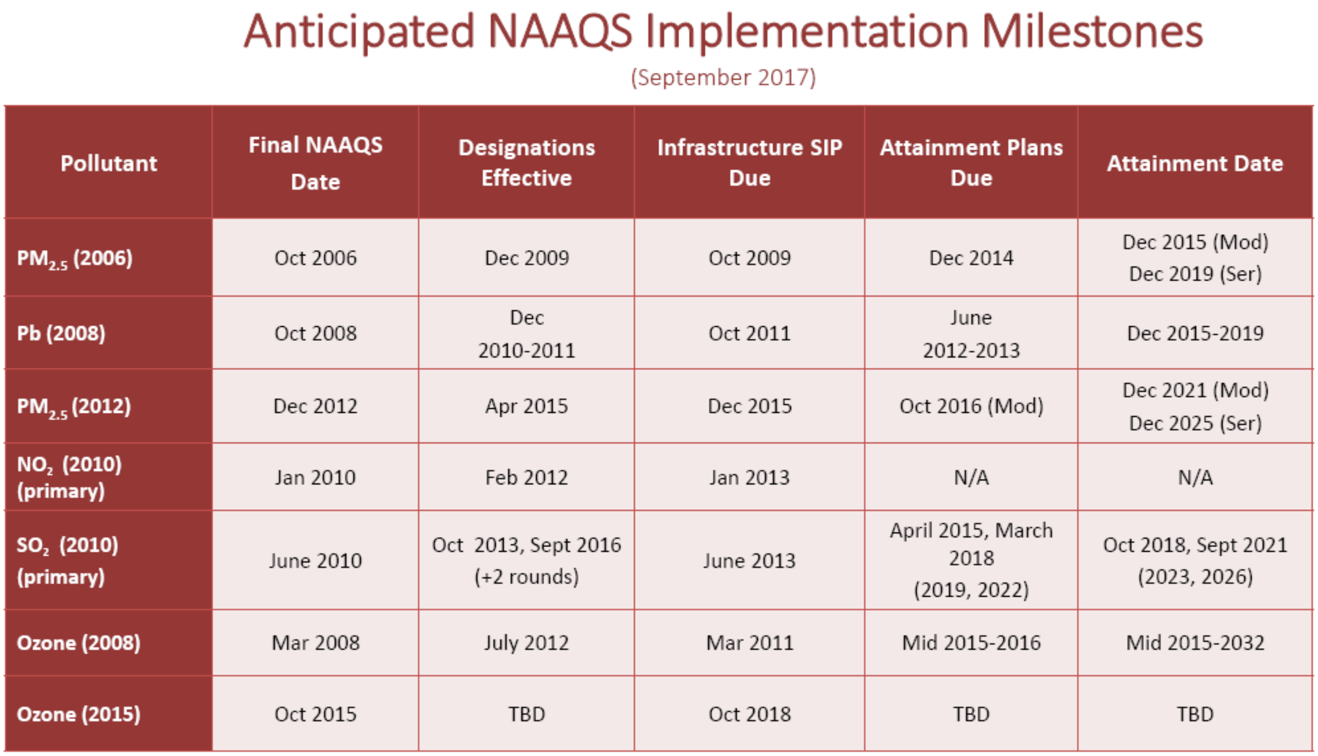
[9] From EPA website: https://www.epa.gov/criteria-air-pollutants/naaqs-table.

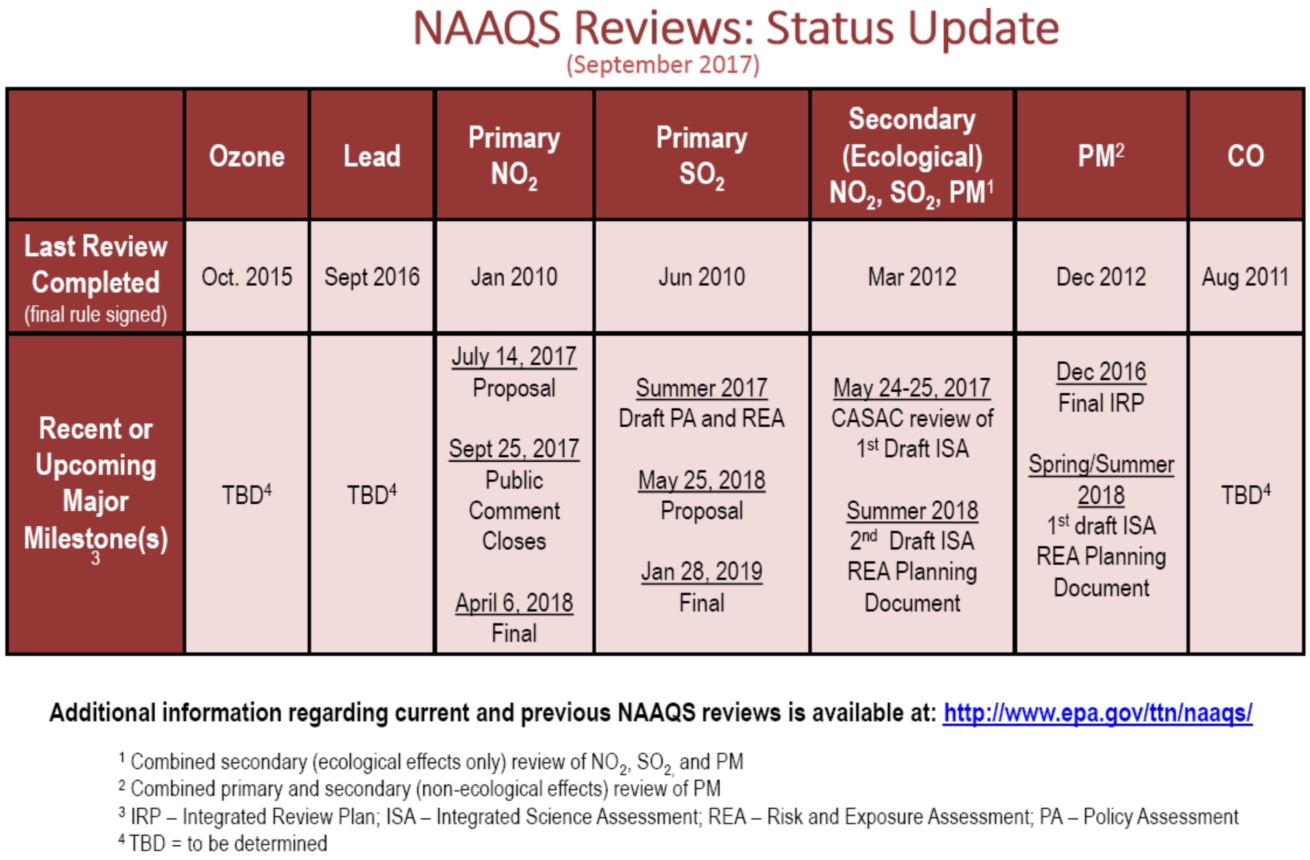
[10] "NAAQS and Other Implementation Updates." U.S. EPA presentation at AAPCA Fall Meeting (Sept. 21, 2017).



Anticipated NAAQS Implementation Milestones

(September 2017)

Pollutant	Final NAAQS Date	Designations Effective	Infrastructure SIP Due	Attainment Plans Due	Attainment Date
$PM_{2.5}$ (2006)	Oct 2006	Dec 2009	Oct 2009	Dec 2014	Dec 2015 (Mod) Dec 2019 (Ser)
Pb (2008)	Oct 2008	Dec 2010-2011	Oct 2011	June 2012-2013	Dec 2015-2019
$PM_{2.5}$ (2012)	Dec 2012	Apr 2015	Dec 2015	Oct 2016 (Mod)	Dec 2021 (Mod) Dec 2025 (Ser)
NO_2 (2010) (primary)	Jan 2010	Feb 2012	Jan 2013	N/A	N/A
SO_2 (2010) (primary)	June 2010	Oct 2013, Sept 2016 (+2 rounds)	June 2013	April 2015, March 2018 (2019, 2022)	Oct 2018, Sept 2021 (2023, 2026)
Ozone (2008)	Mar 2008	July 2012	Mar 2011	Mid 2015-2016	Mid 2015-2032
Ozone (2015)	Oct 2015	TBD	Oct 2018	TBD	TBD



NAAQS Reviews: Status Update

(September 2017)

	Ozone	Lead	Primary NO_2	Primary SO_2	Secondary (Ecological) NO_2, SO_2, PM[1]	PM[2]	CO
Last Review Completed (final rule signed)	Oct. 2015	Sept 2016	Jan 2010	Jun 2010	Mar 2012	Dec 2012	Aug 2011
Recent or Upcoming Major Milestone(s)[3]	TBD[4]	TBD[4]	July 14, 2017 Proposal Sept 25, 2017 Public Comment Closes April 6, 2018 Final	Summer 2017 Draft PA and REA May 25, 2018 Proposal Jan 28, 2019 Final	May 24-25, 2017 CASAC review of 1st Draft ISA Summer 2018 2nd Draft ISA REA Planning Document	Dec 2016 Final IRP Spring/Summer 2018 1st draft ISA REA Planning Document	TBD[4]

Additional information regarding current and previous NAAQS reviews is available at: http://www.epa.gov/ttn/naaqs/

[1] Combined secondary (ecological effects only) review of NO_2, SO_2 and PM

[2] Combined primary and secondary (non-ecological effects) review of PM

[3] IRP – Integrated Review Plan; ISA – Integrated Science Assessment; REA – Risk and Exposure Assessment; PA – Policy Assessment

[4] TBD = to be determined