Appendix A. MPCA's Regional Haze Technical Support Document

This appendix contains the technical support document (TSD) the MPCA prepared to support the policy decisions made in the comprehensive update to Minnesota's Regional Haze State Implementation Plan (SIP) for the second implementation period.

The TSD details the modeling analyses conducted for the second implementation period that support the:

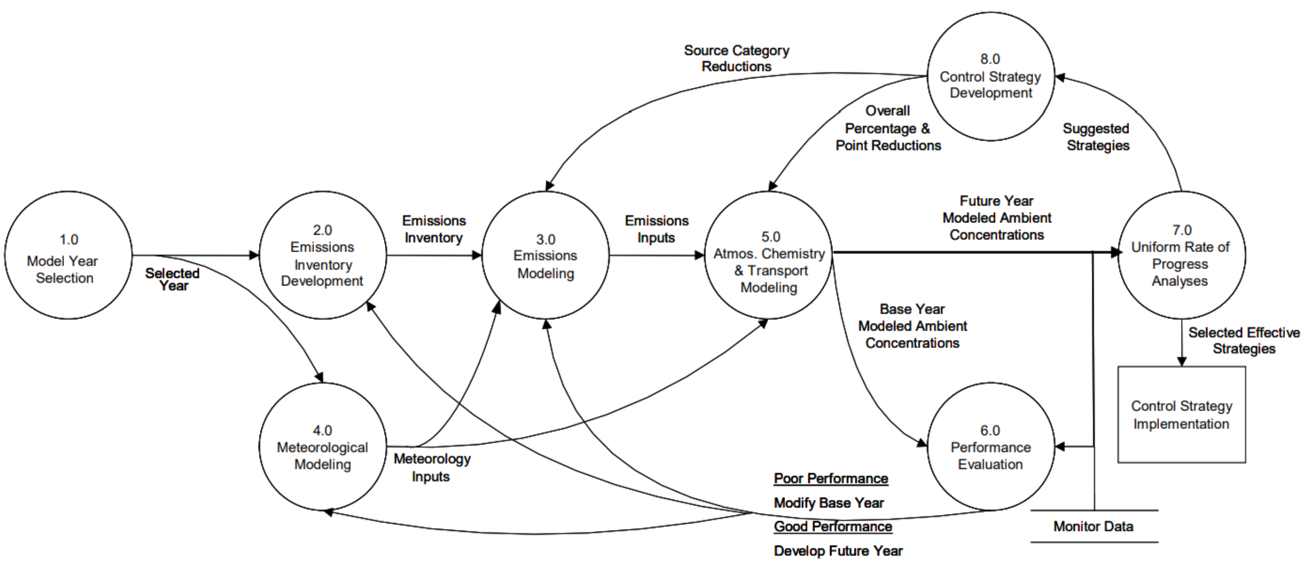
- Establishment of Reasonable Progress Goals (RPGs) for the Boundary Waters Canoe Area Wilderness and Voyageurs National Park Class I areas that ensure visibility on the most impaired days improves towards natural visibility conditions, and that ensure no degradation of visibility occurs on the clearest days.
- Determination of future visibility causing pollutants emission levels needed, and reductions needed from individual states, to meet the RPGs.
- Calculation of the resulting degree of visibility improvement that would be achieved at each Class I area.
- Comparison of visibility improvement between proposed control strategies.
- Conclusion that the long-term strategy provides for reasonable progress.

Regional Haze

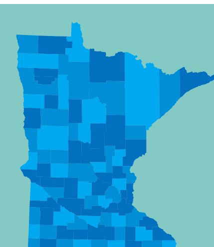
December 2022

Technical Support Document for Minnesota’s State Implementation Plan for Regional Haze

Models, data and analysis procedures to support the long-term strategy and reasonable progress goals for the second implementation period (2018 - 2028)



MINNESOTA POLLUTION CONTROL AGENCY



Authors

Margaret McCourtney, MPCA

Hassan Bouchareb, MPCA

Contributors/acknowledgements

This effort was prepared with assistance and input from several people across multiple organizations. Special thanks to the following groups and people:

United States Environmental Protection Agency, Office of Air Quality Planning and Standards, Alison Eyth for the 2016 v1 model platform and processing program package

Lake Michigan Air Directors Consortium (LADCO), Mark Janssen for state emissions representation to U.S. EPA and emissions modeling of industry and electric generating facility sectors, Donna Kenski (retired) for identifying missing days "Kenski days" in tracking metrics, and Zac Adelman for Amazon Web Service resources for MPCA to model visibility contributions in the cloud

National Emissions Inventory Collaborative for providing a forum for improved, consistent emissions inventories across the contiguous United States

Cooperative Institute for Research in the Atmosphere (CIRA), Dr Jenny Hand for updates on handling organic carbon for analysis, and Scott Copeland for sharing his knowledge and team work on tracking metrics

MPCA, Carl Stenoien, for making everything work in the interactive internet tools for emissions modeling and performance evaluation (links within this document)

Minnesota Pollution Control Agency

520 Lafayette Road North | Saint Paul, MN 55155-4194 |

651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us

This report is available in alternative formats upon request, and online at www.pca.state.mn.us.

Document number: aq-sip2-19a

Executive summary

The state of Minnesota is home to two mandatory Class I Federal areas (Class I areas), the Boundary Waters Canoe Area Wilderness (Boundary Waters) and Voyageurs National Park (Voyageurs), located along the state's border with Canada. In compliance with the Regional Haze Rule, the Minnesota Pollution Control Agency (MPCA) is submitting to the U.S. Environmental Protection Agency (U.S. EPA) a comprehensive update to Minnesota's Regional Haze State Implementation Plan (SIP) to meet the goal of restoring Class I areas to natural visibility conditions by 2064. This Technical Support Document (TSD) complements the SIP with detail on models, data and analysis procedures conducted to support the long-term strategy and reasonable progress goals (RPG) for the second implementation period (2018 – 2028).

The TSD describes how MPCA assessed significant improvements in visibility at Boundary Waters and Voyageurs, established the uniform rate of progress projected to 2064, and set RPGs for 2028. It also includes the MPCA assessment of causes for the remaining visibility impairment projected for year 2028.

Visibility trends. Visibility continues to improve at Boundary Waters and Voyageurs. MPCA continues to demonstrate that there is no degradation on the clearest days at Boundary Waters and Voyageurs. For the most impaired days, Boundary Waters improved from 18.5 deciviews (dv) in 2004 to 13.4 dv in 2019. Voyageurs improved from 17.9 dv in 2004 to 13.5 dv in 2019. These levels are below the glidepath for reaching natural visibility conditions by 2064. The main pollutants contributing to visibility impairment in Minnesota's Class I areas are sulfate and nitrate aerosols.

Although MPCA is not proposing an adjustment to the uniform rate of progress to account for international visibility impacts, analyses conducted by others suggest visibility would need to decrease by between 1.3 – 1.8 dv at Boundary Waters and 1.0 – 1.5 dv at Voyageurs to reach an adjusted endpoint goal. Between 2004 and 2009 there were measured increases in visibility impact at both Class I areas, but since 2009 the most impaired visibility impacts have declined per year an average 0.6 dv at Boundary Waters and an average 0.5 dv at Voyageurs. Should this trend continue, Boundary Waters and Voyageurs potentially could reach an adjusted endpoint by the third implementation period (2028 – 2038).

Emission trends and reasonable progress goals. Minnesota has achieved significant nitrogen oxide (NO_X) and sulfur dioxide (SO_2) reductions since the first regional haze implementation period, primarily driven by coal-fired electricity generating unit retirements. From 2002 to the end of the first implementation period in 2018, Minnesota saw a 59% reduction in NO_X emissions and a 79% reduction in SO_2 emissions from stationary sources. Emissions data through 2020 indicates that Minnesota stationary sources have reduced NO_X emissions by 71% and SO_2 emissions by 89% since 2002.

Based on the emissions projected from 2016 to 2028, Minnesota has set the 2028 RPGs for the second implementation period at 13.4 dv for Boundary Waters and 13.6 dv for Voyageurs. This equates to a 1.1 dv reduction at Boundary Waters and 1.4 dv reduction at Voyageurs from 2016. The RPGs are considered fairly conservative because not all the implemented emission control changes since 2016, nor all the proposed emission control measures in the SIP, are reflected in the 2028 modeled projection. Visibility calculations from measurements show the RPGs for 2028 have already been met in 2019.

Proposed emission control measures. In this implementation period, MPCA chose to focus on reducing emissions of NO_X and SO_2 because they lead to the formation of nitrate and sulfate, the particulate species that contribute most to regional haze at Boundary Waters and Voyageurs. In the SIP, Minnesota has included the effects of planned retirements for coal-fired combustion units and the Taconite Federal Implementation Plan requirements in this implementation period. Minnesota's long-term strategy also includes new emission reduction targets (30% by 2025 and 40% by 2028, relative to a 2018 baseline) for point sources in Northeastern Minnesota that emit over 100 tons per year of either NO_X or SO_2.

Also in the SIP, MPCA identified cost-effective control technologies including selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) at smaller electric utilities and industrial boilers. Some facilities chose to retire equipment earlier to avoid installing controls. All emission reductions identified in the SIP submittal are recorded in enforceable permit actions or administrative orders. The emission reduction measures constitute the long-term strategy.

Geographic and sector contribution analysis. MPCA also assessed the contributions to visibility impairment projected to 2028. From this analysis, MPCA concludes that Minnesota continues to be the largest state contributor to visibility impairment at Boundary Waters and Voyageurs, additional NO_X emission reductions are needed, and Boundary Waters and Voyageurs may benefit from emission reductions in other regions or states located to the West and Northwest but also from other directions, in the following order of importance: Canada, North Dakota, Iowa, Nebraska, Wisconsin, and Missouri.

Furthermore, MPCA concludes SO_2 emission reductions from electric generating units (EGUs) in other states may likely lessen visibility impacts at Boundary Waters and Voyageurs as well. North Dakota, Iowa, Nebraska, and Missouri contributions to visibility impairment are primarily from EGU SO_2 emissions. Minnesota and Wisconsin's top two sector contributors to overall visibility impairment at Boundary Waters and Voyageurs, in order of importance, are industry and vehicle emissions.

Leading up to the third regional haze implementation period, MPCA expects to continue to annually assess visibility trends, and to contemplate proposing international impact adjustments to the 2064 endpoint and what that might mean for Boundary Waters and Voyageurs in the Regional Haze Program going forward.

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

Acronym/Abbreviation	Description
µm	Micrometers
Air parcel	Volume of air that tends to be transported about the earth as an intact entity and can be tracked
Air quality planning organization	(see MJO)
Anthropogenic	Caused by humans (e.g. pollutant emissions from industrial processes and vehicles)
Apportionment	Proportional distribution of allocation
Area source	Emissions source not assigned to locational coordinate but instead are assigned to a grid cell (e.g. agricultural operations, residential heating)
Back trajectory	Tracking air parcels arriving at a particular destination back in time to their origination
Baseline conditions	Average visibility conditions in deciviews at each Class I area for the 20% clearest and 20% most impaired days in the 5-year baseline period
Baseline period	Years 2000-2004 for the first SIP implementation period and 2014-2018 for the second SIP implementation period
Base year	The year within the 5-year baseline period modeled to establish the RPG (e.g. 2016)
BC	Boundary conditions
Beta extinction	Light extinction coefficient that provides a direct, but non-linear, measure of the correlation between air concentrations of visibility impairing pollutants and visibility conditions, expressed in units of inverse megameters (Mm^{-1})
b_{ext}	Extinction coefficient, or Beta extinction
Biogenic	Caused by natural processes (e.g. emissions from the respiration of trees)
Boundary conditions	Air concentrations traveling into the model domain from the East, West, North and South and from above the model domain
Boundary Waters	Boundary Waters Canoe Area Wilderness
CAA	Clean Air Act
CAMx	Comprehensive Air quality Model with eXtensions, an Eularian air quality grid model that simulates atmospheric and surface processes affecting the transport, chemical transformation and deposition of air pollutants and their precursors
CENRAP	Central Regional Air Planning Association
CENSARA	Central States Air Resource Agencies, planning organization with membership from States and Tribal areas within Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas and Louisiana
CFR	Code of Federal Regulations
CIRA	Cooperative Institute for Research in the Atmosphere
Class I area	Area of special national or regional value, whether natural, scenic recreational or historic, for which the CAA provides special protection and are managed by FLMs
CMAQ	Community Multiscale Air Quality model – a contemporary of CAMx
CO	Carbon monoxide
CO_2	Carbon dioxide
Coarse particulate mass	Particulate mass with a diameter between 2.5 and 10 microns, $PM_{2.5} – PM_{10}$
CSN	Continuous Speciated Network

Acronym/Abbreviation	Description
Deciview	A standard visual index defined in terms of the extinction coefficient that is linear with perceived changes in visibility, with one to two deciviews the smallest change perceptive to the human eye
DV	Deciview
EC	Elemental carbon
EGU	Electric generating unit
ERTAC	Eastern Regional Technical Advisory Committee
ERTAC model	A model developed by …. an alternative to IPM
Extinction	Attenuation of light due to scattering and absorption as it encounters a particle
Extinction coefficient	b_{ext}
FIP	Federal Implementation Plan
FIPS	Federal Information Processing Standards, a standard set of numeric codes issued by the National Institute of Standards and Technology to ensure uniform identification of geographic entities throughout all federal government agencies
FLMs	Federal Land Managers, a group comprising the U.S. NPS, U.S. FS and U.S.FWS
Glidepath	Another term for the Uniform Rate of Progress, or URP
Grid cell	One of many in a rectangular array of points regularly spaced over a geographic area defined by an x, y coordinate
IC	Initial conditions, the inputs at model start-up that should not appear in the model results when the model set-up accounts for appropriate spin-up time
IMPROVE	Interagency Monitoring of Protected Visual Environments, a cooperative program to monitor visibility in Class I areas
IMPROVE steering committee	A decision-making body on the data, data analysis and performance of tracking metrics associated with the IMPROVE program and its use in the Regional Haze Program, with members from U.S. FS, U.S. NPS, U.S. FWS, U.S. BLM, U.S. EPA, NOAA, NACAA and the planning organizations NESCAUM, WESTAR, MARAMA and associate member from Arizona DEQ
Industry	
IPM	Integrated planning model, a model developed by ICF that U.S.EPA uses to evaluate future impact of pollution control policies on EGUs in combination with projected energy needs
LADCO	Lake Michigan Air Directors Consortium, an air quality planning organization with membership from States and Tribes in Illinois, Indiana, Michigan, Minnesota, Ohio and Wisconsin
LNB	Low NO_X burners
m^3	Cubic meter
MANE-VU	Mid-Atlantic Northeast Visibility Union, an air quality planning organization with State and Tribal membership from within …
MARAMA	Mid Atlantic Regional Air Management Association
MJO	Multi-jurisdictional organization
Mm^{-1}	Inverse megameters
Model domain	Geographic area where CAMx model fully characterizes the physical processes in the atmosphere and predicts species concentrations
Most impaired days	20% of days most visually impaired during each year in the baseline period
MPCA or Agency	Minnesota Pollution Control Agency

Acronym/Abbreviation	Description
MRPO	Midwest Regional Planning Organization
NAAQS	National Ambient Air Quality Standards
NACAA	National Association of Clean Air Agencies
Natural conditions	Estimation of visibility in the absence of human influence
NEI	National Emission Inventory, a compilation of annual emissions by pollutant and source category by county for each state, which the U.S.EPA requires states to submit on a 3-year cycle
NH_3	Ammonia
NH_4	Ammonium ion
NO_3	Nitrate ion
NH_4 NO_3	Ammonium nitrate
NH_4SO_4	Ammonium sulfate
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
Nonroad	Mobile equipment not traveling on roadways (e.g. recreational and construction vehicles) with emissions assigned to a grid cell
OCM	Organic carbon mass
On-road	Mobile sources, automobiles and trucks that travel on paved roadways with emissions assigned to a grid cell
PM	Particulate matter
PM_{10}	Particulate matter with an aerodynamic diameter less than or equal to 10 micrometers
$PM_{2.5}$	Particulate matter with an aerodynamic diameter less than or equal to 2.5 micrometers, or fine PM
Point sources	Industrial sources or EGUs identified by locational coordinate and stack parameters (e.g. facilities with state permits) that are assigned to a grid cell based on the locational coordinate of the stack
PSAT	Particulate Source Apportionment Technology
Rayleigh scattering	Scattering of light by particles smaller than the wavelength of light
Reasonable progress goal	State established interim goals, expressed in deciviews, representing incremental visibility improvement over time toward the ultimate goal of natural conditions
Regional haze	Cloud of aerosols extending up to hundreds of miles across a region impairing visibility
Relative response factor	Ratio of the future year modeled PM2.5 air concentrations to the modeled base year concentrations predicted near a monitor location and averaged over the 20% clearest and the 20% most impaired days
NESCAUM	Northeast States for Coordinated Air Use Management
RH	Relative humidity
RPG	Reasonable progress goal
RPO	Regional Planning Organization
RRF	Relative Response Factor
SCC	Source classification code used by U.S.EPA to classify different types of anthropogenic emission activities
SESARM	Southeastern Air Pollution Control Agencies

Acronym/Abbreviation	Description
SIP	State Implementation Plan
SMOKE	Sparse Matrix Operator Kernel Emissions, model to process and prepare emission data for air quality model input
SO_2	Sulfur dioxide
SO_4	Sulfate ion
tpy	Tons per year
TSD	Technical Support Document
Uniform rate of progress	Linear rate of visibility improvement from the 2000-2004 baseline period to the endpoint natural conditions in 2064 at each Class I area
U.S. BLM	United States Bureau of Land Management
U.S. DA	United States Department of Agriculture
U.S. DI	United States Department of Interior
U.S. EPA	United States Environmental Protection Agency
U.S. FS	United States Forest Service
U.S. FWS	United States Fish and Wildlife Service
U.S. NPS	United States National Park Service
URP	Uniform Rate of Progress
VOC	Volatile organic compound
Voyageurs	Voyageurs National Park
WESTAR	Western States Air Resources Council, see WRAP
WRAP	Western regional air partnership with membership from States and Tribal areas within Arizona, California, Colorado, Idaho, Montana, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington and Wyoming
WRF	Weather Research and Forecasting numerical weather prediction modeling system from scales of tens of meters to thousands of kilometers for atmospheric research

1. Introduction

40 CFR § 51.308(f) requires that states must revise and submit their Regional Haze SIP revision to the United States Environmental Protection Agency (U.S. EPA) by July 31, 2021 (second implementation period), July 31, 2028 (third implementation period), and every 10 years thereafter (subsequent implementation periods). In each Regional Haze SIP revision, states must address regional haze in each mandatory Class I federal area located within the state and each mandatory Class I federal area located outside the state that may be affected by emissions from within the state.

In the second implementation period, the focus of the Regional Haze Rule is on making reasonable progress. Based on knowledge gained from the first implementation period, along with that learned from observed visibility trends (see Section 4.7), MPCA became quite certain that photochemical modeling would show:

- Emissions changes in Minnesota and other states that contribute to visibility at Boundary Waters and Voyageurs continue to result in reasonable progress toward natural visibility conditions
- Minnesota would continue to be the largest contributor to visibility impairment at Boundary Waters and Voyageurs
- NO_X controls would be needed, with observed data trends increasingly showing nitrate dominating most impaired visibility days
- Boundary Waters and Voyageurs may not benefit as much from control measures in states located to the East and Southeast due to prevailing winds from the West and Northwest during periods of high nitrate production

MPCA has conducted air quality modeling to further investigate reasonable progress and support policy decisions made in Minnesota's comprehensive update to the Regional Haze SIP. This technical support document (TSD) describes the models, data and analysis procedures to support the long-term strategy and reasonable progress goals for the second implementation period (2018 – 2028). The information in this TSD

- Sets Reasonable Progress Goals (RPG) for the Boundary Waters and Voyageurs Class I areas that ensure visibility on the most impaired days improves toward natural visibility conditions, and that ensure no degradation of visibility occurs on the clearest days
- Quantifies future emission levels of visibility causing pollutants needed, and reductions needed from individual states, to meet the RPG
- Calculates the resulting degree of visibility improvement that would be achieved at each Class I area
- Compares visibility improvement between proposed control strategies
- Concludes that the long-term strategy provides for reasonable progress

2. Background

In amendments to the Clean Air Act (CAA) in 1977, Congress added Section 169A, establishing a national visibility goal of restoring natural visibility conditions in many national parks and wilderness areas.[1] These areas were designated as mandatory Class I federal areas (Class I areas). Class I areas are composed of all international parks in the United States, all national wilderness areas and memorial

[1] *See* 42 U.S.C. § 7491.

parks larger than 5,000 acres, and all national parks larger than 6,000 acres in size that were in existence by 1977.[2] Figure 1 is a map showing all Class I areas.

Figure 1. Map of Mandatory Class I Areas[3]

Class I areas have the smallest increments of additional pollutants allowed out of the three Classes of areas under the Prevention of Significant Deterioration (PSD) provisions.[4] The purpose of the PSD provisions is "to preserve, protect, and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores, and other areas of special national or regional natural, recreational, scenic, or historic value".[5] In the Class I areas, visibility was identified as an important value.[6] Section 169 states, "Congress hereby declares as a national goal the prevention of any future, and the remedying any existing, impairment of visibility in mandatory Class I Federal areas which impairment results from man-made air pollution."[7]

To achieve the national visibility goals mandated by Congress, in 1999 the U.S. Environmental Protection Agency (U.S. EPA) established a regulatory program called the Regional Haze Rule (40 CFR § 51.308) under the Clean Air Act.[8] This program created regulations designed to improve visibility in national parks and wildernesses designated as Class I areas across the United States and restore them to natural

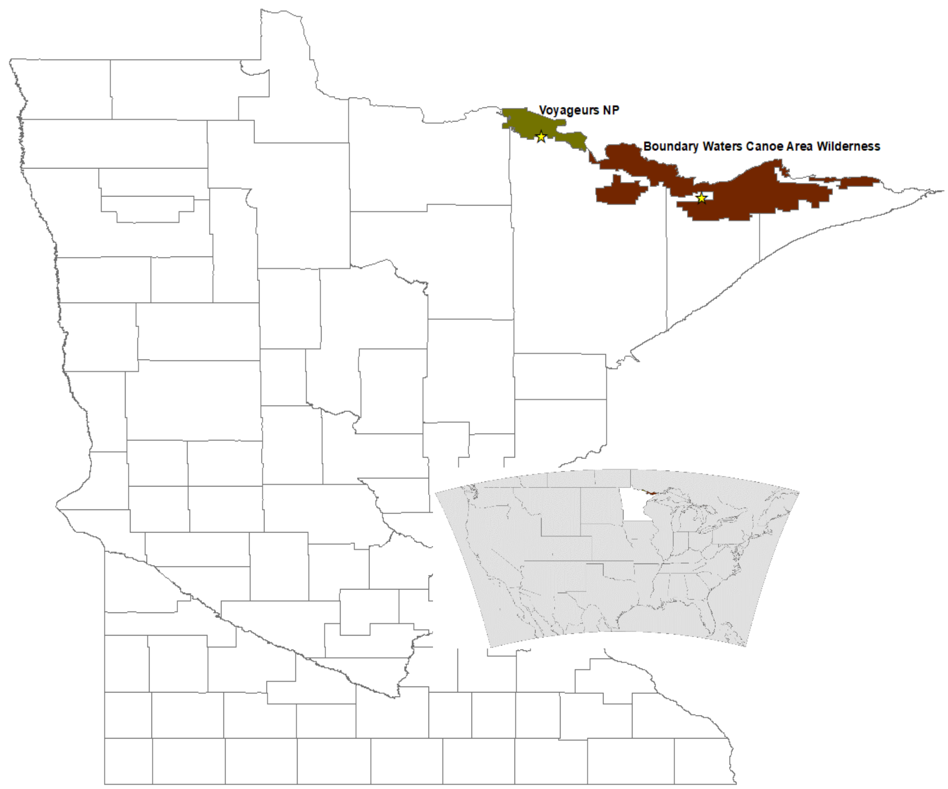
---

[2] *See Clean Air Act § 162, 42 U.S.C. § 7472(a); 40 CFR § 52.21(e).*
[3] *Source: https://www.epa.gov/visibility/regional-haze-program*
[4] *See 40 CFR § 51.166(c); 40 CFR § 52.21(c);* Prevention of Significant Deterioration New Sources Review: Refinement of Increment Modeling Procedures, *72 Fed. Reg. 31374 (June 6, 2007).*
[5] *See CAA § 160, 42 U.S.C. § 7470(2).*
[6] *See* 40 CFR § 81.400; National Visibility Goal for Class I Areas; Identification of Mandatory Class I Federal Areas Where Visibility is an Important Value, *44 Fed. Reg. 69122 (Nov. 30, 1979).*
[7] 42 U.S.C. § 7491(a)(1)
[8] *See* Regional Haze Regulations, 64 Fed. Reg. 35714 (July 1, 1999); Protection of Visibility: Amendments to Requirements for State Plans, 82 Fed. Reg. 3078 (Jan. 10, 2017).

visibility conditions by 2064. The Regional Haze Rule is found in 40 CFR Part 51, Subpart P and covers 156 Class I areas in the United States.

Not all Class I areas are protected. Federal Land Managers (FLMs) have indicated some areas do not have visibility as a valuable feature, such as Rainbow Lake Wilderness Area in Wisconsin, and have excluded them from protection by the Regional Haze program. Minnesota is home to two protected Class I areas, Boundary Waters and Voyageurs, located along the state's border with Canada, as shown in Figure 2. Yellow star shaped icons in the Figure identify the location of ambient air monitoring stations in the Interagency Monitoring of Protected Visual Environments (IMPROVE) network for each Class I area.

Figure 2. Minnesota Class I areas, Voyageurs and Boundary Waters



The regional haze program addresses the combined visibility effects of various pollution sources over a wide geographic region, meaning that even states without Class I areas are required to participate in haze reduction efforts. States are responsible for developing a Regional Haze SIP that addresses regional haze in each Class I area located within the state and in each Class I area located outside the state which may be affected by emissions from sources within the state.

The overall purpose of the regional haze program is to identify existing sources that cause or contribute to visibility impairment; analyze, identify, and apply federally enforceable control strategies for those sources; and periodically demonstrate reasonable progress toward reaching visibility goals. In each Regional Haze SIP, states must set goals reflecting reasonable pollution controls and emission reductions and the resulting visibility improvement achieved by the controls in the specified timeframe. States are also responsible for periodic comprehensive updates to their Regional Haze SIPs that address these same topics. States were required to submit their first Regional Haze SIP to U.S. EPA by December 17, 2007.[9] States must revise and submit their Regional Haze SIP revisions to the U.S. EPA by July 31, 2021, July 31, 2028, and every 10 years thereafter.[10]

In between comprehensive updates, states are responsible for providing interim progress reports that outline the status of required Regional Haze SIP elements. The progress reports evaluate how the state is moving towards the visibility goals for each Class I area to assess whether changes to the state's Regional Haze SIP are needed to achieve these goals. States were required to submit their first periodic progress report to U.S. EPA five years from the submittal of their first Regional Haze SIP.[11] States are required to provide subsequent periodic progress reports to U.S. EPA by January 31, 2025, July 31, 2033, and every 10 years thereafter.[12]

U.S. EPA has encouraged states to collaborate when developing the technical information needed to better understand the causes of visibility impacts in the Class I areas and the measures needed to mitigate visibility impacts. States have grouped into five Regional Planning Organizations (RPOs) to address visibility. In the first implementation period, Minnesota joined the Central Regional Air Planning Association (CENRAP) RPO, which was affiliated with the Central States Air Resource Agencies (CENSARA) Multi-Jurisdictional Organization (MJO).

It soon became evident that the Minnesota and Michigan Class I areas are in the same airshed, due to the proximity of the Class I areas and the highly correlated $PM_{2.5}$ chemical species observed at monitors among these Class I areas. In June 2004, CENRAP and the MidWest RPO, of which Michigan was a member, came to an agreement that MidWest RPO would take the lead in compiling emissions inventories and developing the photochemical modeling framework for the entire airshed. The MidWest RPO was affiliated with the Lake Michigan Air Directors Consortium (LADCO) MJO.

Following the first implementation period, the RPO names reverted to the MJO names. The MJOs address other regional air issues in addition to haze. Minnesota officially joined LADCO. The LADCO member states include Minnesota, Wisconsin, Illinois, Indiana, Michigan, and Ohio. Figure 3 is a map of the current RPO/MJOs.

[9] *See* 40 CFR § 51.308(b).
[10] *See* 40 CFR § 51.308(f).
[11] *See* 40 CFR § 51.308(g).
[12] *See id.*

Figure 3. Regional Planning Organizations/Multi-Jurisdictional Organizations[13]

2.1. Minnesota's Regional Haze SIP (first implementation period)

To meet the core requirements for regional haze, Minnesota had to submit a SIP that contained the plan elements and supporting documentation for all required analyses identified in 40 CFR § 51.308(d) and 40 CFR § 51.308(e).

MPCA submitted its initial SIP addressing the requirements of the Regional Haze Rule to U.S. EPA on December 31, 2009. The 2009 Regional Haze SIP identified visibility conditions, set 2018 visibility goals ("Reasonable Progress Goals," or RPG) for Minnesota's Class I areas (Boundary Waters and Voyageurs), and determined that Minnesota may contribute to visibility impairment at Isle Royale National Park in Michigan. The SIP also outlined control strategies intended to support making progress towards visibility goals in Class I areas affected by Minnesota's emissions. Minnesota developed its SIP with extensive consultation with stakeholders, including FLMs, Tribal representatives, industry representatives, CENRAP, LADCO/MRPO, individual states, and the Ontario Ministry of the Environment.

The focus of the Regional Haze Rule in the first implementation period was on establishing Best Available Retrofit Technology (BART) for certain older sources and reasonable progress goals towards national visibility goals. The SIP had to determine BART and schedules for compliance with BART for each subject-to-BART source that emits any air pollutant which may reasonably be anticipated to cause or contribute to any impairment of visibility in any mandatory Federal Class I area. The state also had an option to demonstrate that an emissions trading program or other alternative would achieve greater reasonable progress toward natural visibility conditions than would be achieved through the installation and operation of BART.

MPCA used the following criteria to identify BART-eligible units:

[13] *U.S. EPA. Visibility - Regional Planning Organizations,* https://www.epa.gov/visibility/visibility-regional-planning-organizations.

1. One, or more, emission(s) units at the facility fit within one of the twenty-six (26) categories listed in 40 CFR Part 51, Appendix Y, Guidelines for BART Determinations Under the Regional Haze Rules;
2. The emission unit(s) were in existence on August 7, 1977 and began operation at some point on or after August 7, 1962; and
3. The sum of the potential emissions from all emission unit(s) identified in the previous two bullets was greater than 250 tons per year of the visibility-impairing pollutants: sulfur dioxide (SO_2), nitrogen oxides (NO_X), and particulate matter less than 10 microns (PM_{10}).

After identifying the BART-eligible units, MPCA chose to evaluate which BART-eligible units became subject-to-BART through an individual source attribution approach to determine which sources caused or contributed to visibility impairment. Modeling was conducted in accordance with the 40 CFR Part 51, Appendix Y Guidelines. BART-eligible units became subject-to-BART when the results of the modeling analysis showed the BART-eligible source contributed to visibility impairment on 21 or more days over a three-year period with a 98% percentile change in visibility greater than or equal to 0.5 dv. Subject-to-BART units were required to conduct a BART analysis.

The determination of BART is based on an analysis of the best system of continuous emission control technology available and associated emission reductions achievable for each subject-to-BART source. This analysis considers the technology available, the costs of compliance, the energy and non-air quality environmental impacts of compliance, any pollution control equipment in use at the source, the remaining useful life of the source, and the degree of improvement in visibility which may reasonably be anticipated to result from the use of such technology.[14]

In addition to BART, Minnesota's SIP analysis indicated that the main pollutants contributing to visibility impairment in Minnesota's Class I areas are ammonium sulfate (sulfate), ammonium nitrate (nitrate), and organic carbon. Modeling indicated that the organic carbon is mostly biogenic, so MPCA chose to focus control measures on the anthropogenic emissions of NO_X and SO_2 that lead to formation of nitrate and sulfate. The main contributors of SO_2 emissions were electric generating units (EGUs), while the main contributors of NO_X were motor vehicles, both on and off road. The main states whose emissions contributed to visibility impairment in Boundary Waters and Voyageurs are Minnesota, Wisconsin, Illinois, Iowa, Missouri, and North Dakota.

Minnesota's multi-prong long-term strategy included the implementation of several federal programs in Minnesota and surrounding states and set a target for a 30% reduction in combined NO_X and SO_2 emissions by 2018 from permitted sources in Northeastern Minnesota that emit over 100 tons per year of either NO_X or SO_2. Data from 2018 shows a combined NO_X and SO_2 reduction of roughly 55% from the 2002 base year, largely due to reductions from the utility sector.

MPCA supplemented its Regional Haze SIP in 2012, updating its BART strategies for both power plants and the taconite industry, as well as its long-term strategy focused on the taconite industry. U.S. EPA approved nearly all elements of Minnesota's Regional Haze SIP, effective July 12, 2012, deferring action on Minnesota's BART determinations for the taconite industry and one electric utility. U.S. EPA subsequently promulgated FIPs that incorporated revised BART determinations for taconite facilities and the electric utility.

[14] *See* 40 CFR Part 51, Appendix Y.

2.2. U.S. EPA's Regional Haze Federal Implementation Plan (FIP) for taconite facilities

In the MPCA's 2009 Regional Haze SIP and subsequent 2012 SIP supplement, MPCA identified site specific NO_X and SO_2 BART determinations for emission sources at taconite facilities. In general, MPCA determined for all taconite pellet furnaces that:

- BART for NO_X emissions was an operating standard of good combustion practices in combination with other process changes to reduce NO_X emissions and improve fuel efficiency
- BART for PM emissions was equivalent to the requirements of 40 CFR Part 63, Subpart RRRRR that requires control of PM emissions to control hazardous air pollutants
- BART for SO_2 emissions was optimizing the existing control equipment for removal of SO_2

However, these limits never became finalized as, on September 30, 2013, U.S. EPA disapproved the proposed NO_X and SO_2 limits contained in the SIP submitted by Minnesota.[15] While U.S. EPA agreed with Minnesota's determination of which sources were subject-to-BART and that BART for PM emissions from these sources was satisfied by the requirements of 40 CFR Part 63, Subpart RRRRR; U.S. EPA developed a FIP to address the deficiencies in the Minnesota SIP.

On February 6, 2013, U.S. EPA promulgated a Taconite Regional Haze FIP that included BART limits for taconite furnaces subject-to-BART in Minnesota with an effective date of March 8, 2013.[16] Cliffs Natural Resources Inc., ArcelorMittal USA LLC, and the State of Michigan petitioned the 8th Circuit Court of Appeals for a review of the FIP and filed a joint motion to stay the FIP which was granted on June 14, 2013.[17] A settlement agreement between the mentioned parties and U.S. EPA was reached to resolve certain items in the 2013 FIP. The settlement agreement was published in the Federal Register on January 30, 2015, executed on April 9, 2015, and prompted U.S. EPA to reconsider the 2013 FIP.[18]

U.S. EPA proposed revisions to the 2013 Taconite Regional Haze FIP on October 22, 2015, which proposed to revise the BART emission limits and compliance schedules for the following taconite facilities: United Taconite, Hibbing Taconite, Tilden Mining (MI), and ArcelorMittal Minorca Mine.[19] U.S. EPA proposed to revise the NO_X limits and compliance schedules for all four facilities and to revise the SO_2 requirements for Tilden Mining and United Taconite. On April 12, 2016, U.S. EPA finalized the revisions to the 2013 FIP and the final rule (2016 FIP) was effective on May 12, 2016.[20]

On November 15, 2016, the 8th Circuit Court of Appeals terminated the June 14, 2013 stay and extended the deadlines in the original 2013 FIP by one day for each day the court's stay was in place. From the day the 2013 FIP was effective to the day it was stayed, 98 days elapsed (March 8, 2013, to June 14, 2013).[21] As a result, the deadlines contained in the 2013 FIP still apply (e.g., 6 months after March 8, 2013), only now from the date the stay was terminated, minus the number of days elapsed prior to the stay being issued. The deadlines contained in the 2016 FIP were never stayed and apply as promulgated (e.g., 6 months after May 12, 2016).

---

[15] *See* Approval and Promulgation of Air Quality Implementation Plans; States of Michigan and Minnesota; Regional Haze, *78 Fed. Reg. 59825 (Sept. 30, 2013).*

[16] *See* Approval and Promulgation of Air Quality Implementation Plans; States of Minnesota and Michigan, *78 Fed. Reg. 8706 (Feb. 6, 2013).*

[17] *See* Revision to Taconite Federal Implementation Plan, *80 Fed. Reg. 64160 (Oct. 22, 2015).*

[18] *See* Proposed Settlement Agreement, *80 Fed. Reg. 5111 (Jan. 30, 2015).*

[19] *See* Revision to Taconite Federal Implementation Plan, *80 Fed. Reg. 64160 (Oct. 22, 2015).*

[20] *See* Revision to 2013 Taconite Federal Implementation Plan Establishing BART for Taconite Plants, *81 Fed. Reg. 21672 (Apr. 12, 2016).*

[21] *See* Order dated November 15, 2016 in response to U.S. EPA's Petition to reconsider the original 2013 Taconite FIP, EPA-R05-OAR-2017-0066-0009 (8th Cir. 2016).

While U.S. EPA reached an agreement with Cliffs Natural Resources Inc., ArcelorMittal USA LLC, and the State of Michigan regarding the issues raised in petitions for the 2013 FIP, the petitions for review of disapproval of Minnesota's Regional Haze SIP remain pending. In response to U.S. EPA's September 30, 2013 disapproval of Minnesota's Regional Haze SIP, Cliffs Natural Resources Inc. petitioned U.S. EPA on November 26, 2013, to reconsider the partial disapproval of Minnesota's Regional Haze SIP.[22] Further, Cliffs Natural Resources Inc. also filed petitions for review and administrative reconsideration of the 2016 FIP.[23] These petitions for review remain pending and are being held in abeyance pending approval of a second settlement agreement.

U.S. Steel also petitioned U.S. EPA on November 26, 2013, to reconsider the partial disapproval of Minnesota's Regional Haze SIP. U.S. Steel also petitioned U.S. EPA to reconsider and stay the 2013 FIP (on November 26, 2013) and 2016 FIP (on June 13, 2016).[24] U.S. EPA later denied those petitions for reconsideration on January 18, 2017, based on their determination that the petitions did not meet the two-step test to determine whether reconsiderations should be granted, as required by section 307(d)(7)(B) of the Clean Air Act.[25] On February 1, 2018, U.S. Steel submitted a petition for review of the denial action.[26] As a result, U.S. EPA and the taconite facilities are currently working to resolve the disagreements through settlement discussions.

U.S. EPA proposed revisions to the FIP for U.S. Steel - Minntac on February 4, 2020, and September 29, 2020.[27] Most recently, U.S. EPA published a final rule revising the FIP as it pertains to U.S. Steel - Minntac on March 2, 2021.[28] If a settlement agreement is reached with the remaining Minnesota taconite facilities named in the FIPs (Cleveland-Cliffs Minorca Mine, Hibbing Taconite Company, Northshore Mining Company, United Taconite - Fairlane Plant and U.S. Steel - Keetac), U.S. EPA must publish a Federal Register notice announcing the settlement agreement and initiate a public notice and comment period. If the settlement agreement revises portions of the Taconite FIP, U.S. EPA must publish the revisions to the Taconite FIP, initiate a public notice and comment period, and respond to any comments received. Until then, the requirements of the Taconite FIP apply as currently promulgated.

2.3. U.S. EPA's Regional Haze Federal Implementation Plan (FIP) for visibility

MPCA initially did not perform a BART determination for subject-to-BART electric generating units (EGUs) to evaluate NO_X and SO_2 because of Minnesota's inclusion in the Clean Air Interstate Rule (CAIR). U.S. EPA found that, as a whole, the CAIR cap-and-trade program improved visibility more than

[22] *See* Revision to Taconite Federal Implementation Plan, 80 Fed. Reg. 64160 (Oct. 22, 2015); Petition for Administrative Reconsideration of the Partial Disapproval of Air Quality Implementation Plans for Regional Haze for the States of Michigan and Minnesota, EPA-R05-OAR-2015-0196 (Nov. 26, 2013).

[23] *See* Revision to 2013 Taconite Federal Implementation Plan Establishing BART for Taconite Plants, 81 Fed. Reg. 21672 (Apr. 12, 2016).

[24] *See* Petition for Reconsideration and for Stay Pending Reconsideration (with Exhibits) of February 6, 2013 Regional Haze FIP, EPA-R05-OAR-2017-0066-0004 (Nov. 26, 2013); June 13, 2016 Petition for Administrative Reconsideration of April 12, 2016 Regional Haze FIP, EPA-R05-OAR-2017-0067-0005 (June 13, 2016).

[25] *See* Final Action on Petitions for Reconsideration, 82 Fed. Reg. 57125 (Dec. 4, 2017); January 18, 2017 Denial of U.S. Steel's Petition for Reconsideration of February 6, 2013 Regional Haze FIP and April 12, 2016 Revised FIP, EPA-R05-OAR-2017-0066-0008 (Jan. 18, 2017).

[26] *See* Petition for Judicial Review, U.S. Steel Corp. v. U.S. EPA, No. 18-1249 (8th Cir. Feb. 2, 2018).

[27] *See* Revision to Taconite Federal Implementation Plan, 85 Fed. Reg. 6125 (proposed Feb. 4, 2020) (to be codified at 40 CFR Part 52). *See also* Revision to Taconite Federal Implementation Plan; Notice of Public Hearing, 85 Fed. Reg. 60942 (Sept. 29, 2020).

[28] *See* Air Plan Approval; Minnesota; Revision to Taconite Federal Implementation Plan, 86 Fed. Reg. 12095 (Mar. 2, 2021).

implementing BART in states affected by CAIR.[29] A state that chose to participate in the CAIR program did not need to require its BART-eligible EGUs to install, operate, and maintain BART. A state using CAIR as BART for its EGUs still needed a BART determination for PM emissions, as NO_X and SO_2 emissions were addressed by CAIR. However, subsequent legal uncertainty concerning CAIR, as well as several comments received on the draft SIP, led to reconsideration of the decision to allow CAIR to substitute for BART. Therefore, MPCA made BART determinations for subject-to-BART EGUs.

Minnesota was removed from the CAIR program, following the remand of the CAIR program to U.S. EPA, and was later included in the Cross-State Air Pollution Rule (CSAPR), as described in 40 CFR § 52.1240 and 40 CFR § 52.1241. On December 30, 2011, U.S. EPA published in the Federal Register a proposal that CSAPR would result in greater visibility improvement in all Class I areas than implementation of source-specific BART at individual power plants.[30] As a result, MPCA determined that CSAPR served as an alternative to BART for subject-to-BART EGUs and those sources simply needed to comply with their obligations under CSAPR to meet their BART obligations. However, MPCA did include site-specific BART requirements for Xcel Energy - Sherburne Generating Plant to address the requirement in 40 CFR § 51.302(c) related to BART for Reasonably Attributable Visibility Impairment (RAVI).[31]

In MPCA's 2009 Regional Haze SIP and subsequent 2012 SIP supplement, MPCA identified site specific NO_X, SO_2, and PM_{10} BART determinations for EGUs at utility power plants. For Xcel Energy - Sherburne Generating Plant, MPCA identified BART for Units 1 and 2 as low NO_X burners and overfire air on Unit 1 and additional computerized combustion controls for both boilers for NO_X emissions, installation of sparger tubes and lime injection in the existing scrubber for SO_2 emissions, and usage of existing wet electrostatic precipitators as emission controls for PM emissions. It also included daily emission limits for NO_X, SO_2, and PM emissions applicable to the common stack for both boilers.

However, these limits never became finalized as BART requirements when U.S. EPA deferred action on the proposed NO_X and SO_2 limits contained in the SIP submitted by Minnesota. While U.S. EPA approved Minnesota's determination of which sources were subject-to-BART and participation in CSAPR as a BART alternative for SO_2 and NO_X emissions from EGUs, they did not approve the limits to represent BART on a source-specific basis. U.S. EPA stated that they intended to act in the future concerning the BART requirements that apply to Xcel Energy - Sherburne Generating Plant as it was certified as a source of RAVI.[32] Subsequently, U.S. EPA developed a FIP to address the RAVI obligations in the Minnesota SIP.

As a means of settling the claims against the U.S. EPA in National Parks Conservation Association v. EPA, Civ. No. 12-3043 (D. Minn.), U.S. EPA entered into a settlement agreement with Xcel Energy on May 15, 2015. On March 7, 2016, U.S. EPA promulgated a FIP for visibility to establish the emission limits identified in the settlement agreement for Xcel Energy - Sherburne Generating Plant with an effective date of April 6, 2016.[33] These emission limits and associated compliance provisions are identified in the Minnesota RAVI FIP under 40 CFR § 52.1236.

---

[29] *See* Regional Haze Regulations and Guidelines for Best Available Retrofit Technology (BART) Determinations, 70 Fed. Reg. 39104 (July 6, 2005)

[30] *See* Regional Haze: Revisions to Provisions Governing Alternatives to Source-Specific Best Available Retrofit Technology (BART) Determinations, Limited SIP Disapprovals, and Federal Implementation Plans, 76 Fed. Reg. 82219 (Dec. 30, 2011); *see also* Regional Haze: Revisions to Provisions Governing Alternatives to Source-Specific Best Available Retrofit Technology (BART) Determinations, Limited SIP Disapprovals, and Federal Implementation Plans, 77 Fed. Reg. 33642 (June 7, 2012).

[31] *See* Approval and Promulgation of Air Quality Implementation Plans; Minnesota; Regional Haze, 77 Fed. Reg. 34801 (June 12, 2012).

[32] *See id.*

[33] *See* Air Plan Approval; Minnesota; Revision to Visibility Federal Implementation Plan, 81 Fed. Reg. 11668 (March 7, 2016).

2.4. Minnesota's five-year progress report (first implementation period)

The Regional Haze Rule also requires states provide interim progress reports outlining the status of required Regional Haze SIP elements, originally due five years after submittal of each state's initial Regional Haze SIP. The five-year progress report provides states the opportunity to assess, and if necessary, strengthen and/or correct their Regional Haze SIP. It also provides the "opportunity for public input on the state's (and the U.S. EPA's) assessment of whether the approved regional haze SIP is being implemented appropriately and whether reasonable visibility progress is being achieved consistent with the projected visibility improvement in the SIP."[34]

The report reviewed plan elements as specified in 40 CFR § 51.308(g) of the Regional Haze Rule, including:

- Status of control strategies in the Regional Haze SIP
- Emissions reductions from Regional Haze SIP strategies
- Visibility progress
- Emissions progress
- Assessment of changes impeding visibility progress
- Assessment of current strategy
- Review of visibility monitoring strategy
- Determination of Adequacy

The submittal of Minnesota's Regional Haze SIP to U.S. EPA in 2009 set the deadline for submittal of the first implementation period five-year progress report as December 31, 2014. The progress report was required to be in the form of an implementation plan revision that complies with SIP procedural requirements outlined in 40 CFR §§ 51.102-103.

In the progress report, MPCA stated that controls identified in Minnesota's Regional Haze SIP have either been implemented or were expected to be implemented by 2018. Although some of the Regional Haze SIP strategies had not yet produced quantifiable emissions reductions, at the time Minnesota had met the emissions reduction goal from the Northeast Minnesota Plan portion of the long-term strategy. Additionally, although CSAPR had not yet been implemented, Minnesota's power plants reduced emissions to levels below those identified in CSAPR budgets.

When the progress report was submitted both of Minnesota's Class I areas had seen improvements in worst-day visibility conditions, and Minnesota had achieved the reasonable progress goal for Voyageurs and Boundary Waters. Minnesota achieved its statewide modeled 34% emissions reduction in total SO_2 emissions (2002-2018) by 2008 and saw a 63% reduction in SO_2 point-source emissions by 2012. Minnesota achieved a 38% emissions reduction in total NO_X emissions by 2011, nearly reaching its entire (2002-2018) modeled emissions reductions goal of 41% and saw a 52% reduction in NO_X point-source emissions by 2012.

Minnesota did not anticipate any significant changes in either in-state or out-of-state emissions that would impede visibility progress. Based on the already-achieved emissions reductions and reasonable progress goals, and the anticipation of further emissions reductions, Minnesota believed its current Regional Haze SIP strategy was sufficient. Furthermore, Minnesota continued to rely upon participation in the IMPROVE program to meet its monitoring strategy requirements with no modifications to the strategy determined necessary at the time.

[34] U.S. EPA, General Principles for the 5-Year Regional Haze Progress Reports for the Initial Regional Haze State Implementation Plans (Intended to Assist States and EPA Regional Offices in Development and Review of the Progress Reports) 3 (Apr. 10, 2013), https://www.epa.gov/sites/default/files/2016-03/documents/haze_5year_4-10-13.pdf.

MPCA submitted its five-year progress report on December 30, 2014, and determined that Minnesota's Regional Haze SIP was adequate and required no further substantive revision at the time to achieve 2018 reasonable progress goals. U.S. EPA approved Minnesota's progress report on June 28, 2018, with an effective date of July 30, 2018.[35]

3. Objective

The objective of this TSD is not to provide information to support specific control measure decisions leading to the long-term strategy in Minnesota's Regional Haze SIP for the second implementation period. Instead, the TSD supports the development of reasonable progress goals and assesses the contributions to visibility impairment from geographic regions and emissions sectors based on the long-term strategy.

4. Technical support approach and results

U.S. EPA guidance for conducting regional haze modeling analyses is open to some interpretation.[36] In the interest in promoting some consistency among the various States and MJOs, the national emissions inventory collaborative was established first to develop a 2011 model platform, followed by development of the 2016 model platform. Even so, there are differences among approaches taken by various States and/or the RPO in which they belong.

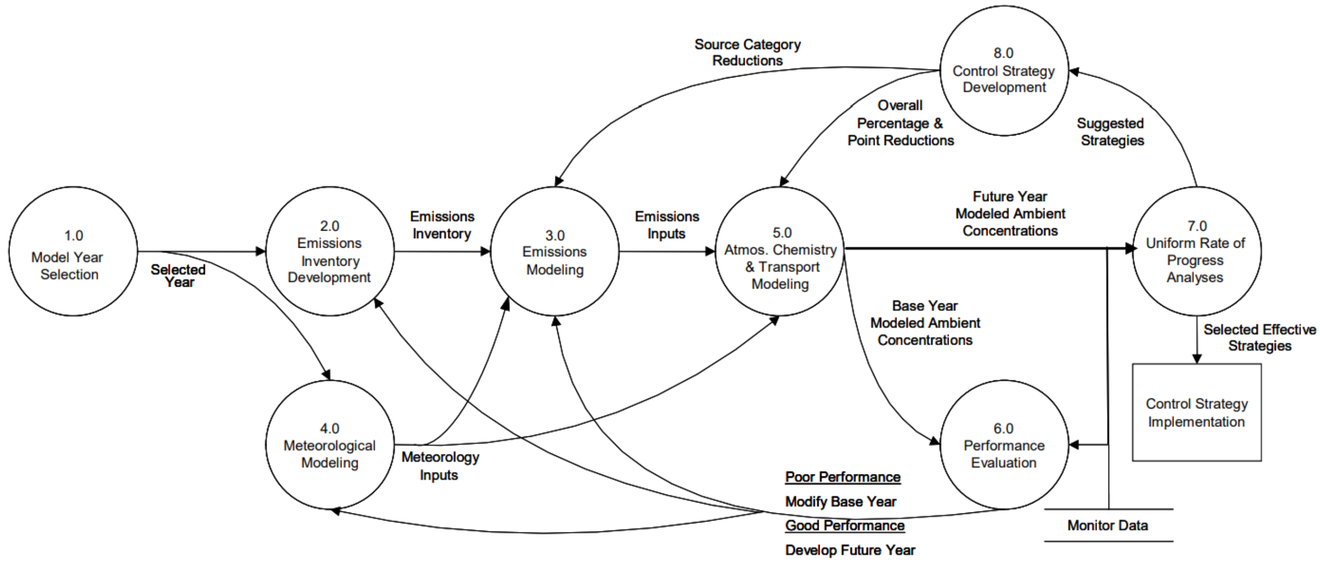
MPCA acted along with other organizations to complete the initial stages of the modeling analysis for the Regional Haze Program, as follows.

- Collaborate with LADCO on emissions that are incorporated
- Participate in the National Emissions Inventory Collaborative
- Obtain from U.S. EPA meteorology and emissions files and programs to process emissions
- Obtain from LADCO replacement emissions files for further processing

Many steps are required when using models to support a reasonable progress goal for Regional Haze. Although many of the parts of the process overlap in practice, for ease of discussion they are identified in this document as a series of steps. Figure 4 illustrates the procedural flow of the ambient air quality modeling analysis to support the Regional Haze SIP. The diagram illustrates the iterative nature of these analyses.

[35] *See* Approval and Promulgation of Air Quality Implementation Plans; Minnesota; Regional Haze Progress Report, 83 Fed. Reg. 30350 (June 28, 2018).
[36] *USEPA 2018 November*

Figure 4. Procedural flow for demonstrating reasonable progress for regional haze



The first step in conducting the model demonstration is to select the period of time to model. Visibility issues occur throughout the year and modeling typically coincides with a year scheduled for emissions inventory development. States develop emissions inventories every three years.

The second step is to develop an emissions inventory of the primarily formed fine particulate ($PM_{2.5}$) and the precursors to the secondarily formed portion of $PM_{2.5}$. These precursors include SO_2, NO_X, volatile organic compounds (VOC) and ammonia (NH_3). The inventory also includes coarse particulate mass ($PM_{10} – PM_{2.5}$). Emissions are caused by human activity (anthropogenic) and by natural processes (biogenic). Biogenic releases are primarily VOCs from vegetation, for example trees. Anthropogenic releases of varied $PM_{2.5}$ precursors are from industrial facilities, power plants, vehicles and household sources such as residential wood burning.

Steps three through five are more fluid. Meteorological modeling output (step four) is both an input to emissions modeling (step three) and to air quality modeling (step five). Emissions modeling output is an input to air quality modeling (step five). Emissions models take the emissions inventory from step five and prepare them for input to the air quality model. Meteorological data is processed through meteorological models. The air quality model simulates the transport of emissions and chemical reactions in the atmosphere to produce ambient air concentrations of the component species of $PM_{2.5}$, sulfate (SO_4), nitrate (NO_3), organic carbon (OC), elemental carbon (EC) ammonium (NH_4) and soil, and of the coarse particulate.

The results of the air quality modeling are evaluated against monitoring data over the same time period in step six, model performance evaluation. Statistical analyses and other means are used to compare modeled results with observed concentrations. Should the model performance evaluation indicate poor correlation, adjustments could be made to the modeling system. Adjustments could be made to the size, coverage and grid-resolution of the domain, the time period modeled, the inventory, the emissions modeling, the meteorological modeling or the air quality model (e.g. revising code). The ambient monitors and how they collect samples also could be explored. Good model performance means that various permutations, such as attempts to predict emissions in future years, can be incorporated in the modeling with some degree of accuracy.

Successful development of future year emissions leads to the uniform rate of progress analysis and tracking of visibility progress in step seven. This analysis establishes where future visibility falls along a uniform rate of progress line, or glidepath, toward natural background visibility conditions. The modeling alone does not dictate reasonable progress goals, nor does it determine whether the goals have been met. It does, however, provide a haze index value that reflects reasonable emission reduction or control measures which in turn is the goal. Potentially reasonable control measures are quantified in step eight.

Each of the steps summarized above are discussed in more detail below as they apply to the air quality modeling analysis for the second implementation period of the Regional Haze Program.

4.1. Model year selection

The inventory collaborative agreed upon 2016 as the base year to determine reasonable progress for the second implementation period. Comprehensive modeling emissions inventories for regulatory purposes are typically developed on a three-year schedule. The previous full modeling inventory was developed for 2011 which suggests the next two inventories would be scheduled for 2014 and 2017. An evaluation of data available for 2014 indicated it was an atypical year for ozone formation, attainment of the National Ambient Air Quality Standard for ozone being another regulatory purpose for the inventory, but 2016 was promising. At the time, year 2017 would have required an extensive wait for data to become available. The inventory collaborative proceeded to develop the 2016 base year platform and project emissions to 2028 from 2016 for regional haze. Unlike other RPOs, the Western Regional Air Partnership (WRAP) separately developed a 2014 modeling platform for regional haze.[37]

4.2. Emissions inventory development

For the most part, base year inventories are developed by each individual state. These are the same inventories states report to the U.S. EPA for the National Emissions Inventory (NEI). MPCA submits to the NEI emissions every year from larger facilities with air permits, such as electric power plants and refineries. Submittals for other emission sources are every three years, for example dry cleaners, gasoline service stations, residential wood combustion, cars, trucks, agricultural and construction equipment and fire. MPCA develops emissions for some of the other emissions sources such as residential wood combustion and for others MPCA adopts emissions calculated by U.S. EPA such as gasoline service stations, wildfire and VOC emissions from trees.

The emissions for larger permitted facilities are calculated as an annual average by facility process. Other emissions sources are typically calculated as an annual average aggregated by county. Emissions of individual VOC species are lumped into a total VOC for the $PM_{2.5}$ precursor emissions.

Development of the 2016 modeling platform, detailed in Section 4.3, started with the 2014 NEI version 2 and built from there. NEI 2016 data supplanted the 2014 as it became available. And MPCA supplanted 2016 emissions with more typical 2017 emissions for some taconite facilities that were not operating, or not operating at full capacity in 2016.

4.3. Emissions modeling

Minnesota's modeling platform consists of the U.S. EPA 2016 modeling platform, version 1 with some parts replaced with those provided by LADCO; culminating in a 2016 modeling platform version 1b.[38] The modeling platform consists of meteorology, emissions and other inputs needed to run an air quality model.

---

[37] *Unlike the other RPOs, the WRAP continued to develop a 2014 modeling platform for regional haze. WRAP technical support system for regional haze planning, 2021-09-30, https://views.cira.colostate.edu/tssv2/Docs/WRAP_TSS_emissions_reference_final_20210930.pdf*

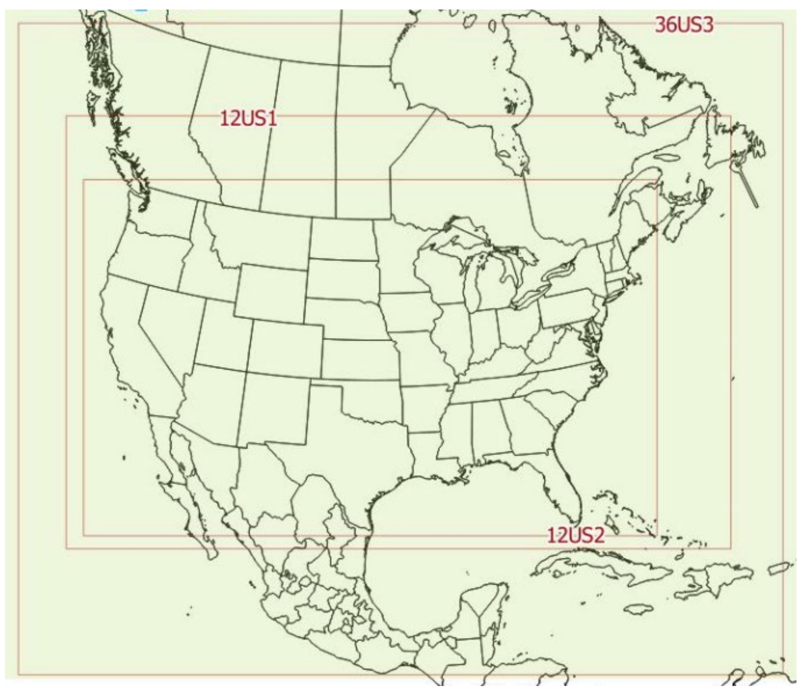
[38] *USEPA 2021 March*

The comprehensive nationwide emissions inputs were developed by the National Emissions Inventory Collaborative, a group of state, local, tribal, regional, and federal air planning agencies.[39] The regional air planning agencies are the RPOs, such as LADCO. The federal air planning agencies include U.S. EPA and FLMs. U.S. EPA processed, packaged, and distributed the emissions in a model ready format along with job scripts and programs to reformat files for other model applications.[40] Much of the U.S. EPA distributed emissions were retained, but industry and power generation sector emissions were replaced with those processed and distributed by LADCO. MPCA further processed all emissions inputs, and other miscellaneous inputs, for its own photochemical model application.

Emissions inputs. Model-ready emissions inputs for the 2016 model platform were primarily developed with the Sparse Matrix Operator Kernel Emissions (SMOKE) tool version 4.7 with some updates.[41] SMOKE spatially and temporally allocates emissions for input to the air quality model. The air quality model requires hourly emissions allocated to either points, with a longitude and latitude coordinate, or into grid cells of a defined size. The grid size chosen depends on the extent of the domain and computational resources.

The U.S. EPA platform domain includes the 48 states of the contiguous United States and parts of Canada and Mexico. There are three grids, two smaller grids nested within a larger grid, as shown in Figure 5. SMOKE derived emissions for two modeling domains comprised of two grid cell sizes. The largest domain "36US3" has 36 km resolution grid cells and the inner "12US1" has 12 km resolution grid cells. For air quality model computations, U.S. EPA extracted a smaller domain "12US2" from "12US1".

Figure 5. 2016 Model Platform domains



SMOKE also allocates emissions species into those required by the air quality model using speciation profiles by emissions sector. Emissions species prepared for SMOKE include all criteria air pollutants and

[39] *National Inventory Collaborative. 2016v1 emissions modeling platform, http://views.cira.colostate.edu/wiki/wiki/10202/inventory-collaborative-2016v1-emissions-modeling-platform*
[40] *Baek, Bok Haeng, 2019, "National Emission Inventory (NEI) 2016 modeling platform version 1", https://doi.org/10.15139/S3/KTP4WB, UNC Dataverse, V1*
[41] *SMOKE 4.7 documentation, https://www.cmascenter.org/help/documentation.cfm*

their precursors; carbon monoxide (CO), lead, SO_2, NO_X, VOC, NH_3, $PM_{2.5}$ and coarse particulate mass. Some emissions species included are hazardous to health; chlorine (Cl), hydrogen chloride (HCl), benzene, acetaldehyde, formaldehyde, methanol, and naphthalene. How SMOKE allocates emissions species depends on the chemical mechanism applied in the air quality model. Emissions for the 2016 model platform were prepared for the Carbon Bond 6 chemical mechanism.

Emissions were combined into sectors based on the similarity of the techniques used to process the emissions. U.S. EPA and LADCO have assigned abbreviations to identify the iteration of a particular emission sectors development. Table 1 below contains the source of emissions for each sector in the 2016 Model Platform version v1b.

“Sector grouping” refers to the emissions summary tables elsewhere in this document and reflect how emissions were aggregated into files for the air quality model to track the source of the emissions. “Platform sector abbreviation” cross-references the sector grouping with information in the U.S. EPA or LADCO 2016 platform. “Platform sector description” describes the sector abbreviations in the U.S. EPA or LADCO platform. “Source 2016” and “Source 2028” indicate the iteration and or configuration of the 2016 base and 2028 projection emissions, respectfully. The U.S. EPA “f” represents the modeling platform iteration and the “h” represents the eighth configuration for most sectors of this platform; the “i” being the ninth configuration for airports. The LADCO “v1b” represents substitute emission estimates for the electric power sector (ERTAC version 16.1) and other facilities that emit through stacks. LADCO v1b also includes the 2028 projection for U.S. EPA 2016fi airport emissions, as the future year projection was not available from U.S. EPA.

Although the model platform retains the v1b version number, it actually includes LADCO “v1b2” for post-ERTAC 16.1—as of September 2020—retirements of additional electric power generating units.

Table 1. Source of emissions for each sector in 2016 Model Platform version 1b

Sector grouping	Platform sector abbreviation	Platform sector description	Source 2016	Source 2028
Agriculture	ag	Livestock and fertilizer application	USEPA 2016fh	USEPA 2028fh
Area	nonpt	Remaining sources due to human population activity data (not emitted through stacks)	USEPA 2016fh	USEPA 2028fh
	othar	Non-road equipment and other nonpoint sectors in Canada and Mexico	USEPA 2016fh	USEPA 2028fh
Dust	afdust_adj	Fugitive dust from roads, building and road construction, agricultural tilling, mining and quarrying (not at industrial facilities)	USEPA 2016fh	USEPA 2028fh
	othafdust_adj	Fugitive dust from roads, building and road construction in Canada	USEPA 2016fh	USEPA 2028fh
	othptdust_adj	Fugitive dust from agricultural tilling in Canada	USEPA 2016fh	USEPA 2028fh
Electric Generating Units (EGU)	ptertac	Electric power generation	LADCO 2016v1b	LADCO 2028v1b2

Sector grouping	Platform sector abbreviation	Platform sector description	Source 2016	Source 2028
Fire	ptagfire	Agricultural fires	USEPA 2016fh	USEPA 2016fh
	ptfire_othna	Wild and prescribed fires in Canada & Mexico	USEPA 2016fh	USEPA 2016fh
	ptfire	Wild and prescribed fires	USEPA 2016fh	USEPA 2016fh
Industry	ptmntaconite	"Typical" taconite mine emissions that account for facilities/units not operating or not operating at full capacity in 2016 in Minnesota	LADCO 2016v1b	LADCO 2028v1b
	ptnonertac	Remaining units that emit through stacks not covered in other sectors	LADCO 2016v1b	LADCO 2028v1b
	othpt	Point sources from Canada and Mexico	USEPA 2016fh	USEPA 2028fh
Natural	beis	Natural vegetation	USEPA 2016fh	USEPA 2016fh
	seasalt	Ocean salt	Calculated_2016	Calculated_2016
Off-Road	airports	Aircraft up to 3,000 feet elevation and ground support equipment	USEPA 2016fi	LADCO 2028v1b
	cmv_c1c2	Category 1 and 2 commercial marine vessels in State and Federal waters, and non-US waters	USEPA 2016fh	USEPA 2028fh
	cmv_c3	Category 3 commercial marine vessels	USEPA 2016fh	USEPA 2028fh
	nonroad	Vehicles that do not travel by road, excluding commercial marine, rail and aircraft. Includes recreational vehicles, pleasure craft, construction, agricultural, mining and lawn and garden equipment.	USEPA 2016fh	USEPA 2028fh
	rail	Line haul rail locomotives, including freight and commuter rail	USEPA 2016fh	USEPA 2028fh
Oil/Gas	np_oilgas	Oil and gas upstream activities of exploration and drilling wells, and equipment to extract the product and deliver it to a central collection point or processing facility. Includes separators, dehydrators, storage tanks, and compressor engines.	USEPA 2016fh	USEPA 2028fh
	pt_oilgas	Oil and gas upstream exploration, production, pipeline-transportation, and distribution emissions sources, both onshore and offshore.	USEPA 2016fh	USEPA 2028fh

Sector grouping	Platform sector abbreviation	Platform sector description	Source 2016	Source 2028
On-Road	onroad	Gasoline and diesel-powered vehicles, moving and non-moving, that travel on roads. Includes refueling, exhaust, extended idle, auxiliary power, evaporation, permeation, and break and tire wear. Excludes California	USEPA 2016fh	USEPA 2028fh
	onroad_ca_adj	Gasoline and diesel-powered vehicles that travel on roads for California only	USEPA 2016fh	USEPA 2028fh
	onroad_can	Gasoline and diesel-powered vehicles that travel on roads in Canada	USEPA 2016fh	USEPA 2028fh
	onroad_mex	Gasoline and diesel-powered vehicles that travel on roads in Mexico	USEPA 2016fh	USEPA 2028fh
Residential Wood Combustion (RWC)	rwc	Residential wood combustion	USEPA 2016fh	USEPA 2028fh

Explore emissions inputs for modeling Minnesota 2028 interim visibility goals

This interactive tool shows the emissions input to the atmospheric chemistry model to develop our visibility goals at Minnesota Class I areas.

MPCA has developed an interactive online tool accessible from the Pollution Control Agency website (ctrl + click on icon above)[42] that allows the user to explore the base year 2016 emissions and the change in emissions from the 2016 to the 2028 projection emissions. The tool provides spatial maps showing the gradient of emissions across the entire domain and by region and provides graphs of the emissions by pollutant and by sector grouping. The tool provides the same emissions as a monthly profile. Finally, the tool examines 2016 and 2028 emissions by individual Minnesota facilities that make up about 80 percent of emissions from all facilities in the State. Hovering over various places in the tool reveal additional information, for example in the Minnesota facilities tab hovering over an up or down arrow may provide known reasons for an emission change from the base year to the future year.

Base year inventory - 2016. For some sectors, methods initially available to states for emissions inventory development described in Section 4.2 were inadequate for air quality modeling. For these sectors, the national emissions inventory collaborative is invaluable to support improvement of state-developed inventories where the other methodology, insufficient for modeling purposes, was used. For example, it is important to have accurate ammonia emissions because ammonia combines with sulfuric and nitric acid to form aerosol sulfate and nitrate, significant components of $PM_{2.5}$ and of visibility impairment. Also, states do not create inventories for biogenic sources, so these inventories had to be

[42] *https://public.tableau.com/app/profile/mpca.data.services/viz/Regionalairemissions2016platform/Viewbysector#1*

created for modeling purposes. The collaborative also limited the variation in the emissions characterization of a state among those in the RPO in which it is a member and other RPOs (which commonly occurred during the first implementation period).

LADCO prepared both an "actual" and "typical" emissions inventory for Minnesota. The actual emissions inventory was only used for evaluating air quality model performance. The typical emissions inventory was used for establishing RPGs and for the contribution assessment described in Section 4.8.3. of this document. Table 2 below contains 2016 typical emissions in tons per year by sector for the contiguous United States, Canada, Mexico and offshore regions within the 12US2 domain.

Table 2. 2016 base year typical annual emissions in tons by region and sector[43]

Contiguous United States							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Agriculture		3,420,000					176,000
Area	2,650,000	78,900	713,000	572,000	465,000	139,000	3,510,000
Dust				7,200,000	1,000,000		
EGU	613,000	26,300	1,290,000	173,000	132,000	1,520,000	37,700
Industry	1,460,000	64,500	977,000	398,000	256,000	691,000	744,000
Oil/gas	925,000	4,350	907,000	24,200	23,900	52,200	3,180,000
On-road	19,100,000	89,300	3,410,000	217,000	106,000	26,000	1,930,000
Off-road	11,100,000	2,220	1,940,000	138,000	130,000	20,900	1,300,000
RWC	2,130,000	15,600	31,500	320,000	319,000	7,750	305,000
Fire	14,000,000	291,000	238,000	1,500,000	1,260,000	115,000	2,530,000
Natural	7,120,000		1,470,000				40,100,000
Canada							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Area	2,100,000	3,600	265,000	232,000	192,000	13,900	622,000
Dust				714,000	148,000		
Industry	511,000	352,000	233,000	63,800	24,800	511,000	373,000
On-road	1,180,000	5,200	273,000	17,800	9,550	1,210	112,000
Fire	346,000	5,730	7,500	37,700	31,900	3,430	60,400
Natural	1,240,000		114,000				7,660,000
Mexico							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Area	198,000	171,000	183,000	92,600	43,700	6,170	418,000
Industry	170,000	4,560	365,000	63,600	49,600	428,000	60,400
On-road	1,590,000	2,430	389,000	12,900	9,080	5,260	158,000
Fire	291,000	5,660	12,900	33,200	28,100	2,040	91,400
Natural	1,120,000		145,000				4,960,000

[43] *Emissions are back-calculated from the air quality modeling files used in this analysis. The lumped model species are not constant but can vary depending on the speciation profile. Emission total differences of VOC can vary by sector as large as 10%, or higher, between totals calculated before and after speciation.*

Offshore							
Sector	CO	NH_3	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC
Oil/gas	50,900	18.0	49,500	689	687	699	59,400
Off-road	60,200	365	523,000	20,500	18,900	106,000	29,000

The only difference between the actual and typical emissions inventories involves the characterization of emissions from some of the taconite facilities in Minnesota. During the first implementation period, U.S. EPA promulgated a FIP for taconite facilities subject-to-BART. Some of these facilities were either not operating or operating at reduced production in 2016. To simulate the impact of the control measures in the FIP this implementation period, MPCA substituted the 2016 emissions with emissions from 2017, the typical case. This allowed MPCA to represent the emissions changes in 2028.

Table 3 contains annual actual and typical 2016 emissions in tons from four of six taconite facilities for which MPCA had information on the U.S. EPA FIP at the time the modeling was conducted. The two facilities for which FIP limits were unknown are Hibbing Taconite Company and Cleveland Cliffs (formerly ArcelorMittal) Minorca Mine. The four facilities for which U.S. EPA advised MPCA on FIP limits are US Steel Corp – Minntac, US Steel Corp – Keetac, United Taconite LCC – Fairlane Plant and Northshore Mining Co – Silver Bay.

The actual emissions represent the standard SMOKE processing of 2016 annual emissions into hourly air quality model input. In all but one case the typical emissions represent SMOKE processing of a full year of Continuous Emission Monitoring System (CEMS) data of NO_X and SO_2 emission rates in pounds per hour and heat input rates in Million British Thermal Units (MMBtu) per hour provided by the taconite companies. CEMS data for 2016 was used for US Steel Corporation – Minntac. CEMS data for 2017 was used for US Steel Corporation – Keetac and United Taconite LCC – Fairlane Plant. MPCA used 2017 annual emissions for Northshore Mining Co – Silver Bay for the typical case because the two units affected by the FIP would be idled in 2028 and did not require hourly adjustments of CEMS data for the projection.

MPCA processed the CEMS data into SMOKE input files for LADCO to generate the air quality model input files. To address the extra day in February for the leap year 2016, each hour CEMS value was interpolated by averaging the hour value of the day before and after in the 2017 data.

Table 3. Actual and typical 2016 emissions for taconite facilities advisedly affected by U.S. EPA FIP

Inventory pollutant	US Steel Corp Minntac		US Steel Corp Keetac		United Taconite LCC Fairlane Plant		Northshore Mining Co Silver Bay	
	Actual tons	Typical tons	Actual tons	Typical tons	Actual tons	Typical tons	Actual tons	Typical tons
CO	450	449	0.0	61.4	21.9	58.9	254	197
NH_3	20.2	20.1	0.0	0.0	0.016	0.046	3.49	0.319
NO_X	6,380	6,430	0.0	5,030	1,010	3,790	2,400	2,180
PM_{10}	2,370	2,370	28.6	527	192	585	374	453
PM_{25}	1,750	1,750	8.48	405	127	401	225	319
SO_2	1,150	1,160	0.0	536	167	278	1,470	1,540
VOC	140	140	0.0	36.7	11.3	34.3	21.3	14.8

Future year inventory – 2028. The national emissions inventory collaborative used methods specific to the type of emissions source to project emissions to 2028. Some methods involved projection models. For example, LADCO incorporated electric generating unit emissions projected by the Eastern Regional

Technical Advisory Committee (ERTAC) model version 16.1.[44] Other sectors were projected using forecast information from sector organizations and other methodologies.

EGU retirement forecasts. In its Regional Haze modeling TSD[45], LADCO lists 60 known or planned electric power generating unit retirements in LADCO states between 2016 and 2058 that may or may not have been included in the ERTAC 16.1 model. The purpose of the list was to identify announced retirements that came after the ERTAC 16.1 emissions were developed but will occur before the end of 2028. Of the 60 units listed—known as of September 2020—46 retirements take place by 2028. Minnesota has 23 units at nine facilities on the list, of which 14 units from five facilities are slated for retirement by 2028. Two units totaling nearly 5,000 tons NO_X and 760 tons SO_2 planned for retirement in 2023 and 2026 at Xcel Energy – Sherburne Generating Plant were included in ERTAC 16.1. LADCO made some post-ERTAC 16.1 emissions adjustments for other units on the list by zeroing out 2028 emissions for 11 electric power generating units at three facilities in Minnesota, Blue Lake Generating Plant (4 units totaling 28 tons NO_X in 2023), Inver Hills (6 units totaling 19 tons NO_X and 2 tons SO_2 in 2026) and Xcel Energy – Allen S King (1 unit at 1,380 tons NO_X and 1,505 tons SO_2 in 2028). One unit emitting 375 tons NO_X and 39 tons SO_2 in 2016 at Benson Power Biomass Plant was physically retired in 2018 but was not retired in the 2028 forecast because the facility was allocated to the 'ptnonertac' sector rather than the 'ptertac' sector. In emissions modeling, EGUs supplying electricity to the electric grid are assigned to the 'ptertac' sector to which ERTAC 16.1 and zero out was applied.

Table 4 contains the list of Minnesota EGU implemented and planned retirements on the LADCO list, and how they were characterized in the 2028 air quality modeling input files. According to this list, an expected reduction in emissions of a total 4,480 tons NO_X and 8,960 tons SO_2 will appear in the third implementation period (2028 – 2036) of the Regional Haze program due to planned EGU retirements during this period.

Table 4. Minnesota EGU retirements since 2016, implemented and planned as of September 2020

Oris ID	BLRID	Retirement year	Facility name	Sector	NO_X tons		SO_2 tons		Retirement treatment in model
					2016	2028	2016	2028	
1897	3	2048	Minnesota Power - Hibbard Renewable Energy	ptnonertac	311	311	57	57	N/A - post 2028
	4				152	152	33	33	
1904	5	2032	Black Dog	ptertac	67	67	3	3	N/A - post 2028, #6 not in 2016 files
	6	2058		N/A					
1913	1 - 6	2026	Inver Hills	ptertac	19	0	2	0	Zero out
1915	1	2028	Allen S King	ptertac	1,380	0	1,505	0	Zero out
1927	9	2049	Riverside (1927)	ptertac	77	78	3	3	N/A - post 2028
	10				77	77	3	3	

[44] *Eastern Regional Technical Advisory Committee (ERTAC) Electricity Generating Unit Emission Projection Tool. https://www.epa.gov/air-emissions-inventories/eastern-regional-technical-advisory-committee-ertac-electricity*
[45] *LADCO 2021*

Oris ID	BLRID	Retirement year	Facility name	Sector	NO_X tons		SO_2 tons		Retirement treatment in model
					2016	2028	2016	2028	
6090	2	2023	Sherburne County	ptertac	1,929	0	306	0	ERTAC 16.1
	1	2026			3,057	0	451	0	
	3	2030			3,483	4,007	7,748	8,916	N/A - post 2028
8027	1	2023	Blue Lake Generating Plant	ptertac	7	0	0	0	Zero out
	2				9	0	0	0	
	3				6	0	0	0	
	4				6	0	0	0	
	7	2034			15	14	0	0	N/A - post 2028
	8				16	16	0	0	
55867	BLR-1	2018	Benson Power Biomass Plant	ptnonertac	375	375	39	39	None

Taconite FIP emissions for the projected typical emissions inventory. LADCO prepared a 2028 projected "typical" emissions inventory for Minnesota by incorporating state provided emissions projections for taconite facilities that apply FIP limits from the first implementation period.

MPCA estimated the emissions reduction needed to meet the FIP limit by focusing on the CEMS data that showed the indurating furnace exceed what would become the FIP limit. To compare heat input and emissions data from hourly CEMS readings with the current FIP limits, MPCA converted the hourly CEMS data into the units equivalent to those used for the FIP limits, a 720-hour rolling average NO_X emission rate in lb/MMBtu and a 720-hour rolling average SO_2 emission rate in lb/hour. The needed reduction to meet the FIP was calculated for each hour, with the assumption the heat input rate would stay the same in future. The calculation was done for all 8760 hours in the year (8784 hours in the leap year) to obtain annual emissions for the year, which then allowed for estimating the average annual percent reduction, shown in Table 5.

Table 5. Estimated average annual percent reduction at taconite facilities due to FIP

Facility name[46]	Unit name	NO_X % change	SO_2 % change
US Steel Corporation - Minntac	Line 3	-36	0
	Line 4	-33	0
	Line 5	-34	0
	Line 6	-33	0
	Line 7	-37	0
US Steel Corporation - Keetac	Grate Kiln	-73	0

[46] *U.S. Steel - Minntac percent reduction is for 2016 to 2028, U.S. Steel - Keetac percent reduction is for 2017 to 2028, and United Taconite - Fairlane Plant reduction is for 2017 to 2028.*

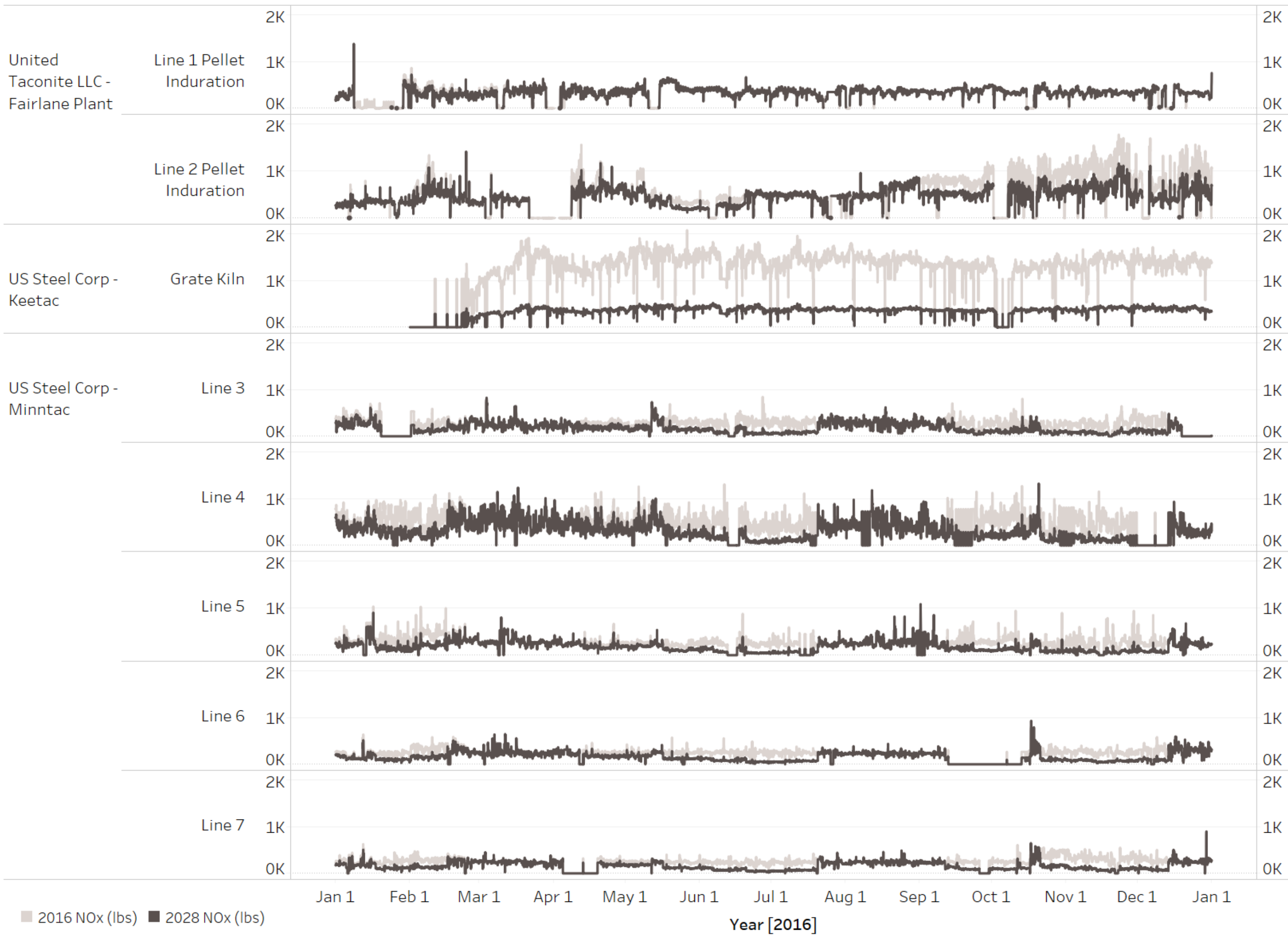
Facility name[46]	Unit name	NO_X % change	SO_2 % change
United Taconite LLC - Fairlane Plant	Line 1 Pellet Induration	-2	0
	Line 2 Pellet Induration	-23	0

Minnesota considers the taconite emissions projection fairly conservative—post-FIP controls resulting in lower emissions—for a few reasons:

- The calculations determine the hourly reduction needed to meet the applicable limit
- The hourly reduction is applied only to the specific hour of emissions, while keeping the heat input static
- While some hours of the year didn't need a percent reduction to meet the FIP limit and were retained at the measured emission level, low-NO_X burners presumably would provide additional control during these times

Figure 6 shows the hourly CEMS data prepared for input to the air quality model for each applicable taconite facility and unit. The light gray lines are the base year 2016 NO_X measurements, and the dark gray lines are the 2016 NO_X measurements adjusted to reflect post-FIP controls in 2028. Individual hourly 2028 NO_X emission adjustments shown in the Figure are a function of heat input and fuel type—natural gas, coal, biomass combusted within a unit—product production capacity, and uptime/downtime of the emission unit or CEM.

Figure 6. Minnesota taconite facility CEMs of typical 2016 and 2028 adjusted for post-FIP controls, NO_X in pounds per hour



At the time the 2016 modeling platform version v1b was developed, the data was not available for MPCA to apply the FIP calculation method to Hibbing Taconite Company, from which we now expect about a 54% reduction in NO_X and Cleveland-Cliffs Minorca Mine, from which we now expect about a 65% reduction in NO_X.

Table 6 contains modeled 2028 emissions—projected from 2016 typical—in tons per year by sector for the contiguous United States, Canada, Mexico and offshore regions within the 12US2 domain.

Table 6. 2028 future year annual emissions in tons by region and sector[47]

Contiguous United States							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Agriculture		3,580,000					186,000
Area	2,680,000	80,000	711,000	596,000	486,000	107,000	3,590,000
Dust				7,280,000	1,020,000		
EGU	728,000	57,700	898,000	156,000	130,000	913,000	40,200
Industry	1,480,000	64,700	966,000	403,000	261,000	601,000	745,000
Oil/gas	958,000	4,410	911,000	29,300	28,800	73,700	3,800,000
On-road	9,930,000	78,400	1,150,000	168,000	49,700	10,400	866,000
Off-road	11,700,000	2,470	1,380,000	84,000	78,200	39,600	1,000,000
RWC	2,040,000	14,700	32,300	302,000	302,000	6,830	292,000
Fire	14,000,000	291,000	238,000	1,500,000	1,260,000	115,000	2,530,000
Natural	7,120,000		1,470,000				40,100,000
Canada							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Area	2,040,000	3,440	190,000	219,000	171,000	13,500	637,000
Dust				837,000	169,000		
Industry	568,000	491,000	199,000	55,200	27,800	372,000	369,000
On-road	930,000	4,110	115,000	18,600	6,600	535	46,700
Fire	346,000	5,730	7,500	37,700	31,900	3,430	60,400
Natural	1,240,000		114,000				7,660,000
Mexico							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Area	229,000	169,000	212,000	96,900	47,100	6,570	509,000
Industry	215,000	6,580	420,000	80,900	61,700	390,000	87,900
On-road	1,410,000	3,260	346,000	15,400	10,200	7,180	164,000
Fire	291,000	5,660	12,900	33,200	28,100	2,040	91,400
Natural	1,120,000		145,000				4,960,000
Offshore							
Sector	**CO**	**NH_3**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**VOC**
Oil/gas	50,900	16.9	49,400	692	690	819	59,600
Off-road	79,400	335	496,000	18,800	17,400	51,300	38,100

[47] Emissions are back-calculated from the air quality modeling files used in this analysis. The lumped model species are not constant but can vary depending on the speciation profile. Emission total differences of VOC can vary by sector as large as 10%, or higher, between totals calculated before and after speciation.

4.4. Meteorological modeling

Meteorology for the 2016 model platform was prepared for input to both the emissions model—some emission sources depend on meteorology for the calculations—and the air quality model using the meteorological model Weather Research and Forecasting (WRF) version 3.8. WRF simulated mesoscale and regional scale atmospheric circulation every hour the entire year 2016 allocated to both a 36km and 12km gridded resolution domain with 35 vertical layers. U.S. EPA conducted an evaluation of the meteorological model output compared to measurements and determined the WRF simulations reasonably approximate the actual meteorology for regional haze purposes.[48] In the air quality model, meteorology remains constant in the base year and future projected year, 2028. The meteorological inputs were provided by U.S. EPA through its contract with CSRA LLC and distributed through the Intermountain West Data Warehouse.[49] The WRF data was processed for air quality input with the WRFCAMx program version 3.4.

4.5. Atmospheric chemistry and transport modeling

MPCA conducted modeling with the emissions modeling output and meteorological input described above. The foundation for the air quality model input processing was provided by U.S. EPA in an electronic file package named “smoke_2016v1_platform_core_04feb2020”. U.S. EPA and LADCO both had processed emissions through the SMOKE emissions model for input to the Community Multiscale Air Quality (CMAQ) model.[50] The file package from U.S. EPA included Fortran programs and shell script templates MPCA used to convert CMAQ files for input to the Comprehensive Air quality Model with extensions (CAMx) model.[51]

Both CMAQ and CAMx are Eulerian models that compute a numerical solution on a fixed grid. The models simulate atmospheric and surface processes affecting the transport, chemical transformation and deposition of air pollutants and their precursors. CAMx also allows for tracking the original source of particulate species by geographic region or source sector with the module Particulate Source Apportionment Technology (PSAT), which MPCA applied for a contribution assessment. MPCA used CAMx version 7.00 to develop the RPGs and CAMx version 7.10 to conduct a contribution assessment. Table 7 contains the MPCA configuration for running the CAMx model.

Table 7. CAMx model configuration

Science options	Simulation	
	2016 v1b (actual, typical), 2028 (typical)	2028 source apportionment
Version	Version 7.00	Version 7.10
Vertical grid mesh	35 layers, no collapsing	35 layers, no collapsing
Horizontal grids	12 km, 396 columns x 246 rows	12 km, 396 columns x 246 rows
Map projection parameters	Lambert conformal conic spheroid Longitude pole: -97 deg Latitude pole: 40 deg	Lambert conformal conic spheroid Longitude pole: -97 deg Latitude pole: 40 deg

[48] USEPA 2019 July
[49] Intermountain West Data Warehouse. https://views.cira.colostate.edu/iwdw/RequestData/Default.aspx
[50] CMAQ model at https://www.epa.gov/cmaq
[51] CAMx model at https://www.camx.com/

Science options	Simulation	
	2016 v1b (actual, typical), 2028 (typical)	2028 source apportionment
	True latitude1: 33 deg True latitude2: 45 deg Southwest corner X,Y coordinate: -2412, -1620 km	True latitude1: 33 deg True latitude2: 45 deg Southwest corner X,Y coordinate: -2412, -1620 km
Initial conditions	10 days spin-up	10 days spin-up
Boundary conditions	12km hemispheric CMAQ day specific	12km hemispheric CMAQ day specific
Chemistry		
Gas phase chemistry	CB6r4 gas phase mechanism	CB6r4 gas phase mechanism
Aerosol chemistry	CF2E coarse/fine particle size distribution + elements ISORROPIA inorganic gas-aerosol partitioning Secondary Organic Aerosol Processor (SOAP) version 2.2 organic gas-aerosol partitioning	CF2E coarse/fine particle size distribution + elements ISORROPIA inorganic gas-aerosol partitioning Secondary Organic Aerosol Processor (SOAP) version 2.2 organic gas-aerosol partitioning
Aqueous chemistry	Regional Acid Deposition Model (RADM)-like	Regional Acid Deposition Model (RADM)-like
Photolysis mechanism	Tropospheric Ultraviolet and Visible (TUV) radiation model version 4.8 with Total Ozone Mapping Spectrometer (TOMS) ozone column data	Tropospheric Ultraviolet and Visible (TUV) radiation model version 4.8 with Total Ozone Mapping Spectrometer (TOMS) ozone column data
Source attribution		
Source apportionment	None	Particulate Source Apportionment (PSAT)
Vertical transport		
Diffusivity scheme	K-theory	K-theory
Vertical diffusivity corrections	Yonsei University (YSU) Kv-patch	Yonsei University (YSU) Kv-patch
Planetary boundary layer	K-theory	K-theory
Deposition scheme	Zhang 2003 Default surface resistance for ammonia (RSCALE=1)	Zhang 2003 Default surface resistance for ammonia (RSCALE=1)
Numerics		
Gas phase chemistry solver	Euler backward iterative (EBI)	Euler backward iterative (EBI)
Horizontal advection scheme	Piecewise parabolic method (PPM)	Piecewise parabolic method (PPM)

Science options	Simulation	
	2016 v1b (actual, typical), 2028 (typical)	2028 source apportionment
Parallelization	OpenMP-Message Passing Interface (OMP-MPI)	OpenMP-Message Passing Interface (OMP-MPI)
Output		
Species names	NO, NO2, O3, SO2, H2O2, HNO3, NH3, PNO3, PSO4, PNH4, POA, PEC, FPRM, CPRM, CCRS, FCRS, SOA1, SOA2, SOA3, SOA4, SOPA, SOPB, NA, PCL, PH2O, PFE, PMG, PMN, PCA, PK, PAL, PSI, PTI	PN3, PN4, PS4

The U.S. EPA file package also included the OCEANIC version 4.1.1 program which MPCA used to create sea salt emission input files for the CAMx model. Sea salt emissions are created with the meteorology described above, and files for land use, saltwater mask and dimethylsulfide concentrations.

Initially, emissions and meteorology were generated by U.S. EPA for every hour and allocated to 36km grids over the 36US3 domain and 12km grids over the 12US1 and 12US2 domains shown in Figure 5. U.S. EPA distributed emissions for the 12US1 domain and in the file package provided a program and template shell scripts to window the emissions down to the 12US2 domain. Minnesota windowed the inputs to the 12US2 domain described in the top section of Table 7. This domain was agreed upon by the inventory collaborative as the basic domain from which to model, but more importantly, it requires fewer computational resources than the full 12US1 domain, and the initial and boundary condition files provided by U.S. EPA were for the 12US2 domain. Initial and boundary conditions were distributed through the Intermountain West Data Warehouse.[52] They are described further below.

Initial Conditions. Air quality models require an initial emissions file to input as a starting point from which to model. Effects of the initial condition concentrations on modeling results are mitigated by simulating a ramp-up period of several days prior to the beginning of the desired model results. MPCA used the initial conditions file distributed by U.S. EPA, however only one file was distributed presuming the CAMx model simulation would run the full year sequentially by days. Because MPCA broke up the simulation into smaller chunks, MPCA created new initial condition files that coincide with the simulation start dates.

Boundary Conditions. U.S. EPA developed boundary condition files generated with a hemispheric version of CMAQ that incorporated updated global emissions. Output from a larger regional or global modeling simulation feeds hourly lateral boundary conditions to the domain being modeled. Sources outside the modeling domain can have an important influence on concentrations within the domain modeled with the air quality model.

Landuse, and ozone column and photolysis rates for photochemical mechanisms were included in the 2016 model platform package distributed by U.S. EPA. However, MPCA created new photolysis rates files for input to CAMx v7.00 and to CAMx v7.10.

PSAT file preparation was not part of the U.S. EPA file package. MPCA created a CAMx region mapping file with a PostGIS query from an enterprise-level agency database. MPCA created Fortran programs to flag specific Minnesota industry and electric power generation facilities in emissions input files and

[52] *Intermountain West Data Warehouse. 2016 modeling platform https://views.cira.colostate.edu/iwdw/RequestData/Default.aspx*

merge point and grid files into sector groupings. MPCA also created Python scripts to extract and process data from all CAMx model output files.

4.6. Performance evaluation

MPCA evaluated air quality model performance for the $PM_{2.5}$ component species against IMPROVE and Continuous Speciated Network (CSN) monitor data in Minnesota and surrounding states. MPCA assessed model performance in more detail and within a more focused area because other organizations have assessed model performance more generally across the entire domain for various iterations and versions of the 2016 v1 model platform.

In its Regional Haze modeling TSD[53] U.S. EPA focused on seasonal and monthly average PM component species across multi-state geographical regions throughout the contiguous United States and focused on visibility at IMPROVE sites in those regions. In general, U.S. EPA concluded modeled visibility performance was good overall with some exceptions. The exceptions to overall good performance occurred in regions other than the Upper Midwest[54] region of which Minnesota was a part, and the Ohio Valley[55], a region with a state contributing to visibility impairment in Minnesota (see Section 4.8.5). But a different region with two states contributing to visibility impairment in Minnesota, the Northern Plains[56], was found by U.S. EPA to underpredict nitrate, especially in winter. In its modeling, U.S. EPA modified the CAMx v7.0 default RSCALE setting for ammonia from RSCALE=1 to RSCALE=0. The RSCALE=0 setting removes surface resistances, maximizing deposition rates of ammonia resulting in less formation of nitrate. CAMx developers found that setting RSCALE=0 results in too much ammonia deposition in rural non-agricultural areas[57]. Without drawing conclusions, the revised model setting potentially could have influenced the overall Northern Plains nitrate underprediction in U.S. EPA simulation. Within the Northern Plains region, the only two states in the MPCA analysis are North Dakota and South Dakota, both agricultural areas.

LADCO, in its Regional Haze modeling TSD, focused on annual and seasonal average PM component species concentration within the LADCO region[58] by monitoring network type (CSN or IMPROVE). In general, LADCO concluded the model performance goals or criteria were achieved for most species in winter and spring, the model predictions were better at rural (IMPROVE) sites than urban (CSN) sites, and the model predictions for organic aerosols did not perform well. The LADCO 2016 model platform is version 1b based on actual emissions, the same emissions used as MPCA.

MPCA will refer back to the U.S. EPA and LADCO model performance results in the summary discussion toward the end of this section. The following describes the MPCA model performance assessment on its own modeling using the 2016 v1b model platform.

MPCA conducted an operational model performance evaluation as recommended by U.S. EPA in guidance[59] for fine particulate ($PM_{2.5}$) species components measured on a routine basis at monitoring sites that collect $PM_{2.5}$ species components; nitrate, sulfate, ammonium, organic carbon, elemental carbon and soil. The summary statistics of mean bias, mean error, root mean square error, fractional bias, fractional error, normalized mean bias and normalized mean error, correlation coefficient, as well as bugle plots, scatter plots, boxplots, timeseries, and model/observation pairs are various ways to

---

53 USEPA 2019 September
54 Minnesota, Iowa, Wisconsin and Missouri
55 Missouri, Illinois, Indiana, Ohio, Tennessee, Kentucky and West Virginia
56 North Dakota, South Dakota, Nebraska, Montana and Wyoming
57 Email correspondence with Chris Emery, Ramboll, 10/30/2020
58 Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin
59 USEPA 2018

assess how well the model captures the magnitude and temporal variability of measured observations. Table 8 contains a description of the various statistical metrics.

Table 8. Statistical metrics for operational evaluation of air quality model performance

Measure name and abbreviation	Definition	Units
Mean bias (MB)	$\mathrm{MB} = \frac{1}{n}\sum_1^n(P - O)$	Micrograms per cubic meter (µg/m³)
Mean error (ME)	$\mathrm{ME} = \frac{1}{n}\sum_1^n\lvert P - O\rvert$	Micrograms per cubic meter (µg/m³)
Root mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{n}\sum_1^n(P - O)^2}$	Micrograms per cubic meter (µg/m³)
Fractional bias (FB)	$FB = \frac{2}{n}\sum_1^n\frac{(P - O)}{(P + O)} * 100$	Percent (%)
Fractional error (FE)	$FE = \frac{2}{n}\sum_1^n\frac{\lvert P - O\rvert}{(P + O)} * 100$	Percent (%)
Normalized mean bias (NMB)	$\mathrm{NMB} = \frac{\sum_1^n(P-O)}{\sum_1^n(O)} * 100$	Percent (%)
Normalized mean error (NME)	$\mathrm{NME} = \frac{\sum_1^n\lvert P-O\rvert}{\sum_1^n(O)} * 100$	Percent (%)
Correlation coefficient (r)	$r = \frac{\sum_1^n((P - \overline{P}) * (O - \overline{O}))}{\sqrt{\sum_1^n(P - \overline{P})^2 * \sum_1^n(O - \overline{O})^2}}$	Unitless
Coefficient of determination (r^2)	$r^2 = \left(\frac{\sum_1^n((P - \overline{P}) * (O - \overline{O}))}{\sqrt{\sum_1^n(P - \overline{P})^2 * \sum_1^n(O - \overline{O})^2}}\right)^2$	Unitless

The model performance evaluation was done for 24-hour averaging times for Prediction/Observation pairs. The observations are daily samples, and the modeled predictions are hourly, so the 24 hour modeled predictions are averaged to obtain a daily value for comparison. As model predictions are in Coordinated Universal Time (UTC), MPCA shifted hourly modeled values to the local time in which the monitor resides prior to daily averaging. The predictions are extracted from a model simulation conducted with the "actual" 2016 emissions described in Section 4.3.

Observations and model predictions are not comparable without some additional processing of the data. Table 9 contains a parameter cross-reference between $PM_{2.5}$ species measurement observations from the U.S.EPA Air Quality System (AQS) and prediction estimates from CAMx model v7.00. $PM_{2.5}$ component species are in units of micrograms per meter cubed (µg/m³).

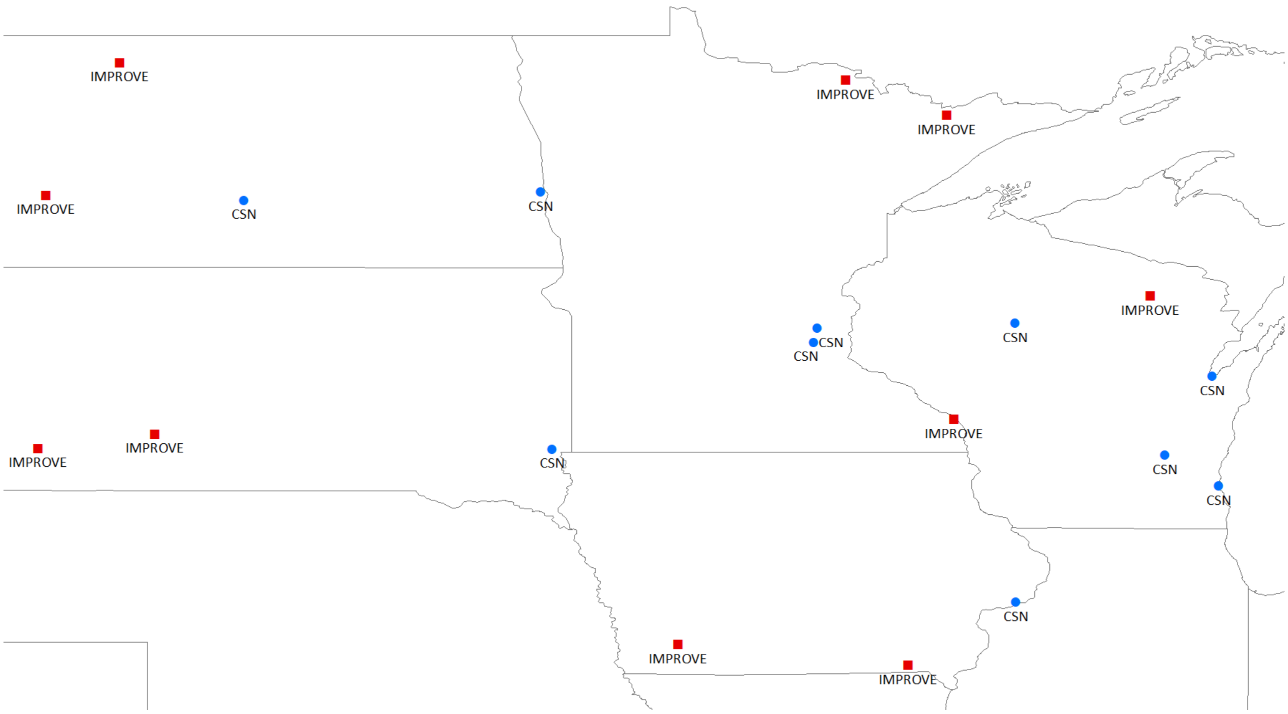
Table 9. $PM_{2.5}$ species measurements and modeled estimates cross-reference

Particulate species name	CSN/IMPROVE measurement data		CAMx v7.00 species & data processing
	AQS parameter description	AQS parameter code & data processing	
Sulfate aerosol	Sulfate Pm2.5 Lc	88403	PSO4
Nitrate aerosol	Total Nitrate Pm2.5 Lc	88306	PNO3
Ammonium aerosol	Ammonium Ion Pm2.5 Lc	88301	PNH4
Organic carbon mass	Oc Pm2.5 Lc Tor Before adjusting for mass concentration	*IMPROVE*[60]: 1.5 * '88320' in Jan, Feb, Mar 1.6 * '88320' in Apr 1.7 * '88320' in May, Oct, Nov, Dec 1.9 * '88320' in Jun 2.0 * '88320' in Jul, Sep 2.1 * '88320' in Aug *CSN*[61]: 1.6 * '88320' in Jan – May, Dec 1.8 * '88320' in Jun - Nov	POA + SOA1 + SOA2 + SOA3 + SOA4 + SOPA + SOPB
Elemental carbon	Ec Pm2.5 Lc Tor	88321	PEC
Soil	Aluminum Pm2.5 Lc Silicon Pm2.5 Lc Calcium Pm2.5 Lc Iron Pm2.5 Lc Titanium Pm2.5 Lc	2.20 * '88104' + 2.49 * '88165' + 1.63 * '88111' + 2.42 * '88126' + 1.94 * '88161'	2.20 * PAL + 2.49 * PSI + 1.63 * PCA + 2.42 * PFE + 1.94 * PTI
$PM_{2.5}$	Acceptable Pm2.5 Aqi & Speciation Mass	88502	PSO4 + PNO3 + PNH4 + SOA1 + SOA2 + SOA3 + SOA4 + SOPA + SOPB + POA + PEC + NA + PCL + FPRM + PFE + PMN + PK + PCA + PMG + PAL + PSI + PTI

[60] *Hand 2021*
[61] *Philip, S., et al.*

$PM_{2.5}$ species monitors are sited to evaluate population exposure and regional transport of $PM_{2.5}$ specie component concentrations. Sites are located in rural, suburban and urban environments. Deployed as part of the visibility program, IMPROVE network sites are typically located in rural areas. Chemical Speciation Network (CSN) sites are typically located in suburban and urban areas. The MPCA evaluation focuses on monitors sited in Minnesota and the surrounding states, North Dakota, South Dakota, Iowa and Wisconsin, shown in Figure 7.

Figure 7. CSN and IMPROVE network monitors included in model performance evaluation



Measured annual concentrations of $PM_{2.5}$ species nitrate and sulfate in each state assessed, both urban and rural areas, are near or less than 1.0 µg/m³. The same applies to seasonal concentrations, except wintertime nitrate in urban areas in all states and rural Iowa, can reach over 2.0 µg/m³. While lower concentrations are desirable for air quality, the model has greater difficulty correctly simulating concentrations at low concentrations. The statistics tend to look better at longer averaging times, for example annual average data likely will look better than monthly average data, and over larger geographic areas. In the context of this assessment, a positive bias means the model estimates a higher concentration than observed and a negative bias means the model estimates a lower concentration than observed.

While U.S. EPA recommends various operational performance metrics in the modeling guidance[62], it does not provide the goals or criteria for interpreting the comparison of observation-model pairs. U.S. EPA does clarify that any goals or criteria used are not to be construed as a pass/fail test but are meant to instill a level of confidence in the application of the model simulation. Operational performance metric results outside goals or criteria might point to an issue that warrants further investigation, for

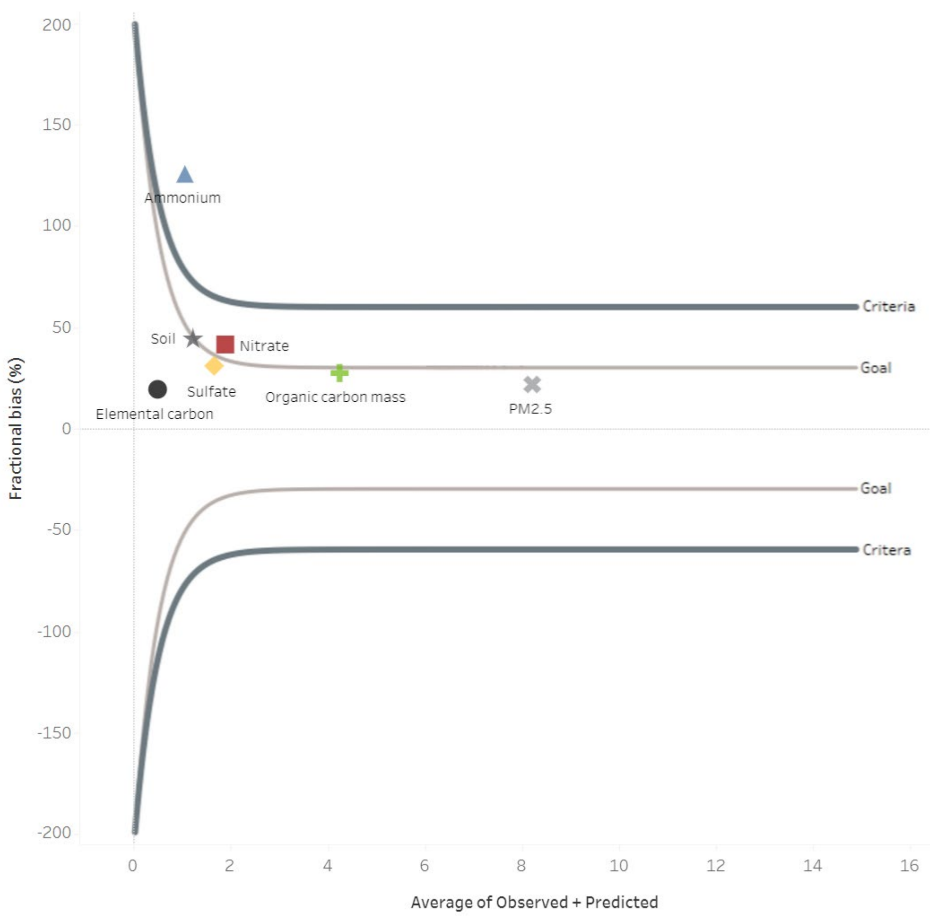
[62] *USEPA 2018*

example. MPCA consulted two articles[63] on model performance goals and criteria while appraising the performance statistics.

Boylan,et al. introduced the *bugle plot* as a means of assessing general confidence in the model data with goals and criteria set for fractional bias[64]. Points plotted within the "goal" represented by thin solid lines indicate the model simulates observed the best it could be expected to achieve. Points plotted within the "criteria" represented by the thick solid lines indicate the model simulates observed acceptable for standard modeling applications. At higher concentrations of $PM_{2.5}$ components, the goal is ±30% and the criteria is ±60%. At zero concentration, the goal and criteria merge at ±200% and asymptotically approach the goals and criteria. A higher percentage bias is allowed at low concentrations because the model has greater difficulty predicting lower concentrations. The shape of the lines gave rise to the name bugle plot.

Figure 8 shows the annual fractional bias for all the network monitors across the MPCA model performance region. Overall, the model has a positive bias for all $PM_{2.5}$ species components. On an annual basis, model performance is good, with sulfate, organic carbon mass, elemental carbon, soil and $PM_{2.5}$ all fitting the goals, and nitrate fitting the criteria. Ammonium concentrations are outside the criteria.

Figure 8. Annual fractional bias over model performance region for $PM_{2.5}$ species components



[63] *Boylan, et al., Emery, et al.*
[64] *Boylan, et al. also have criteria for fractional error, but MPCA found it does not provide additional value to this particular assessment*

Figure 9 shows the monthly fractional bias for all the network monitors across the MPCA model performance region. Monthly **elemental carbon** concentrations are very low and all fit within the goals. **Ammonium** is outside the criteria for all months.

Sulfate fits within the goals April – September, December and January. Sulfate fits within the criteria February, March, October and November.

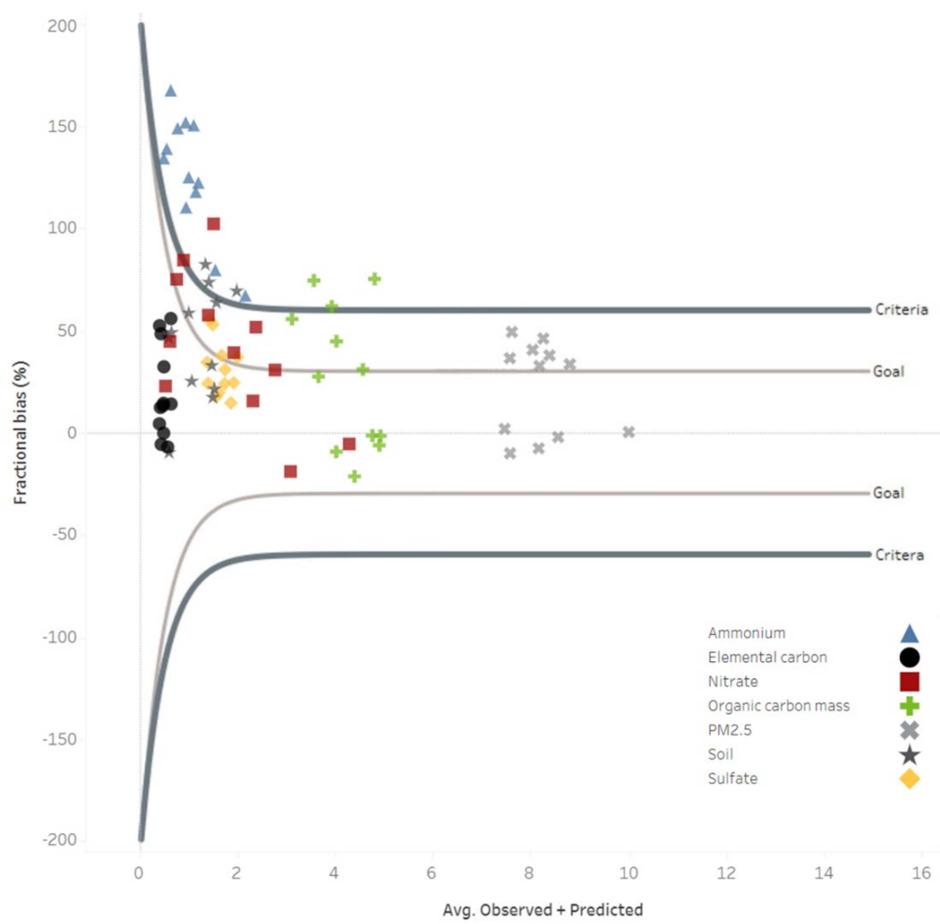
Nitrate fits within the goals January and February with a slight negative bias, while nitrate fits within the goals March, June and July with a positive bias. Nitrate fits the criteria April, May, August, September, November, and December. Nitrate is outside the criteria for one month, October.

Organic carbon mass fits within the goals May – September with a slight negative bias, while organic carbon mass fits within the goals in October with a positive bias. Organic carbon fits the criteria April, November and December. Organic carbon is outside the criteria January – March.

Soil fits within the goals in December with a slight negative bias, while soil fits within the goals in January, February, April – July with a positive bias. Soil fits the criteria March and August. Soil is outside the criteria September – November.

Total **$PM_{2.5}$** fits within the goals May – September and within the criteria January – April and October – December.

Figure 9. Monthly fractional bias over model performance region for $PM_{2.5}$ species components



Emery, et al. updated Boylan,et al. by developing new goals and criteria for normalized mean bias (NMB) and error (NME), and correlation coefficient (*r*), to see where current model results fall in the spectrum of past published results. Table 10 contains the new goals and criteria. Emery, et al. recommends temporal scales no more than seasonal (3 months) and spatial scales within 1,000 km. Number of prediction-observation values will influence the agreement and should be considered alongside the statistical metrics.

Table 10. Contextual assessment of model simulation performance through quantitative goals and criteria[65]

Performance Statistic	Normalized mean bias				Normalized mean error				*r*
Goal	$PM_{2.5}$, SO_4, NH_4: <±10%	NO_3: <±15%	OC: <±15%	EC: <±20%	$PM_{2.5}$, SO_4, NH_4: <35%	NO_3: <65%	OC: <45%	EC: <50%	$PM_{2.5}$, SO_4, NH_4: >0.70
Criteria	$PM_{2.5}$, SO_4, NH_4: <±30%	NO_3: <±65%	OC: <±50%	EC: <±40%	$PM_{2.5}$, SO_4, NH_4: <50%	NO_3: <155%	OC: <65%	EC: <75%	$PM_{2.5}$, SO_4, NH_4: >0.40

NMB is the average of the difference of the modeled prediction and the observed species concentration over the sum of the observed values, expressed as a percentage. NME is the average of the absolute difference of the modeled prediction and the observed species concentration over the sum of the observed values, expressed as a percentage. Both NMB and NME avoid over inflating the importance of biases at lower observed concentrations.

Pearson correlation coefficient provides the strength and direction of the linear relationship between measured observations and the modeled predictions. Values of *r* range from -1 to +1. The larger the absolute value of *r*, the stronger the relationship. Observations and predictions that increase or decrease together have a positive *r* value. One that increases when the other decreases will have a negative *r* value.

Table 11 contains seasonal NMB, NME and correlation coefficient for all the network monitors across the MPCA model performance region, which has a spatial scale of about 1,260 x 860 km. Excluding elemental carbon, the species that fit within the NMB and NME goals are those with seasonal average observed concentrations above 1.00 $\mu g/m^3$. These species are **nitrate**, **organic carbon** and total **$PM_{2.5}$**. **Elemental carbon** fits within the NMB and NME goals and criteria with observed concentrations around 0.25 $\mu g/m^3$. Total $PM_{2.5}$, nitrate, organic and elemental carbon, fit within the NMB and NME goals in seasons where the observed concentration is highest, and within the criteria in seasons where the observed concentrations are next highest.

Seasonal average **sulfate** observed concentrations do not reach above 1.00 $\mu g/m^3$. Sulfate does not fit the NMB and NME goals for any season, however, sulfate does fit within or near the criteria when observed concentrations are at or above 0.74 $\mu g/m^3$.

Seasonal average **ammonium** observed concentrations are quite low, the highest seasonal average is 0.62 $\mu g/m^3$. The other three seasonal averages are at or below 0.31 $\mu g/m^3$. Ammonium does not fit the NMB and NME goals nor the criteria.

Goals and criteria for correlation coefficient were only provided for $PM_{2.5}$, sulfate and ammonium. All three species fit within either the goals or criteria for correlation coefficient.

[65] *Emery, et al.*

Table 11. Seasonal model performance metrics for Minnesota evaluation region[66]

Species	Season	Observation Average (µg/m³)	Prediction Average (µg/m³)	NMB (%)	NME (%)	Pearsons *r*	Number of Values
$PM_{2.5}$	winter	3.60	4.59	27	48	0.77	273
	spring	3.93	4.86	23	55	0.53	262
	summer	4.12	4.00	-3	33	0.67	272
	fall	3.24	4.55	40	55	0.73	274
SO_4	winter	0.79	1.00	27	48	0.70	488
	spring	0.74	0.98	33	44	0.69	506
	summer	0.74	0.87	18	41	0.77	501
	fall	0.62	0.90	45	60	0.74	494
NH_4	winter	0.62	0.99	60	77	0.77	233
	spring	0.31	0.80	161	171	0.65	241
	summer	0.14	0.53	284	288	0.64	229
	fall	0.14	0.69	383	385	0.69	222
NO_3	winter	1.79	1.66	-7	44	0.78	488
	spring	0.78	1.12	44	77	0.66	506
	summer	0.18	0.51	179	196	0.57	500
	fall	0.46	1.09	136	151	0.71	492
OCM	winter	1.10	2.79	153	159	0.67	482
	spring	1.80	2.48	38	79	0.44	497
	summer	2.33	2.38	2	41	0.51	512
	fall	1.81	2.28	26	54	0.66	504
EC	winter	0.17	0.33	97	111	0.69	482
	spring	0.25	0.27	9	56	0.51	500
	summer	0.20	0.24	20	53	0.66	513
	fall	0.23	0.29	27	60	0.71	504

MPCA has compiled a full set of operational statistics and plots for the 2016 v1b model platform in an interactive online tool. To reach the online performance evaluation tool ctrl + click on the following URL: https://public.tableau.com/app/profile/mpca.data.services/viz/Photochemicalmodeling2016v1bperformanceforfineparticulatespecies/Introduction

[66] *Dark blue shading indicates modeled prediction within performance goals, light orange shading indicates modeled prediction within performance criteria quantified by Emery, et al. for the three metrics NMB, NME and r. Gray shading indicates goals and criteria were not quantified for the parameter.*

With the additional information in the online interactive tool, MPCA has the following additional observations. State-wide average concentrations are generally the same at IMPROVE sites in rural and some CSN sites in urban areas, but generally bias high at CSN sites in more densely populated urban and suburban areas, especially in the Twin Cities metropolitan area in Minnesota.

For **sulfate**, the model performs well, especially at sites with lower population. Performance improves significantly when limiting values to the 90th percentile or greater. Seasonality doesn't appear to meaningfully impact model performance.

For **nitrate**, the model performs well at most sites. Population (urban/rural) is not a clear factor in model performance. The model underpredicts nitrate across the region when limiting values to the 90th percentile or greater. The model most accurately predicts nitrate during the winter. Nitrate predominantly forms in the atmosphere during cooler temperatures.

For **organic carbon mass** and **elemental carbon**, the model performs well at all sites, except Minnesota sites in the CSN network for which the model overpredicts. The overprediction at these sites improves markedly when limiting values to the 90th percentile or greater. Limiting values this way has an opposite effect on some sites especially in the Dakotas, where model biases become more negative. Across the region for all values, model performance is best in the summer.

Many sites do not collect **soil** in winter. Including all seasons, the model has a marked positive bias in Minnesota and Wisconsin, and a negative bias in the other states when limiting values to the 90th percentile or greater. The model overpredicts when including all values at the sites located in the eastern-most part of the model performance focus area in Figure 7.

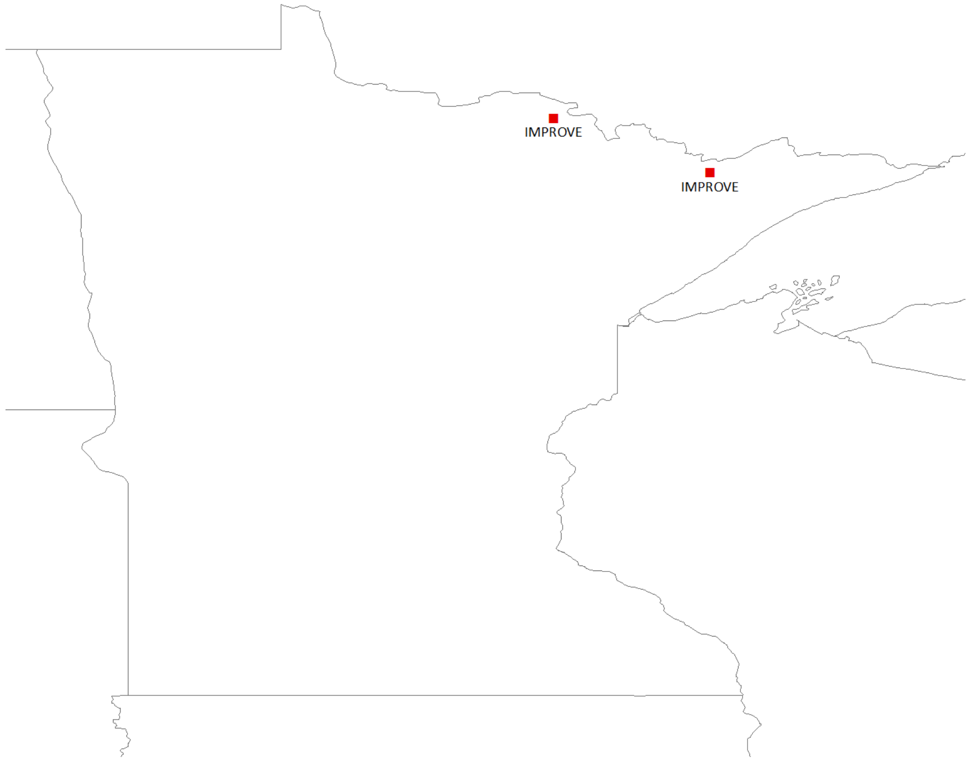
Only CSN network sites in this assessment collect **ammonium** and collection varies among the seasons. The model generally overpredicts, although it performs well at some sites in the winter months. At all but the North Dakota site, the model accurately predicts wintertime ammonium when values are limited to the 90th percentile or greater.

Only IMPROVE network sites in this assessment collect **total $PM_{2.5}$** for which the model performs well.

4.6.1. Boundary Waters and Voyageurs model performance for all days

The following discussion focuses on model performance in the Minnesota Class I areas, **Boundary Waters** and **Voyageurs**. Figure 10 shows the location of the two monitoring sites within Minnesota. MPCA did not conduct a statistical assessment on calculated visibility metrics (e.g. light extinction) at the Class I areas, but on the species concentrations.

Figure 10. IMPROVE network monitors at Voyageurs (left) and Boundary Waters (right) in model performance evaluation



The statistical metrics annual and monthly mean fractional bias are assessed for all the days observation samples were collected. Figure 11 shows the annual fractional bias for Boundary Waters and Voyageurs. The model has a positive bias for all $PM_{2.5}$ species components. On an annual basis, model performance is good, with sulfate, nitrate, elemental carbon and soil all fitting the goals, and organic carbon and $PM_{2.5}$ fitting the criteria.

Figure 11. Annual fractional bias at Boundary Waters and Voyageurs for $PM_{2.5}$ species components

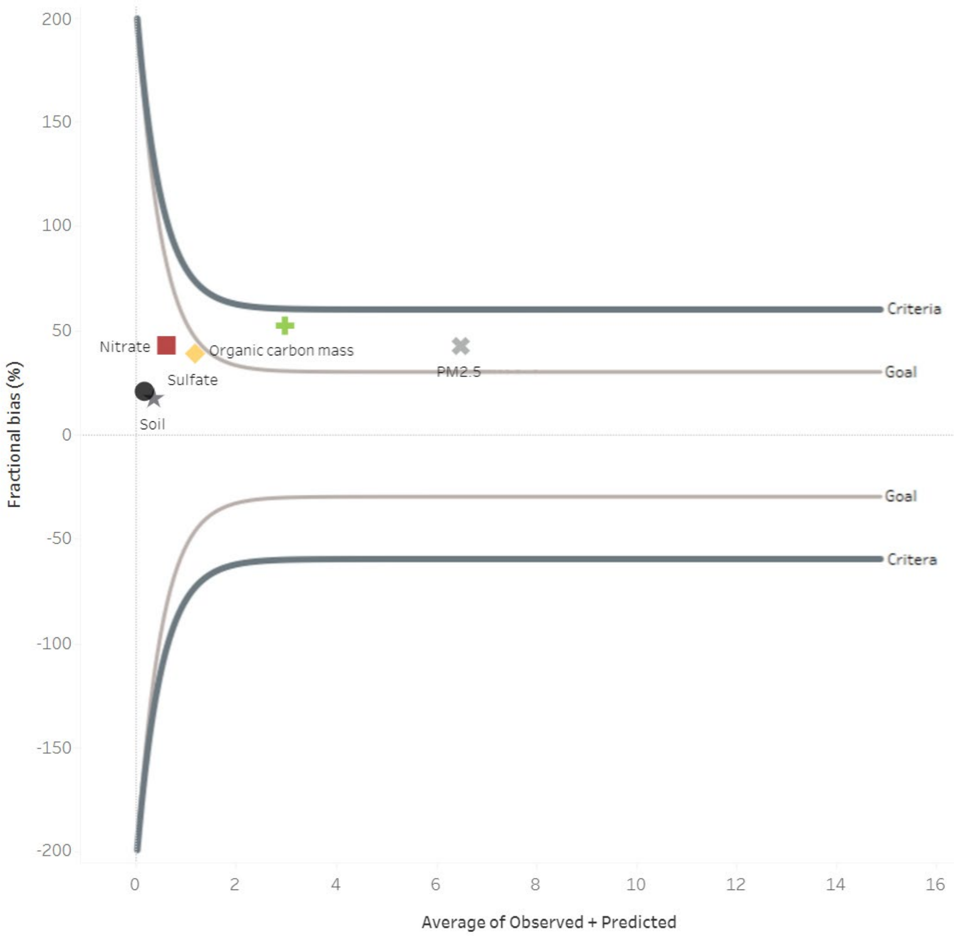


Figure 12 shows the monthly fractional bias for Boundary Waters and Voyageurs. The monthly data shows a greater spread in bias especially with the lower concentrations of nitrate, soil and elemental carbon. Monthly **elemental carbon** and **soil** concentrations are very low and all fit within the goals.

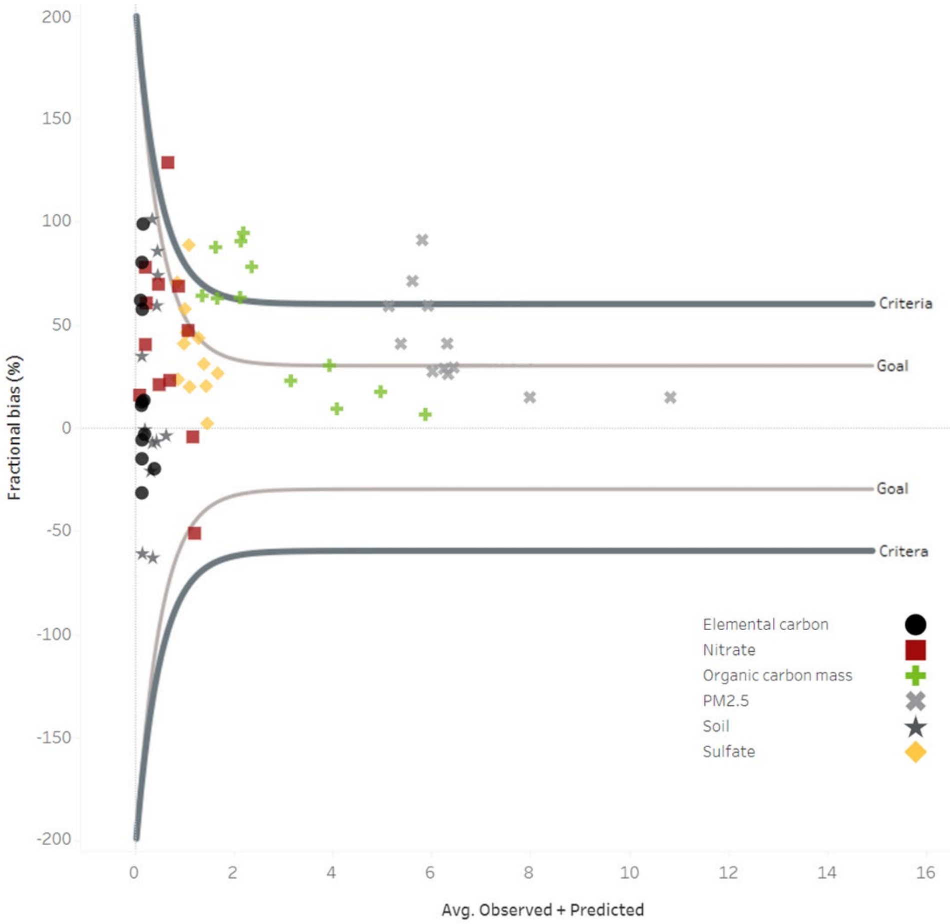
Sulfate fits within the goals January, February, April, May, July-September and December. Sulfate fits within the criteria March, June and October. Sulfate is outside the criteria for one month, November.

Nitrate fits within the goals in January with a slight negative bias, while nitrate fits within the goals March – September and December with a positive bias. Nitrate fits the criteria February with a negative bias and November with a positive bias. Nitrate is outside the criteria for one month, October.

Organic carbon mass fits within the goals May – September. Organic carbon fits the criteria April and December. Organic carbon is outside the criteria January – March, October and November.

Total **$PM_{2.5}$** fits within the goals February, May - September and within the criteria January, March, April and December. $PM_{2.5}$ is outside the criteria October and November.

Figure 12. Monthly fractional bias at Boundary Waters and Voyageurs for $PM_{2.5}$ species components



4.6.2. Boundary Waters and Voyageurs model performance for 20% most impaired visibility days

NMB, NME, correlation coefficient and daily model prediction (P) and measured observation (O) pairs are assessed for the days identified as the 20% most impaired based on visibility calculation metrics, although the performance evaluation remains on $PM_{2.5}$ component species concentrations. Selection procedures in federal guidance[67] for the 20% most impaired days aim to moderate the effect of organic and elemental carbon due to fires before selecting the most visibility impaired days (See Section 4.7). The regional haze program focuses on days impaired by human activity associated with production of nitrates and sulfates.

Table 12 contains seasonal NMB, NME and correlation coefficient. Excluding elemental carbon, the species that fit within the NMB and NME goals are those with seasonal average observed concentrations near or above 1.00 µg/m³. These species are **sulfate**, **nitrate**, **organic carbon** and total **$PM_{2.5}$**. **Elemental carbon** fits within the NMB and NME goals and criteria with observed concentrations less than or equal to 0.15 µg/m³. Total $PM_{2.5}$, nitrate, organic and elemental carbon, fit within the NMB and NME goals in seasons where the observed concentration is highest, and within the criteria in seasons where the observed concentrations are next highest. Seasonal average sulfate observed concentrations are near

[67] *Insert reference to tracking metrics for 2nd implementation period*

and above 1.00 µg/m³. Sulfate fits the NMB and NME goals for winter, spring and fall and fits within the criteria in summer.

Goals and criteria for correlation coefficient were only provided for $PM_{2.5}$ and sulfate. Both species fit within either the goals or criteria for correlation coefficient in spring and summer. $PM_{2.5}$ fits within the goals for fall, and neither $PM_{2.5}$ nor sulfate fit within the criteria in winter.

Table 12. Seasonal model performance metrics for Boundary Waters and Voyageurs on 20% most impaired days[68]

Species	Season	Observation Average (µg/m³)	Prediction Average (µg/m³)	NMB (%)	NME (%)	Pearsons *r*	Number of Values
$PM_{2.5}$	winter	4.04	5.32	32	51	0.19	21
	spring	2.96	4.38	48	50	0.90	15
	summer	5.63	6.34	12	12	0.63	3
	fall	3.89	5.40	39	54	0.41	9
SO_4	winter	1.04	1.05	1	39	0.31	21
	spring	0.86	0.95	10	26	0.52	15
	summer	1.08	1.37	27	36	0.60	3
	fall	1.07	1.17	9	30	0.35	9
NO_3	winter	1.31	0.99	-24	55	-0.02	21
	spring	0.28	0.63	124	142	0.89	15
	summer	0.07	0.43	539	539	0.63	3
	fall	0.48	1.00	111	145	0.24	9
OCM	winter	0.74	1.98	168	168	0.23	21
	spring	0.77	1.46	89	94	0.84	15
	summer	2.40	2.87	19	19	0.57	3
	fall	1.57	1.71	9	47	0.13	9
EC	winter	0.09	0.15	57	61	0.36	21
	spring	0.10	0.09	-4	24	0.88	15
	summer	0.15	0.11	-26	27	-0.38	3
	fall	0.14	0.11	-20	34	0.51	9

NMB and NME for the 20% most impaired days (Table 12) fit within criteria and goals for all seasons, the average for each season being near or just greater than 1.0 µg/m³. Sulfate forms with or without the presence of ammonia—unlike nitrate—and in the presence of ammonia preferentially forms over nitrate. Individual days among the 20% most impaired visibility days show sulfate concentrations higher

[68] Dark blue shading indicates modeled prediction within performance goals, light orange shading indicates modeled prediction within performance criteria quantified by Emery, et al. for the three metrics NMB, NME and r. Gray shading indicates goals and criteria were not quantified for the parameter.

than nitrate from March through October. Sulfate prediction and observation concentration differences range from -0.84 to +1.20 µg/m³ at Boundary Waters and from -1.17 to + 1.02 µg/m³ at Voyageurs. Figure 14 contains measured observation (Observed) and model prediction (Modeled) pairs as side-by-side $PM_{2.5}$ component species stacked bars, one pair for each of the 20% most impaired visibility days at Boundary Waters and at Voyageurs. Out of 116 samples collected at Boundary Waters and 118 samples collected at Voyageurs in 2016, 24 samples comprise the 20% most impaired at each monitoring site. The stacked bar charts show that concentrations of organic carbon, nitrate and sulfate comprise most of the $PM_{2.5}$.

In the monthly fractional bias bugle plots (Figure 12), which include all sample days, the best performance for ***organic carbon*** is when concentrations are highest, in May – September. NMB and NME for the 20% most impaired days (Table 12) are in agreement that the model performs best in summer and fall. Because the visibility tracking metrics attempt to moderate the effect of fires the 20% most impaired days are less likely to contain days with the highest measured organic carbon. Only two of the 20% most impaired days at Boundary Waters are in May – September, both days the model prediction is lower than the observed by -0.09 and -0.19 µg/m³. Six of the 20% most impaired days at Voyageurs are in May – September, two where the model prediction is lower than the observed by -0.24 and -0.25 µg/m³. For the remaining months and samples, model predicted organic carbon concentrations are routinely higher than observed on the 20% most impaired days by between 0.10 and 2.89 µg/m³.

In the monthly fractional bias bugle plots (Figure 12), which include all sample days, the best performance for ***nitrate*** occurs all months except October when nitrate is outside the performance criteria. The fractional bias goals and criteria are more forgiving for low concentrations than perhaps the NMB and NME goals and criteria. Seasonal nitrate NMB and NME for the 20% most impaired days (Table 12) fit within criteria and goals only in the winter, the seasonal average being greater than 1.0 µg/m³. Winter claims 11 of the 24-20% most impaired visibility days at Boundary Waters and 10 of the 24-20% most impaired visibility days at Voyageurs. Nitrate is predominantly formed in the cooler months, and none of the 20% most impaired visibility days appear in Summer at Boundary Waters. While two of the 20% most impaired visibility days appear in Summer at Voyageurs, they are not due to nitrate. The 20% most impaired days also show variability in whether the model or the observation has the higher nitrate concentration of the pair, with no particular discernable pattern. Nitrate prediction and observed concentration differences range from -2.34 to +2.15 µg/m³ at Boundary Waters and from -2.41 to + 1.82 µg/m³ at Voyageurs.

In the monthly fractional bias bugle plots (Figure 12), which include all sample days, the best performance for ***sulfate*** occurs all months except November when sulfate is outside the performance criteria. NMB and NME for the 20% most impaired days (Table 12) fit within criteria and goals for all seasons, the average for each season being near or just greater than 1.0 µg/m³. Sulfate forms with or without the presence of ammonia—unlike nitrate—and in the presence of ammonia preferentially forms over nitrate. Individual days among the 20% most impaired visibility days show sulfate concentrations higher than nitrate from March through October. Sulfate prediction and observation concentration differences range from -0.84 to +1.20 µg/m³ at Boundary Waters and from -1.17 to + 1.02 µg/m³ at Voyageurs.

Figure 13. Boundary Waters observed and modeled $PM_{2.5}$ species concentrations on 20% most visibility impaired days

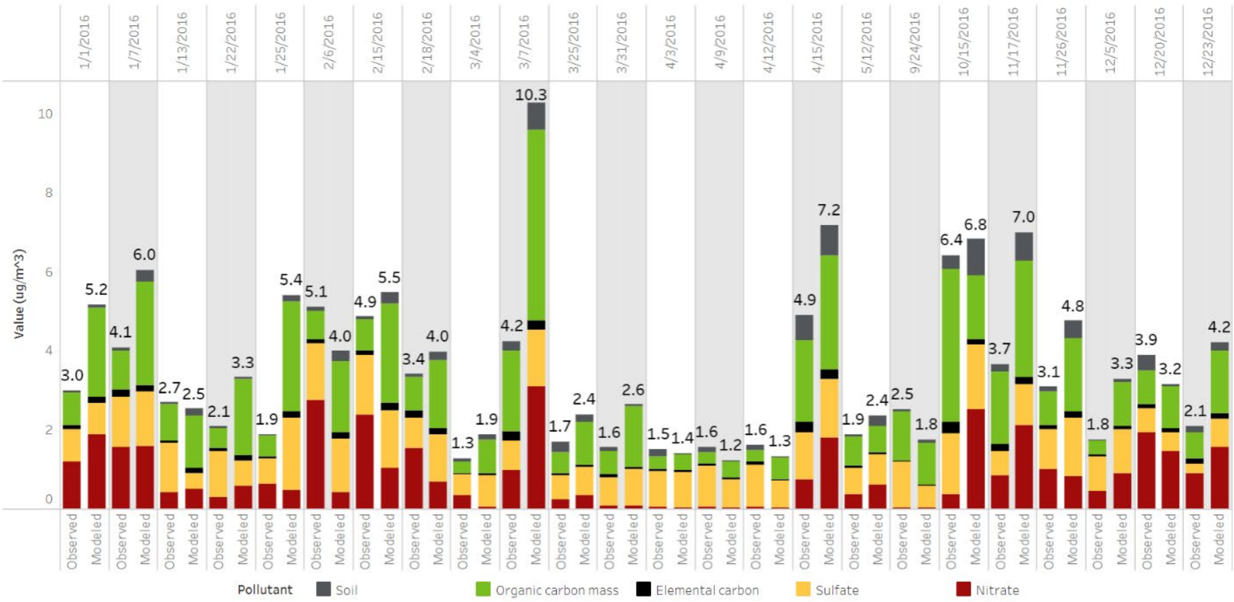
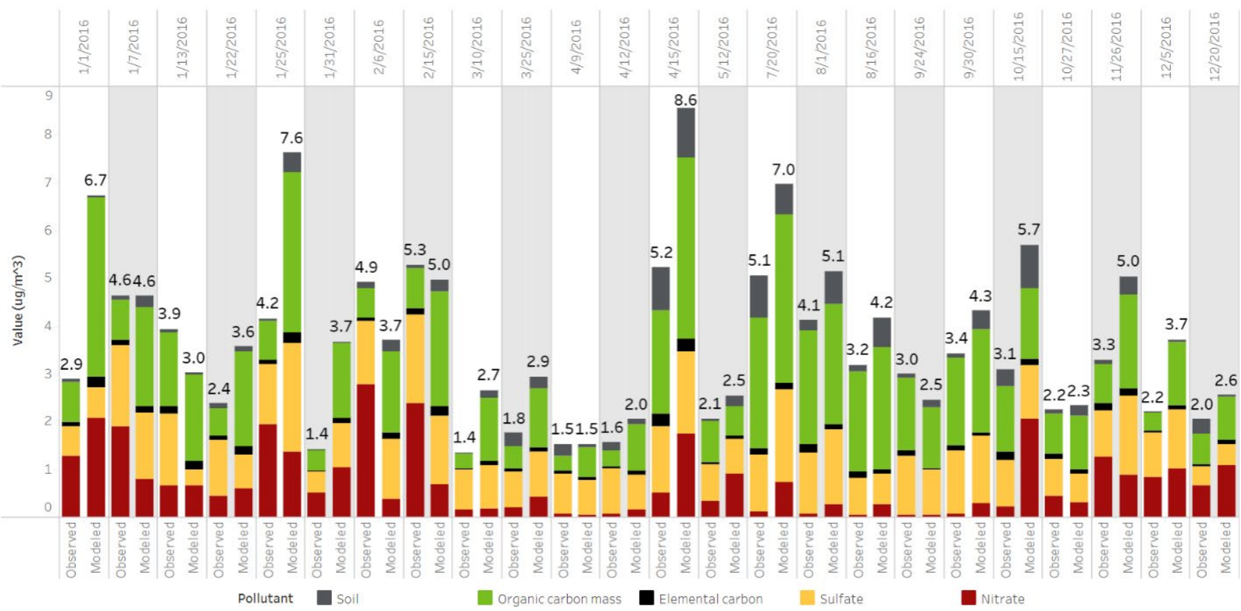


Figure 14. Voyageurs observed and modeled $PM_{2.5}$ species concentrations on 20% most visibility impaired days



4.6.3. Implications of the model performance evaluation

The model performance evaluation was conducted on the $PM_{2.5}$ component species. The stacked bar charts in Figure 13 and Figure 14 show the species that comprise $PM_{2.5}$ on the 20% most impaired days are organic carbon, nitrate and sulfate. In terms of concentration, organic carbon plays a more significant role than in terms of extinction. Table 13 shows the relative importance of $PM_{2.5}$ component species as a concentration compared to calculated light extinction (See Section 4.7 for calculation methodology). Nitrate and Sulfate have significantly greater roles in visibility, which make model performance more critical for these species.

Table 13. Relative importance of $PM_{2.5}$ component species as a concentration compared to calculated light extinction, expressed as a percentage

Species	Boundary Waters		Voyageurs	
	Concentration (Percent of µg/m³)	Extinction (Percent of Mm^{-1})	Concentration (Percent of µg/m³)	Extinction (Percent of Mm^{-1})
OCM	32	12	34	12
EC	4	4	3	5
NO_3	27	37	23	40
SO_4	32	47	34	43
Soil	5	1	6	1

MPCA came to similar conclusions for the region as U.S. EPA in the model performance for their 2016 v1 model platform. However, MPCA does not see the same nitrate underpredictions in the two States within the MPCA evaluation region that overlap with the U.S. EPA Northern Plains region, likely because North Dakota and South Dakota are agricultural states. MPCA also came to some similar conclusions for the region as LADCO in the model performance for the 2016 v1b model platform. However, MPCA does not see the same poor performance for organic carbon within the MPCA evaluation region that LADCO encounters in their evaluation.

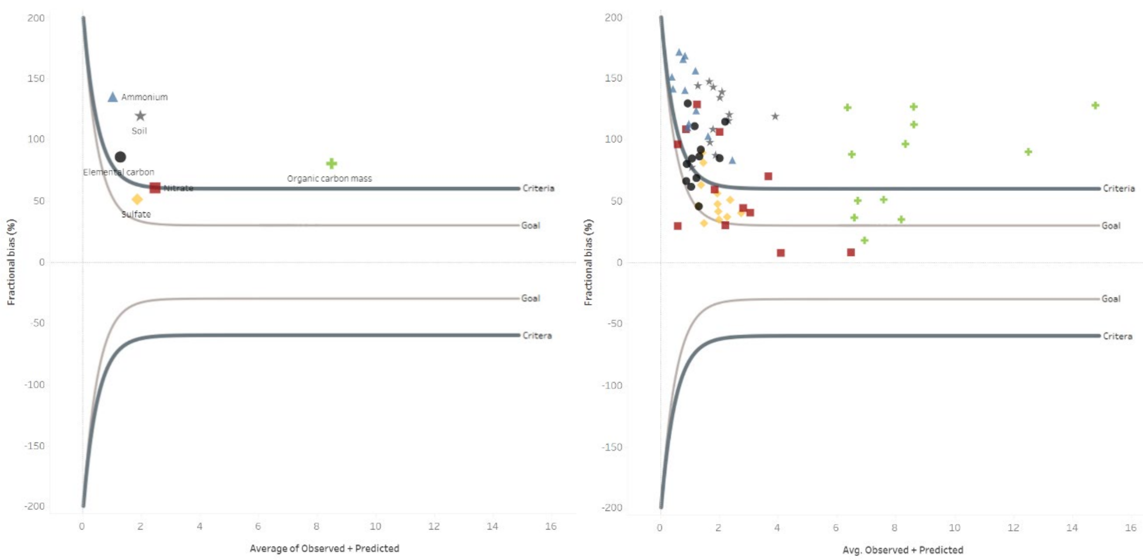
While the MPCA assessment shows acceptable model performance for regional haze visibility purposes, there are several areas operational performance metric results outside goals or criteria might point to an issue that warrants further investigation.

- **Grid scale needs**. The model performance evaluation indicates the 12 km grid scale is sufficient for regional haze and no further investigation appears warranted.
- **RPG development**. U.S.EPA guidance attempts to mitigate uncertainties in model performance by using the model results in a “relative” sense, meaning that future concentrations estimated from the model are anchored to an observed measurement value. Any problems posed by less-than-ideal model performance are reduced.
- **Horizontal extent of domain**. The northern edge of the 12US2 modeling domain is 432 km from the Boundary Waters monitoring site and 385 km from the Voyageurs monitoring site. Boundary Conditions are obtained through a hemispheric CMAQ model simulation conducted by U.S. EPA. The model performance evaluation did not uncover any issues for which an increase in the horizontal extent of the domain would appear warranted. In Section 4.8.3 we see contribution assessment of boundary conditions to visibility impairment at the two Class I areas at nearly 40% that potentially could use a larger horizontal extent. The boundary conditions enter one-way into the 12US2 domain. The boundary condition contribution to visibility at Boundary Waters and Voyageurs could be all Canada. It could be the domain does not have a large enough spatial extent to the north to capture recirculation due to shifting winds of emissions from sources within the 12US2 domain for the source contribution assessment. To capture recirculation, Minnesota considered looking into the feasibility of extending the 12US2 12km domain to include some of the 12US1 12km domain but had limited time and resources and could not develop and implement this configuration for source contribution.
- **Modifications of models**. Model performance evaluations over entire domains have resulted in changes to models but were made for some reason other than achieving regional haze goals in Boundary Waters and Voyageurs. Significant improvements have been incorporated in CAMx versions 7.00 (and 7.10) since CAMx version 4.2 which was used in the first implementation

period. At Boundary Waters and Voyageurs, the $PM_{2.5}$ component species fall within goals and criteria especially when the concentrations are near or above 1.0 µg/m³. Concentrations are becoming so low it's becoming more difficult for the model to simulate.

- **Improvements to emissions inventory**. State-wide average concentrations are generally the same at IMPROVE sites in rural and some CSN sites in urban areas, but generally bias high at CSN sites in more densely populated urban and suburban areas, especially in the Twin Cities metropolitan area in Minnesota. Figure 15 shows the annual and monthly model performance at the two CSN monitors in the Twin Cities metropolitan area. Likely areas to focus on in future inventories in this area include vehicle traffic, area and industry sources with their elevated emissions and aggregation within the urban areas. Agricultural ammonia estimates feeding into the area warrant further scrutiny as well.

Figure 15. Minnesota urban and suburban CSN model performance, annual (left) and monthly (right)



- **Diagnostic tests**. Diagnostic tests can examine the accuracy of the model in characterizing the sensitivity of modeled $PM_{2.5}$ component species to changes in emissions inputs to the model. It may be that reductions in one input component may still result in similar overall $PM_{2.5}$ concentrations because reduction of one precursor may free up another for additional chemical reactions formulating $PM_{2.5}$ concentrations. An example might be an examination of the extent to which sulfate concentration reductions might increase nitrate concentrations by freeing-up ammonia. No specific diagnostic tests were conducted to test performance of the models for this analysis.

4.7. Uniform rate of progress and progress tracking

The Regional Haze Rule requires states to track visibility improvements over time through quantifying historical and projected visibility conditions using specific metrics. States with Class I areas within their borders are required to identify the 20% most visibly impaired days caused by human activity, identify the 20% clearest days, and determine the baseline, current, and natural visibility conditions for each Class I area within the state.

On December 20, 2018, U.S. EPA issued guidance that addresses this topic for the second implementation period in further detail.[69] The guidance updates U.S. EPA's recommended methods on tracking visibility metrics issued September 2003[70], and adds provisions for estimating international anthropogenic impacts and an optional adjustment to the Uniform Rate of Progress (URP) glidepath.

The required content of the uniform rate of progress and progress tracking section that must be covered in the SIP is specified in 40 CFR § 51.308(f)(1). These requirements identify the calculation of baseline, current, and natural visibility conditions; progress to date; and the uniform rate of progress. For the Boundary Waters and Voyageurs, Minnesota must determine the following:

- Baseline visibility conditions for the most impaired and clearest days
- Natural visibility conditions for the most impaired and clearest days
- Current visibility conditions for the most impaired and clearest days
- Progress to date for the most impaired and clearest days
- Differences between current visibility condition and natural visibility condition
- Uniform rate of progress

The core of the visibility assessment is the baseline and natural visibility conditions based on observed data collected at the IMPROVE monitors, made available through the Federal Land Manager Environmental Database (FED).[71] The baseline conditions are developed from five years of monitoring data, and represent the starting point from which reasonable progress is measured. The Regional Haze Rule prescribes the baseline period as the years 2000-2004.[72] The rule defines baseline visibility conditions as the average of the 20% of days with the most impaired visibility and the average of the 20% of days with the least impaired visibility (or "clearest days"). The baseline conditions are calculated from the monitoring data for each year of the baseline, then averaged over the 5-year baseline period. This process is repeated each year, dropping one year of data from the beginning of the 5-year period and adding one year of new data to the end of the 5-year period. The final result of the visibility calculation is assigned to the last year of the 5-year period, e.g. 2000-2004 is assigned to 2004.

Fine particles less than 2.5 microns (µm) in size ($PM_{2.5}$) are primarily responsible for impaired visibility.[73] $PM_{2.5}$ is composed of several pollutant species; nitrate, sulfate, organic carbon, elemental carbon, fine soil, sea salt and water. Coarse particulate mass (>2.5 µm, but ≤10 µm diameter) is also included in the visibility metrics.

MPCA has calculated visibility metrics for Boundary Waters and Voyageurs using the individual measured components described above in the IMPROVE algorithm adopted by the IMPROVE Steering Committee in December 2005.[74]

$$
\begin{aligned}
b_{ext} = {} & 2.2 * f_S(RH) * [\text{small sulfate}] + 4.8 * f_L(RH) * [\text{large sulfate}] \\
& + 2.4 * f_S(RH) * [\text{small nitrate}] + 5.1 * f_L(RH) * [\text{large nitrate}] \\
& + 2.8 * [\text{small organic mass}] + 6.1 * [\text{large organic mass}] \\
& + 10 * [\text{elemental carbon}] \\
& + 1 * [\text{fine soil}]
\end{aligned}
$$

---

[69] *USEPA 2018 December*

[70] *USEPA 2003 September-a*

[71] *Federal Land Manager Environmental Database. http://views.cira.colostate.edu/fed/QueryWizard/*

[72] *40 CFR 51.308(d)(2)*

[73] *Malm 1999*

[74] *Pitchford 2007*

+ 1.7 * f_{SS}(RH) * [sea salt]

+ 0.6 * [coarse mass]

+ Rayleigh scattering (site specific—BOWA1= 11, VOYA2 = 12)

+ 0.33 * [NO_2 (ppb)]

where: b_{ext} is calculated total light extinction in inverse megameters

f_S(RH) is the relative humidity adjustment factor for small particles

f_L(RH) is the relative humidity adjustment factor for large particles

f_{SS}(RH) is the relative humidity adjustment factor for sea salt

The apportionment of the total concentration of sulfate compounds into the concentrations of the small and large size fractions is accomplished using the following equations:

[large sulfate] = ([total sulfate]/20μg/m³) * [total sulfate], for [total sulfate] < 20 μg/m³

[large sulfate] = [total sulfate], for [total sulfate] ≥ 20 μg/m³

[small sulfate] = [total sulfate] – [large sulfate]

The same equations above for large sulfate, are also used to apportion total nitrate and total organic mass concentrations into the large and small size fractions

NO_2 is not currently measured at the IMPROVE monitors, so this factor is not included. The IMPROVE equation assumes sulfate is in the form of ammonium sulfate (NH_4SO_4) and nitrate is in the form of ammonium nitrate (NH_4NO_3)

Monthly f_S(RH) and f_L(RH) values are presented in Table 15

The solution to the IMPROVE equation is in the form of light extinction (b_{ext}) in units of inverse megameters (Mm^{-1}). The Regional Haze Rule requires visibility to be converted to, and expressed in, deciviews (dv). In the deciview scale, "a 1 to 2 deciview difference corresponds to a small, visibly perceptible change in scene appearance…"[75] by the human observer. The following equation converts b_{ext} to the haze index in deciviews (dv):

$$\text{Haze Index (dv)} = 10\ ln(b_{ext}/10)$$

The September 2003 U.S. EPA guidance for tracking progress[76] provides a sequence of steps to calculate data for tracking progress leading to the haze index. The original September 2003 guidance covers Steps 1 - 7 (Sections 4.7.1 - 4.7.7) and Steps 9-10 (Sections 4.7.9 and 4.7.10). The updated December 2018 guidance updates Step 8 (Section 4.7.8 Identify the most impaired and clearest days). MPCA followed these steps when calculating visibility metrics for Boundary Waters and Voyageurs, which are described more fully in the sections below. Sections written based on the September 2003 guidance are updated to reflect the revised IMPROVE algorithm adopted by the IMPROVE program steering committee in December 2005. [77]

[75] *Pitchford 1994*

[76] *USEPA 2003 September and USEPA 2018 December*

[77] *Pitchford 2007*

The September 2003 guidance for tracking progress states that the IMPROVE program calculates these metrics for all Class I areas. During the first implementation period, LADCO identified some days at Upper Mid-West Class I areas (Boundary Waters, Voyageurs, Isle Royale and Seney) that were excluded from the 20 percent "worst days"[78] in the IMPROVE program data because of incomplete capture of insignificant components of visibility. For example, coarse mass and soil were missing, while the remaining components—notably sulfate and nitrate—were present at levels that would cause those days to be on the list of 20 percent worst. Over the five-year period, 2000-2004, used to calculate the baseline visibility conditions, this affected six days at Boundary Waters and three days at Voyageurs. Manually reintroducing the nine days in the selection process increased the baseline by 0.3 dv at Boundary Waters and 0.2 dv at Voyageurs.

Leading up to the second implementation period, LADCO and MPCA consulted with the IMPROVE program about the tracking metrics dropping visibility significant days. It was recommended that LADCO and/or MPCA determine where in the tracking metric calculations the pertinent days were lost and the IMPROVE program steering committee would determine whether a revision to the metric calculations were in order based on the findings. MPCA began calculating the tracking metrics to find the reason for dropped visibility significant days.

MPCA discovered visibility significant days at the Upper Mid-West Class I areas were dropped because of an IMPROVE program interpretation of the tracking guidance in Step 5. Section 4.7.5 – Evaluate feasibility of patching average values, describes the procedure change MPCA incorporated based on its own interpretation of Step 5 to reintroduce the dropped days.

LADCO presented the findings and recommendations[79] to the IMPROVE program steering committee at its October 2018 meeting. The IMPROVE program assessed the impact of the revised interpretation of Step 5 network-wide and recommended[80] at its October 2019 meeting to accept the LADCO/MPCA recommendation to revise the calculation patching procedure, but to allow up to three missing parameters, and reserving the option to revise the approach. IMPROVE program later changed the allowable missing parameters to two in the nation-wide calculations after inspecting the results especially at high elevation sites in the West.

The IMPROVE program, in verbal consultation, has identified its role as ensuring reinterpretations of the tracking guidance applies across the IMPROVE network, which lead to the limit on the number of missing parameters in the data patching. But it was clarified that states or MJOs are not restricted from making their own interpretations to ensure proper inclusion of data in the tracking metrics. MPCA continues to apply its interpretation of Step 5 of the tracking metrics for Boundary Waters and Voyageurs.

4.7.1. Assemble composite components of $PM_{2.5}$

Step 1 in the U.S. EPA September 2003 guidance is to assemble the $PM_{2.5}$ species components for the visibility tracking metrics. The component species are generally the same as those used in the performance evaluation. These are the $PM_{2.5}$ species components measured on a routine basis at IMPROVE monitoring sites that collect $PM_{2.5}$ species components; nitrate, sulfate, organic carbon,

---

[78] *In the first implementation period, the most impaired days were termed the "worst days" and the clearest days were termed the "best days" before U.S. EPA updated the tracking metrics in December 2018*

[79] *LADCO and MPCA presentation to IMPROVE program steering committee meeting October 2018, http://vista.cira.colostate.edu/improve/wp-content/uploads/2018/10/16_Kenski_data-patching.pdf*

[80] *IMPROVE program steering committee presentation, http://vista.cira.colostate.edu/improve/wp-content/uploads/2019/10/20_Copeland-IMPROVE-Data-and-Metrics-10_23_2019.pdf, and minutes, http://vista.cira.colostate.edu/improve/wp-content/uploads/2020/10/IMPROVE_SteeringCommittee_2019_Minutes.pdf , October 2019*

elemental carbon and soil. Coarse mass (PM_{10} – $PM_{2.5}$) and sea salt also are part of the visibility tracking metrics, but they are not included in the model performance evaluation of $PM_{2.5}$ species components.

Table 14 contains a list of $PM_{2.5}$ composite components used in the tracking metrics and the processing they undergo. The organic carbon adjustment to mass concentration in Table 14 differs from the adjustments in Table 9 for the performance evaluation. While the adjustments in Table 9 are valid, any recommendations to apply the new adjustments to the tracking metrics have yet to be posed to the IMPROVE program steering committee. Discussion of each component species and data processing conducted by MPCA within context of the U.S. EPA September 2003 guidance follows in Table 14.

Table 14. Composite components of $PM_{2.5}$ for visibility tracking metric calculations

Component species name	IMPROVE measurement data		AQS parameter code IMPROVE variable code cross-reference
	Variable description	Variable code & data processing	
Ammonium sulfate (NH_4SO_4)	Particulate sulfur or sulfate ion with correction for ammonium ion	4.125 * Sf or 1.375 * SO4f	88169, Sulfur Pm2.5 Lc 88403, Sulfate Pm2.5 Lc
Ammonium nitrate (NH_4NO_3)	Calculated mass of ammonium nitrate	1.29 * NO3f	88306, Total Nitrate Pm2.5 Lc
Organic carbon mass	Sum of four measured organic carbon fractions and pyrolyzed organics with adjustment to mass concentration	1.8 * (OC1f + OC2f + OC3f + OC4f + Opf)	88320, Oc Pm2.5 Lc Tor (aka (88324+88325+88326+88327 +88328)
Elemental carbon (aka Light absorbing carbon)	Sum of three measured elemental carbon fractions less the pyrolyzed organics	EC1f + EC2f + EC3f - OPf	88321, Ec Pm2.5 Lc Tor (aka 88329+88330+88331-88328)
Soil	Sum of five crustal elements with corrections	2.20 * ALf + 2.49 * SIf + 1.63 * CAf + 2.42 * FEf + 1.94 * TIf	88104, Aluminum Pm2.5 Lc 88165, Silicon Pm2.5 Lc 88111, Calcium Pm2.5 Lc 88126, Iron Pm2.5 Lc 88161, Titanium Pm2.5 Lc
Course mass	PM_{10} – $PM_{2.5}$	MT - MF	85101, Pm10 - Lc 88101, Pm2.5 - Local Conditions
Sea salt	Chlorine or Chloride	1.8 * CLf or 1.8 * CHLf	88115, Chlorine Pm2.5 Lc 88203, Chloride Pm2.5 Lc

- Sulfate is preferably calculated from particulate sulfur (Sf). The U.S. EPA September 2003 guidance states that “if the Sf value is below the minimum detection limit, a value of half the minimum detection limit is assigned for sulfate but if that analysis is missing, then the ionic SO_4^-

(SO4f) determined by ion chromatography is used". MPCA does not conduct the "minimum" detection limit test within the tracking metric calculation, but directly substitutes in SO4f when Sf is missing. For all values collected since 2000, Sf has never measured below the method detection limit (mdl) at Boundary Waters or Voyageurs. The total mass of sulfate present is then calculated by applying a factor assuming it exists in the aerosol as ammonium sulfate (NH_4SO_4). The factor for Sf is 4.125 and the factor for SO4f is 1.375. If the result is negative, a value of zero is assigned.

- Nitrate is calculated directly from the measured nitrate ion values with a factor of 1.29 applied to account for associated ammonium ion (NH_4NO_3). If the result is negative, a value of zero is assigned.
- Organic carbon is calculated by summing the four organic carbon (OC) and pyrolyzed organic (OP) fractions with a factor of 1.8 adjustment for mass concentration. If the resultant organic carbon mass concentration is negative, a value of zero is assigned. Organic carbon does not apply the newer monthly derived adjustment factors present in the performance evaluation Section 4.6 because they have yet to come before the IMPROVE steering committee for adoption into the tracking metric calculations.
- Light absorbing carbon (LAC or EC) is calculated by summing the three elemental carbon fractions and subtracting the pyrolyzed organic (OP) fraction. If the result after subtraction is negative, a value of zero is assigned.
- Soil is calculated by summing the five crustal elements in Table 14, accounting for their presence as oxides (e.g. Al_2O_3) and applying adjustment factors to correct for non-soil potassium and the presence of other soil components. If any of the five primary crustal elements is below the minimum detection limit, it is assigned a value half of the minimum detection limit. If any of the five crustal elements is missing from the data set, generally all five will be missing because of the analytical method used for the elements. In that case the soil data are flagged as missing.
- Course mass is calculated by subtracting the $PM_{2.5}$ value from the corresponding PM_{10} value. If the result is negative, a value of zero is assigned.
- Sea salt calculations are not addressed in Step 1 of the U.S.EPA September 2003 guidance because the guidance developed for the original IMPROVE equation did not include sea salt as a variable. The sea salt calculations are included in the article published for the revised IMPROVE algorithm. [81] Sea salt calculations for years 2000 – 2003 are calculated by applying a factor of 1.8 to chlorine (CLf) if the chloride (CHLf) measurement is either below the mdl, missing or invalid. After year 2003, sea salt is simply calculated by applying a factor of 1.8 to CHLf. Resultant sea salt with a negative value is replaced with a value of zero.

4.7.2. Assess missing variables

Step 2 in the U.S. EPA September 2003 guidance allows for the substitution of missing data after reviewing the entire data set in Step 1. The Cooperative Institute for Research in the Atmosphere (CIRA) developed a substitute data set for Boundary Waters because of a lack of complete data for a few years. An equipment malfunction in 2002, 2003 and 2004 caused the loss of the following data:

- Module A – $PM_{2.5}$ particle mass
- Module C – Elemental and organic carbon mass

[81] *Pitchford 2007*

- Module D – PM_{10} particle mass

This data loss invalidated three out of every seven samples from these modules. "Module B" has a denuder that collects nitrate, chloride, sulfate and nitrite. According to CIRA, the "Module B" data from Boundary Waters during this period are valid. To utilize the valid data from Boundary Waters, CIRA substituted the missing components with a linear regression analysis from corresponding valid data collected at Voyageurs. Data substitution reports are available on the FED website. Monitoring at both Boundary Waters and Voyageurs has been stable since 2004 and has not required any additional data substitution.

Step 2 in the guidance also allows for patching missing data. Evaluating the feasibility of patching data and patching the data is described further in Section 4.7.5 (or Step 5). In preparation for evaluating the feasibility of patching the data, Step 3 (Section 4.7.3) and Step 4 (Section 4.7.4) must be followed.

4.7.3. Determine quarterly median concentrations for missing variables

Step 3 in the U.S. EPA September 2003 guidance describes the circumstances in which a quarterly median concentration can patch missing values for a variable in a data set. The steps MPCA took in accordance with the guidance are in the bulleted items below. The steps are taken independently for each variable.

- Divide the number of samples collected by the number of possible sampling days within each calendar quarter and flagging each quarter with at least 50% samples collected
- Identify each quarter with more than 10 consecutive days with missing data
- Assign a quarter as complete when the quarter has at least 50% samples collected and less than 10 consecutive days with missing samples
- Calculate the quarterly median for each complete quarter
- Average the quarterly median values for the year missing values and each of the previous four years of data

In carrying out this step, MPCA relied on CIRA to determine that no siting or procedural changes occurred at Boundary Waters and Voyageurs that would affect the comparability of the data used to calculate the average quarterly median values.

4.7.4. Obtain *f*(RH) values

Relative humidity factors, (*f*(RH)), are required in the light extinction calculations to adjust the light scattering effect of the hygroscopic aerosol species nitrate, sulfate and sea salt to account for particle growth caused by water vapor in the atmosphere. The U.S. EPA September 2003 guidance recommends the *f*(RH) factors be site-specific and on a monthly timeframe. The September 2003 guidance is based on the original IMPROVE algorithm, which didn't account for different water growth curves for small and large size distributions of sulfate, nitrate. Nor did it account for sea salt at all. The 2007 revised IMPROVE algorithm[82] does account for the small and large size distributions and corresponding water growth curves. The hygroscopicity is evaluated and thoroughly discussed in Hand 2006, et al, with relative humidity factors by month and Class I area provided in the FED.[83,84] Table 15 contains the unitless monthly relative humidity factors for Boundary Waters and Voyageurs.

---

[82] *Pitchford 2007*

[83] *Federal Land Manager Environmental Database. http://views.cira.colostate.edu/fed/QueryWizard/*

[84] *Hand 2006*

Table 15. Monthly f_S(RH) and f_L(RH) factors for Boundary waters and Voyageurs

Class I Area	*f*(RH)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Boundary Waters	f_S(RH)	3.24	2.84	2.99	2.64	2.93	3.21	3.44	3.67	3.80	3.07	3.50	3.49
	f_L(RH)	2.50	2.26	2.32	2.09	2.22	2.42	2.57	2.69	2.76	2.37	2.65	2.65
	f_{SS}(RH)	3.74	3.37	3.34	2.92	3.03	3.43	3.68	3.85	3.95	3.44	3.89	3.92
Voyageurs	f_S(RH)	3.16	2.77	2.82	2.59	2.65	3.28	3.25	3.48	3.66	3.02	3.37	3.32
	f_L(RH)	2.46	2.22	2.22	2.07	2.09	2.46	2.46	2.59	2.70	2.35	2.58	2.55
	f_{SS}(RH)	3.69	3.31	3.20	2.90	2.89	3.46	3.55	3.71	3.87	3.42	3.83	3.80

4.7.5. Evaluate feasibility of patching average values

Missing values in the IMPROVE data set are patched with quarterly 5-year median values if patching criteria are met. The process is meant to maximize the number of sample periods available for calculating tracking metrics without significantly degrading the haze calculation. The feasibility of patching missing values is determined by calculating light extinction with the IMPROVE equation for all days with no missing data, and by calculating light extinction again but filling in a proxy value (the quarterly median) for each variable (and a proxy variable-specific Rayleigh value) one at a time. A patch for a missing variable is feasible when the daily difference is less than 10% for at least 90% of the sample days. The following bulleted items describe how the patching feasibility test is executed.

- Separate the quarterly median values (QMV) calculated in step 3 (Section 4.7.3) for nitrate, sulfate and organic carbon into large and small groupings
  - Large group is assigned to the QMV when the QMV is greater than or equal to 20.0. When the QMV is less than 20.0, the large group is assigned after dividing the QMV^2 by 20.0.
  - Small group is assigned the value ‘0’ when the QMV is greater than or equal to 20.0. When the QMV is less than 20.0, the small group is assigned after dividing the QMV^2 by 20.0 and subtracting the result from the QMV.
- Consolidate the composite component values (CCV) in Step 1 (Section 4.7.1) and substitute values in Step 2 (Section 4.7.2), and separate nitrate, sulfate and organic carbon in large and small groupings using the same procedure in the 2nd-level bullets above
- Calculate the IMPROVE equation with multiple variations of value inputs, with results in terms of light extinction (b_{ext})
  - CCV for all variables
  - CCV for nitrate, sulfate, elemental carbon, soil, sea salt and coarse mass, QMV for organic carbon, and a proxy Rayleigh value for organic carbon
  - CCV for nitrate, organic carbon, elemental carbon, soil, sea salt and coarse mass, QMV for sulfate, and a proxy Rayleigh value for sulfate
  - CCV for sulfate, organic carbon, elemental carbon, soil, sea salt and coarse mass, QMV for nitrate, and a proxy Rayleigh value for nitrate
  - CCV for nitrate, sulfate, organic carbon, elemental carbon, soil and coarse mass, QMV for sea salt, and a proxy Rayleigh value for sea salt
  - CCV for nitrate, sulfate, organic carbon, elemental carbon, sea salt and coarse mass, QMV for soil, and a proxy Rayleigh value for soil
  - CCV for nitrate, sulfate, organic carbon, soil, sea salt and coarse mass, QMV for elemental carbon, and a proxy Rayleigh value for elemental carbon

- CCV for nitrate, sulfate, organic carbon, elemental carbon, soil and sea salt, QMV for coarse mass, and a proxy Rayleigh value for coarse mass

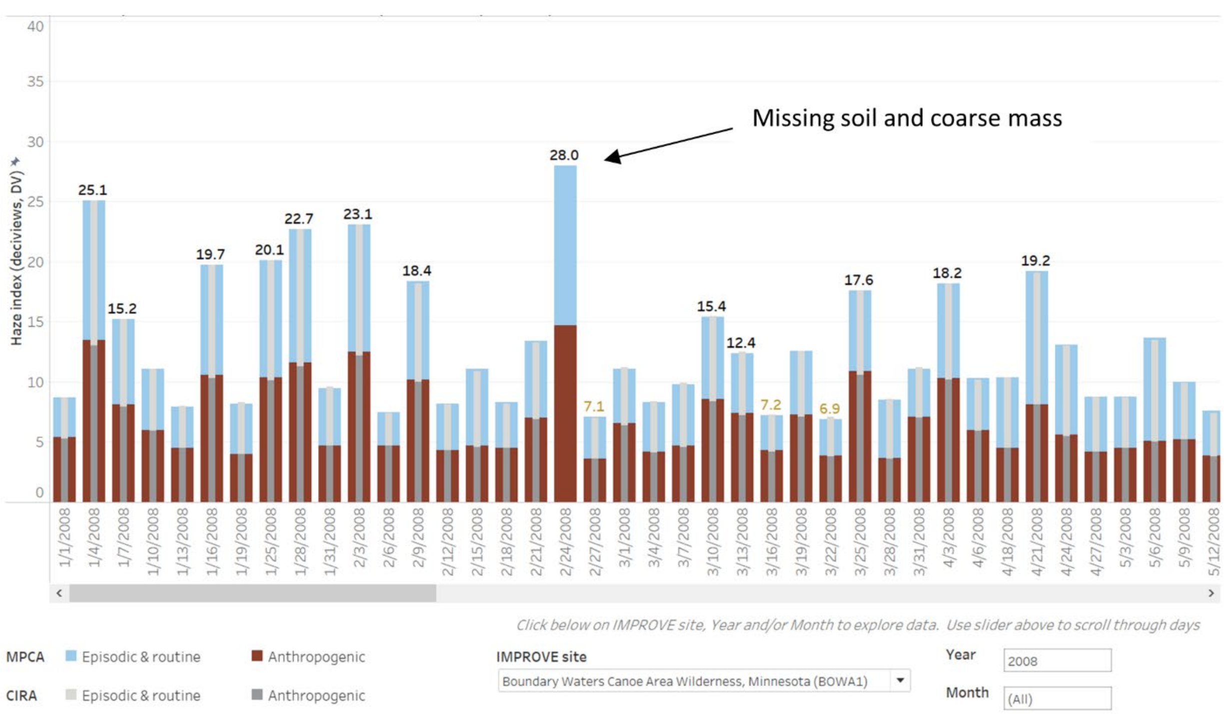
- For each variable, calculate the daily difference between QMV_{bext} and CMV_{bext}

In the first implementation period and up until about year 2019, the IMPROVE program patched missing values with quarterly medians only when one component variable (OC and LAC together are considered one component) was missing. After a recommendation by LADCO and MPCA, and after evaluating many years of data since implementing the 2003 guidance, the IMPROVE program has reinterpreted the relevant part of the guidance and now patches up to three missing component variables. The relevant paragraph in Step 5 of the guidance is below.

"Instances in which data on more than one aerosol component are missing in the same sample are likely to be rare. As a result, the process for dual substitution is not presented at length here. However, substitution of two variables in the same sample could be done, subject to adequate justification and testing, such as in the substitution test described previously. The same acceptance criterion of less than 10% difference in b_{ext} values in 90% of the data should apply."

The instances in which data on more than one aerosol component are missing in the same sample was found not to be rare. When making the recommendation to the IMPROVE program, MPCA provided an example of a day excluded from patching due to missing soil and coarse mass components. Figure 16 contains a comparison of MPCA and IMPROVE program CIRA calculated haze index. Each day haze index value is partitioned by natural (episodic & routine) and human-caused (anthropogenic), further discussed in Section 4.7.8 on identifying the most impaired and clearest days. Haze index totals at the top of a bar flag either the most impaired (black font) or the clearest days (gold font) at Boundary Waters as estimated by MPCA. Missing CIRA haze index bars indicate a failure to meet criteria for patching quarterly four-year average median values for any one component species in the CIRA calculations. An arrow in the Figure points to a stacked bar on February 28, 2008, a day excluded from the IMPROVE program patching by CIRA but included in the MPCA patching. That day had the highest haze index for the entire year due to nitrate and sulfate.

Figure 16. Example in 2008 of data excluded from 20% most impaired visibility days at Boundary Waters because of more than one missing aerosol component, soil and coarse mass



4.7.6. Patch composite component values

After determining the feasibility of patching the composite components with substitutions, patching the data occurs where the feasibility test passes.

4.7.7. Check data completeness

Once finished patching, Step 7 checks the data for completeness. A data set deemed ready to proceed to calculating tracking metrics has all quarters 50% complete, all years 75% complete, all years with four complete quarters, and no more than 10 consecutive missing sampling days a year. Boundary Waters and Voyageurs each have 20 years (2000 – 2019) of complete data.

4.7.8. Identify the most impaired and clearest days

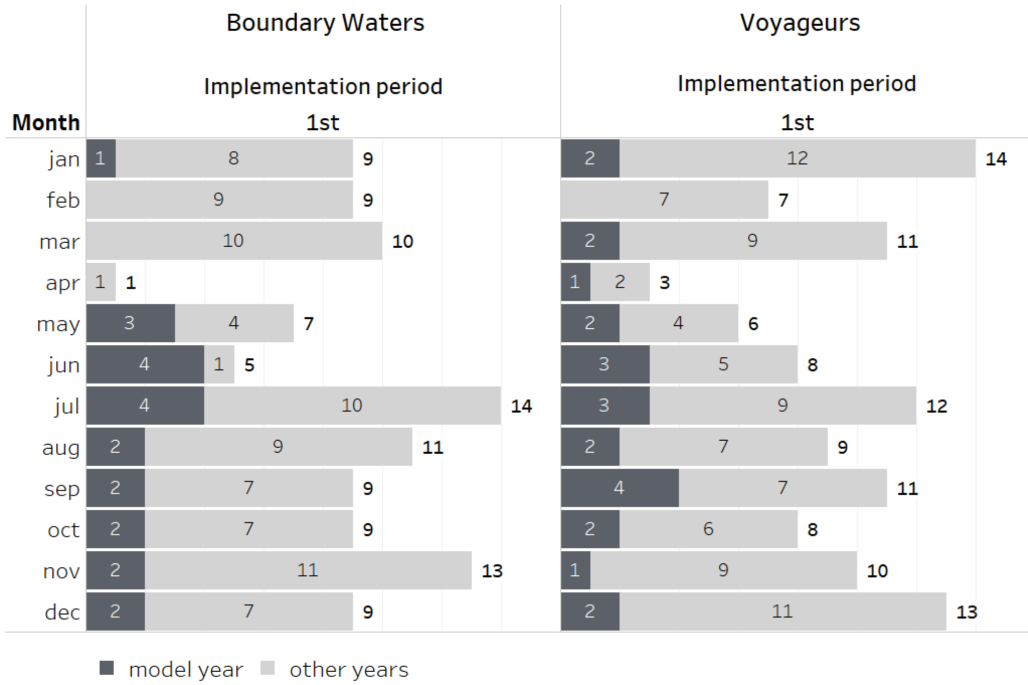
The tracking metric calculations start in Step 8 by identifying the most impaired and clearest days from a complete data set at each Class I area. These days are determined from calculated daily haze index values in units of deciview.

In the **first implementation period** the most impaired and clearest days were termed the “worst” and the “best” days and were selected simply by calculating haze index for each sample day, sorting the daily values from highest to lowest and choosing the days with 20% worst and 20% best daily values. The final Regional Haze Rule promulgated in 1999 did not distinguish between natural and human-caused contributions to visibility impairment when selecting the “worst days” and “best days” from the IMPROVE network monitoring data.[85] The worst and best visibility included days affected by natural wildfire. While wildfire had some impact on the visibility tracking metrics for Boundary Waters and Voyageurs, it had remarkable impact on Class I areas in the Western United States, prompting a change in guidance for the second implementation period.

In the first implementation period, observed values at Boundary Waters and Voyageurs during the baseline period, 2000 – 2004, indicate that the 20 percent worst visibility days are spread across all months of the year. During the warmer months several days were likely influenced by wildfires, which can contribute large amounts of organic carbon that significantly affect extinction. The monthly distribution of the number of worst visibility days calculated with the old metric procedures are shown in Figure 17.

[85] Regional Haze Regulations, 64 Fed. Reg. 35765 (July 1, 1999) (to be codified at 40 CFR Part 51).

Figure 17. Count of worst visibility days by month calculated with old tracking metric procedures for the model year and the other four years depicted in the tracking metric (years 2000-2004)[86]

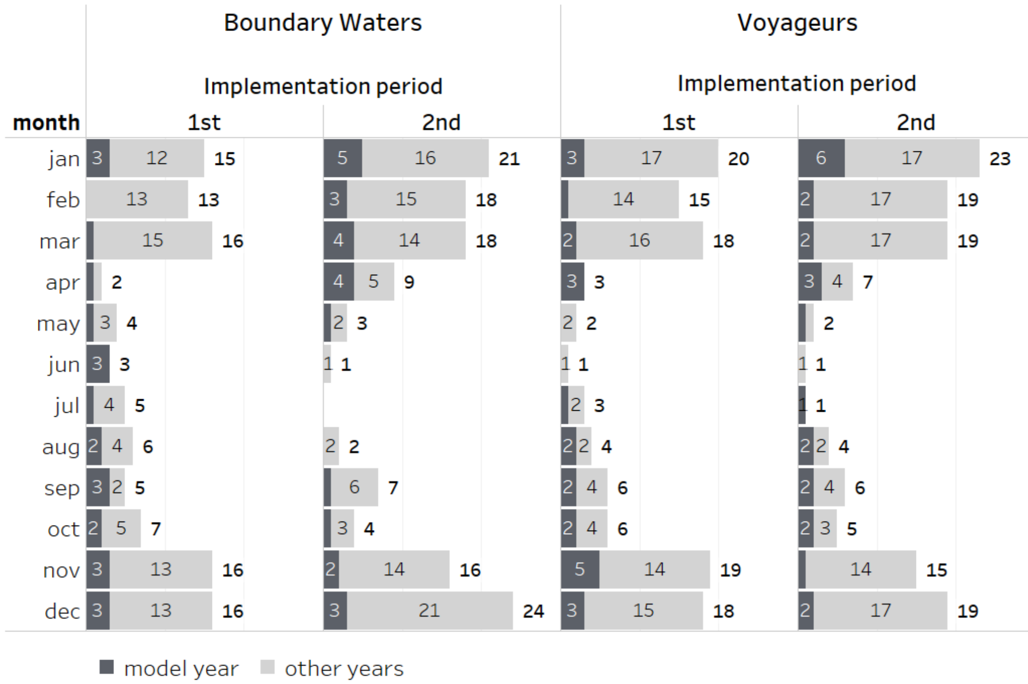


For the **second implementation period** U.S. EPA published new guidance December 2018 that altered the tracking metric calculations to account for natural wildfire impact on the selection of the 20% most impaired and 20% clearest visibility days.[87] The new tracking metric calculation procedures generally split organic carbon species into compartments; one compartment associated with natural wildfire and the other caused by human activities. The compartment containing human-caused organic carbon was retained in the sorting of days to identify the most impaired. The new metrics show many fewer most impaired days in the warmer months for both the first and second implementation periods. The monthly distribution of the number of worst visibility days calculated with the new metric procedures at Boundary Waters and Voyageurs are shown in Figure 18.

[86] *For the first implementation period, the model year is 2002 and the other four years in the tracking metric are 2000, 2001, 2003 and 2004*

[87] *See* Dec. 2018 EPA Technical Guidance, *supra*.

Figure 18. Count of most impaired visibility days by month calculated with new tracking metric procedures for the model year and the other four years depicted in the tracking metric (1st 2000-2004, 2nd 2014 – 2018)[88]



The new metrics designed to limit wildfire impacts in tracking visibility impairment may also have other implications for Boundary Waters and Voyageurs. Modeling in the first implementation period was weighted toward days in the summer months when winds were predominantly from the South and Southeast. Modeling in the second implementation period is weighted more toward days in the fall and winter months when winds are predominantly from the Northwest and West.

4.7.9. Calculate annual average deciviews

Step 9 in the U.S. EPA September 2003 guidance is simply to calculate the annual average haze index from the daily data.

4.7.10. Calculate 5-year deciview averages

Step 10 in the U.S. EPA September 2003 guidance is simply to calculate the 5-year rolling average haze index from the annual values.

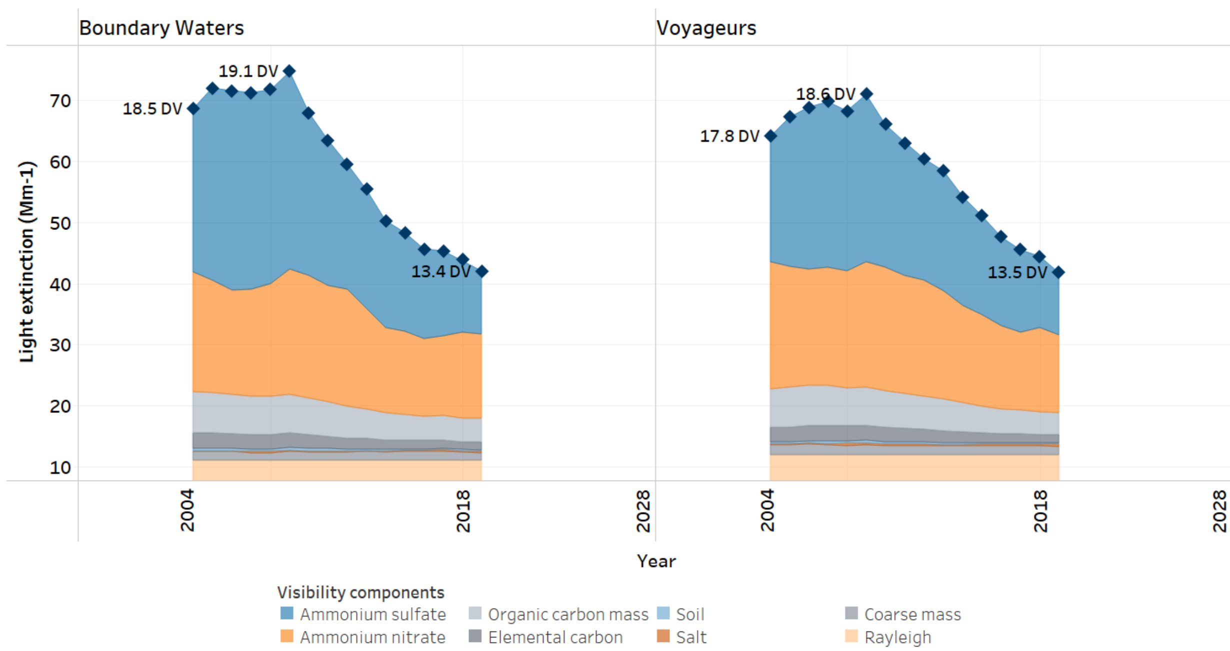
4.7.11. Visibility trends

Data from the IMPROVE monitoring sites at Boundary Waters and Voyageurs indicate that sulfates and nitrates continue to be the largest contributors to visibility impairment in these areas. The primary precursors of sulfates and nitrates are emissions of SO_2, NO_X, and NH_3. Other pollutants that can impair visibility include $PM_{2.5}$, coarse particulate matter and VOCs.

[88] For the first implementation period, the model year is 2002 and the other four years in the tracking metric are 2000, 2001, 2003 and 2004. For the second implementation period, the model year is 2016 and the other four years in the tracking metric are 2014, 2015, 2017 and 2018

Figure 19 shows the monitored visibility impairment, as light extinction, from the identified visibility components through 2019 for the most impaired visibility conditions at Boundary Waters and Voyageurs. The 5-year rolling average value of total light extinction is converted to the haze index in deciviews and superimposed at the top of each year.

Figure 19. Visibility components for most impaired visibility conditions at Boundary Waters and Voyageurs



Minnesota's Class I areas have shown marked improvements in visibility since the initial baseline period. The measured improvements in visibility impairment on the most impaired days can be attributed to reductions in sulfate, and to a lesser extent nitrate. These improvements are likely a result of enforceable controls/reductions for SO_2 and NO_X emissions at power plants, industrial facilities, and motor vehicles.

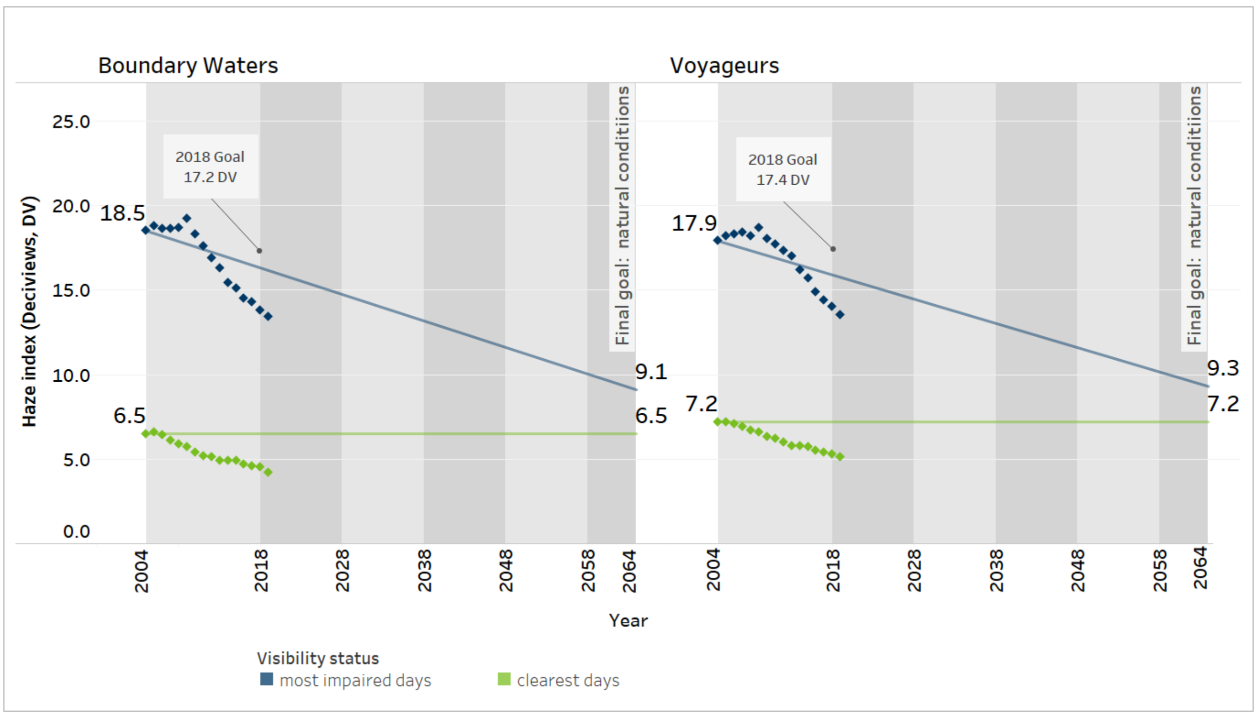
Data for specific years is presented Table 16, further illustrating the relative dominance nitrates and sulfates have in causing visibility impairment at Boundary Waters and Voyageurs. For example, at Boundary Waters sulfates and nitrates account for roughly 68% of the total visibility impairment in the initial baseline year (2004), 60% in the current baseline year (2016), and 59% in the initial projection year (2018).

Table 16. Visibility components at Boundary Waters and Voyageurs at initial baseline (2004), current baseline (2016), and initial projection year (2018)

Class I area	Year	Total (dv)	Light extinction by component (b_{ext} expressed in Mm^{-1})[89]							
			Total	NH_4SO_4	NH_4NO_3	OCM	EC	Soil	Salt	Coarse Mass
Boundary Waters	2004	18.5	68.6	26.7	19.6	6.8	2.5	0.4	0.1	1.5
	2016	14.5	45.6	14.8	12.6	4.0	1.4	0.2	0.2	1.5
	2018	13.8	43.9	11.7	14.1	3.8	1.3	0.2	0.2	1.4
Voyageurs	2004	17.9	64.1	20.4	20.8	6.4	2.4	0.3	0.1	1.6
	2016	14.9	47.6	14.5	13.7	4.0	1.5	0.2	0.2	1.5
	2018	14.0	44.3	11.6	13.8	3.7	1.4	0.2	0.3	1.4

Figure 20 shows the visibility status at Boundary Waters and Voyageurs in the form required by the Regional Haze Rule. The calculations for the 5-year rolling average haze index values in units of deciview are detailed in Sections 4.7.1 through 4.7.10. The other parts of this Figure are described below in more detail within context of the Regional Haze Rule. The 2018 Reasonable Progress Goals (RPG) from the first implementation period also appear on this Figure for reference. Section 4.8 describes the development of RPGs for the second implementation period and sets a new 2028 RPG displayed on an updated figure.

Figure 20. Visibility status at Boundary Waters and Voyageurs for the 20% most visibility impaired days and 20% clearest days



MPCA has created an interactive tool accessible from the Pollution Control Agency website (ctrl + click on icon below) that allows the user to explore the visibility data for Boundary Waters and Voyageurs.[90]

[89] *The value for the total column (b_{ext} as expressed in Mm^{-1}) includes the contribution of Rayleigh scattering; natural light scattering by gases in the atmosphere. The light extinction from Rayleigh scattering at Boundary Waters is 11 Mm^{-1} and at Voyageurs is 12 Mm^{-1}.*

[90] https://public.tableau.com/app/profile/mpca.data.services/viz/RegionalHaze_visibility_metrics_public/Visibilityprogress

The tool provides the visibility metrics and species components that are updated each year, and regional influences on the 20 percent most impaired and clearest visibility days at Boundary Waters and Voyageurs.

Explore visibility data for Minnesota Class I areas

This interactive tool shows the progress made toward interim goals for visibility, components of impaired visibility, and regional influences on the air in Minnesota Class I areas.

A breakdown of each rule requirement for each component of the tracking metrics for Boundary Waters and Voyageurs is provided below, along with tables containing calculated values for each element depicted in Figure 20.

Baseline visibility conditions for the most impaired and clearest days. 40 CFR § 51.308(f)(1)(i) specifies the requirements for calculating baseline visibility conditions:

> *The period for establishing baseline visibility conditions is 2000 to 2004. The State must calculate the baseline visibility conditions for the most impaired days and the clearest days using available monitoring data. To determine the baseline visibility condition, the State must calculate the average of the annual deciview index values for the most impaired days and for the clearest days for the calendar years from 2000 to 2004. The baseline visibility condition for the most impaired days or the clearest days is the average of the respective annual values. For purposes of calculating the uniform rate of progress, the baseline visibility condition for the most impaired days must be associated with the last day of 2004. For mandatory Class I Federal areas without onsite monitoring data for 2000-2004, the State must establish baseline values using the most representative available monitoring data for 2000-2004, in consultation with the Administrator or his or her designee. For mandatory Class I Federal areas with incomplete monitoring data for 2000-2004, the State must establish baseline values using the 5 complete years of monitoring data closest in time to 2000-2004.*

Both Boundary Waters and Voyageurs each have a complete set of data 2000-2004. Boundary Waters has a substitute dataset for this period because an equipment malfunction in 2002, 2003 and 2004 caused the loss of some $PM_{2.5}$ particle mass, elemental organic carbon mass and PM_{10} particle mass. The data loss invalidated three out of every seven samples for these components. In order to use the valid data, e.g. the nitrates and sulfates, missing elements were substituted with data from Voyageurs. Baseline visibility conditions are provided in Table 17. The calculations and data substitution are further described Section 4.7.6.

Table 17. Baseline visibility conditions at Boundary Waters and Voyageurs

Minnesota Class I area	Year	Most impaired (dv)		Clearest (dv)	
		Annual	Five-year Average	Annual	Five-year Average
Boundary Waters	2000	18.6		6.0	
	2001	19.4		6.9	
	2002	18.8		7.1	
	2003	18.5		6.8	
	2004	17.1	18.5	5.8	6.5

Minnesota Class I area	Year	Most impaired (dv)		Clearest (dv)	
		Annual	Five-year Average	Annual	Five-year Average
Voyageurs	2000	18.0		7.1	
	2001	17.7		7.1	
	2002	17.8		7.5	
	2003	18.8		7.7	
	2004	17.2	17.9	6.4	7.2

Natural visibility conditions for the most impaired and clearest days. 40 CFR § 51.308(f)(1)(ii) specifies the requirements for calculating natural visibility conditions:

> *A State must calculate natural visibility condition by estimating the average deciview index existing under natural conditions for the most impaired days or the clearest days based on available monitoring information and appropriate data analysis techniques.*

U.S. EPA published in September 2003[91] a separate guidance specifically for the estimation of natural visibility conditions under the Regional Haze Program. In the first implementation period, MPCA followed an updated procedure for establishing updated natural conditions[92] to adjust for small and large fractions in the revised IMPROVE algorithm. The U.S. EPA December 2018 guidance for the second implementation period adopts the term "natural" to mean both episodic + routine component fractions and clarifies the former meaning as only routine. The guidance also contains a footnote that "the agency may be updating the natural visibility conditions estimates in spring 2019, as necessary." No adjustments to the procedure for Boundary Waters and Voyageurs has been made. When used in the context of a goal, MPCA also refers to the natural visibility conditions as the unadjusted 2064 endpoint. The bulleted items below summarize the procedure for developing the natural visibility conditions, or 2064 endpoint.

- Calculate the annual arithmetic mean of each component species for the first five years of complete substituted and patched data for each Class I area
- Calculate Trijonis scaling factors by dividing the annual arithmetic mean by the relevant Trijonis default natural conditions value[93] (Table 18) when the annual arithmetic mean is greater than or equal to the Trijonis value, otherwise assign '1' as the scaling factor[94]
- Scale the daily component value for each variable by dividing by the scaling factor
- Split the scaled daily component values for nitrate, sulfate and organic carbon into large and small
- Apply the IMPROVE algorithm to the resulting scaled and size-adjusted daily component values and convert extinction to haze index
- Identify the 20% most impaired and 20% clearest visibility days, calculate the arithmetic mean for each year, then calculate the arithmetic mean over the five-years for the 20% most impaired and the 20% clearest visibility days

[91] USEPA 2003 September-b
[92] Copeland 2008
[93] USEPA 2003 September-b
[94] Sea salt does not have a Trijonis default natural conditions value and has a scaling factor of '1'

Table 18. Trijonis default natural conditions

Component species name	Trijonis default natural conditions[95] (µg/m³)	
	Contiguous U.S. – West	Contiguous U.S. – East
Ammonium sulfate	0.12	0.23
Ammonium nitrate	0.10	0.10
Organic carbon mass	0.60	1.80
Elemental carbon (aka Light absorbing carbon)	0.02	0.02
Soil	0.50	0.50
Course mass	3.00	3.00

Table 19 contains the calculated 2064 end point at Boundary Waters and Voyageurs using the above methodology.

Table 19. 2064 end points at Boundary Waters and Voyageurs

Visibility Conditions	Boundary Waters		Voyageurs	
	Most impaired	Clearest	Most impaired	Clearest
End point (2064) (dv)	9.1	6.5	9.3	7.2

Current visibility conditions for the most impaired and clearest days. 40 CFR § 51.308(f)(1)(iii) specifies the requirements for calculating current visibility conditions:

> *The period for calculating current visibility conditions is the most recent 5-year period for which data are available. The State must calculate the current visibility conditions for the most impaired days and the clearest days using available monitoring data. To calculate each current visibility condition, the State must calculate the average of the annual deciview index values for the years in the most recent 5-year period. The current visibility condition for the most impaired or the clearest days is the average of the respective annual values.*

Current conditions defined here include available measurement data for the five-year period 2015 - 2019. Current conditions for most impaired visibility far surpass the 2018 interim progress goals set in Minnesota's first round SIP submitted to U.S. EPA in 2009. Current conditions for clearest visibility become more clear and do not degrade from baseline, as shown in Table 20.

Table 20. Current visibility conditions at Boundary Waters and Voyageurs

Minnesota Class I area	Year	Most impaired (dv)		Clearest (dv)	
		Annual	Five-year average	Annual	Five-year average
Boundary Waters	2015	13.8	15.1	4.5	4.9
	2016	12.0	14.5	4.2	4.7
	2017	14.5	14.3	5.0	4.6
	2018	13.7	13.8	4.0	4.5
	2019	13.1	13.4	3.5	4.2

[95] *"West" and "east" are defined as west or east of the 98th meridian. Boundary Waters and Voyageurs fall into east*

Minnesota Class I area	Year	Most impaired (dv)		Clearest (dv)	
		Annual	Five-year average	Annual	Five-year average
Voyageurs	2015	13.5	15.7	5.4	5.7
	2016	12.6	14.9	4.9	5.5
	2017	14.1	14.4	5.8	5.4
	2018	14.2	14.0	4.9	5.3
	2019	13.2	13.5	4.3	5.1

Progress to date for the most impaired and clearest days. 40 CFR § 51.308(f)(1)(iv) specifies the requirements for calculating progress to date:

> *Actual progress made towards the natural visibility condition since the baseline period, and actual progress made during the previous implementation period up to and including the period for calculating current visibility conditions, for the most impaired and for the clearest days.*

As described above, Minnesota Class I areas show marked progress toward clear air from baseline (2000 – 2004) to present. Table 21 contains the calculated visibility haze index for each year since the baseline 2004.

Table 21. Visibility progress to date at Boundary Waters and Voyageurs

Year	Boundary Waters		Voyageurs	
	Most impaired 5-year average (dv)	Clearest days 5-year average (dv)	Most impaired 5-year average (dv)	Clearest days 5-year average (dv)
2004	18.5	6.5	17.9	7.2
2005	18.8	6.6	18.2	7.2
2006	18.6	6.4	18.3	7.1
2007	18.6	6.1	18.4	6.9
2008	18.7	5.9	18.2	6.7
2009	19.2	5.7	18.7	6.6
2010	18.3	5.4	18.0	6.3
2011	17.6	5.2	17.7	6.2
2012	16.9	5.1	17.3	6.0
2013	16.3	4.9	17.0	5.8
2014	15.4	4.9	16.2	5.8
2015	15.1	4.9	15.7	5.7
2016	14.5	4.7	14.9	5.5
2017	14.3	4.6	14.4	5.4
2018	13.8	4.5	14.0	5.3
2019	13.4	4.2	13.5	5.1

Differences between current visibility condition and natural visibility condition. 40 CFR § 51.308(f)(1)(v) specifies the requirements for calculating the difference between current and natural visibility conditions:

> *The number of deciviews by which the current visibility condition exceeds the natural visibility condition, for the most impaired and for the clearest days.*

Current visibility conditions for the most impaired days at both Boundary Waters and Voyageurs are just above 4 dv over the 2064 endpoint. Visibility conditions for the clearest days are more than 2 dv clearer than the 2064 endpoint. Table 22 contains the number of deciviews by which the current visibility conditions exceed natural conditions at Boundary Waters and Voyageurs.

Table 22. Current vs. natural visibility conditions at Boundary Waters and Voyageurs

Visibility conditions	Boundary Waters		Voyageurs	
	Most impaired	**Clearest**	**Most impaired**	**Clearest**
Current (2019) (dv)	13.4	4.2	13.5	5.1
End point (2064) (dv)	9.1	6.5	9.3	7.2
Difference (2019 – 2064) (dv)	4.3	-2.3	4.2	-2.1

Uniform rate of progress. 40 CFR § 51.308(f)(1)(vi)(A) specifies the requirements for calculating the URP:

> *The uniform rate of progress for each mandatory Class I Federal area in the State. To calculate the uniform rate of progress, the State must compare the baseline visibility condition for the most impaired days to the natural visibility condition for the most impaired days in the mandatory Class I Federal area and determine the uniform rate of visibility improvement (measured in deciviews of improvement per year) that would need to be maintained during each implementation period in order to attain natural visibility conditions by the end of 2064.*

Current conditions for most impaired visibility at both Boundary Waters (13.4 dv) and Voyageurs (13.5 dv) are below the URP reference line through 2028 (the second implementation period), as shown in Table 23.

Table 23. Uniform rate of progress to reach natural visibility conditions

Minnesota Class I area	Uniform rate of progress by implementation period (dv)						
	2004	**2018**	**2028**	**2038**	**2048**	**2058**	**2064**
Boundary Waters	18.5	16.3	14.7	13.2	11.6	10.0	9.1
Voyageurs	17.9	15.9	14.5	13.0	11.6	10.2	9.3

2064 Endpoint adjustments. Additionally, 40 CFR § 51.308(f)(1)(vi)(B) specifies the requirements for proposing an adjustment to the uniform rate of progress to account for impacts from anthropogenic sources outside the United States and/or wildland prescribed fires conducted with a certain described objective described in the rule.

> *As part of its implementation plan submission, the State may propose (1) an adjustment to the uniform rate of progress for a mandatory Class I Federal area to account for impacts from anthropogenic sources outside the United States and/or (2) an adjustment to the uniform rate of progress for the mandatory Class I Federal area to account for impacts from wildland prescribed fires that were conducted with the objective to establish, restore, and/or maintain sustainable and resilient wildland ecosystems, to reduce the risk of catastrophic wildfires, and/or to preserve endangered or threatened species during which appropriate basic smoke management practices were applied. To calculate the proposed adjustment(s), the State must add the estimated impact(s) to the natural visibility condition and compare the baseline visibility condition for the most impaired days to the resulting sum. If the Administrator determines that the State has estimated the impact(s) from anthropogenic sources outside the United States and/or wildland prescribed fires using scientifically valid data and methods, the Administrator may approve the proposed adjustment(s) to the uniform rate of progress.*

MPCA does not believe it has scientifically valid data and methods—this second implementation period—to estimate the impacts from human activity outside the United States and/or wildland prescribed fires to seek U.S. EPA approval to adjust the 2064 endpoint and the uniform rate of progress. Current measurements are well below the URP glidepath and have been steadily trending downward.

While Minnesota does not seek U.S. EPA approval to adjust the 2064 end point this implementation period, readily available information by other organizations suggests Boundary Waters and Voyageurs could reach adjusted goals before year 2064. Table 24 contains adjusted 2064 endpoints for the second implementation period estimated through global or hemispheric photochemical modeling by U.S.EPA and by the Electric Power Research Institute (EPRI) under contract with Ramboll.

Neither U.S.EPA nor EPRI used the same version of the 2016 model platform as MPCA, which used 2016 v1b, and both organizations likely used a different source of 20% most impaired days for their contribution analyses than MPCA. U.S.EPA describes its work as their "first comprehensive estimate of international anthropogenic emissions contributions to visibility impairment at Class I areas" and warrants additional scrutiny. While prescribed fire adjustments to the endpoint are also allowed under rule, neither U.S.EPA nor EPRI included them. Specified reasons for excluding prescribed fire adjustments are, natural conditions may already include some prescribed fire, there uncertainties in the emission estimates, prescribed fire activity varies significantly year to year, and the contribution from prescribed fire would be quite small compared to international impacts.

Table 24. Adjusted 2064 endpoints by other organizations for the most impaired visibility days at Boundary Waters and Voyageurs

Minnesota Class I area	Adjusted 2064 endpoints estimates (dv)		
	Natural conditions	U.S. EPA (September 2019)[96]	EPRI (September 2020)[97]
Boundary Waters	9.1	12.1	11.6
Voyageurs	9.3	12.5	12.0

The U.S.EPA adjusted endpoint suggests visibility impact at Boundary Waters would need to decrease from year 2019 an additional 1.3 dv (13.4 -12.1 dv), and Voyageurs an additional 1.0 dv (13.5 – 12.5 dv) dv, to reach the endpoint goal. The EPRI adjusted endpoint suggests visibility impact at Boundary Waters would need to decrease from year 2019 an additional 1.8 dv (13.4 – 11.6 dv), and Voyageurs an additional 1.5 dv (13.5 – 12.0 dv), to reach the endpoint goal. Between 2004 and 2009 there were measured increases in visibility impact at both Class I areas, but since 2009 the most impaired annual 5-year visibility impacts have declined per year an average 0.6 dv at Boundary Waters and an average 0.5 dv at Voyageurs. Should this trend continue, Boundary Waters and Voyageurs potentially could reach an adjusted endpoint by the third implementation period (2028 – 2038).

4.8. Control strategy development

MPCA has met the requirements of the Regional Haze Rule in the comprehensive update to Minnesota's long-term strategy within the Regional Haze SIP.[98] MPCA evaluated and determined the emission reduction measures needed to make reasonable progress and documented the methodology in the SIP. The emission reduction measures include completed and planned emission unit retirements, utilization of existing effective controls, additional expected reductions achieved through other programs and the creation of new non-binding emission reduction targets in the Northeast Minnesota plan introduced in the first implementation period Regional Haze SIP.

[96] *USEPA 2019 September*
[97] *EPRI*
[98] *MPCA 2022*

The reasonableness of the long-term strategy falls beyond the scope of this TSD. To be reasonable, factors such as the cost effectiveness of the control measures are assessed. The Regional Haze SIP provides discussion on the reasonableness of the long-term strategy. This TSD does, however, provide detail on emissions unit level emissions changes that were modeled to reflect the strategy. The TSD also provides evidence that the RPG at Boundary Waters and Voyageurs appear to be somewhat conservative estimates. As described further below, not all emission reduction measures could be reflected in the modeling, and some emissions increase projections reflected in the modeling are unlikely to occur, suggesting visibility conditions will improve more than predicted.

In the following sections MPCA sets the RPGs for Boundary Waters and Voyageurs for the second implementation period and provides an assessment of the contributing pollutants, geographic regions and emissions sectors to the RPG.

4.8.1. Reasonable progress goals (RPGs) for the second implementation period

States with Class I within their borders are required to establish reasonable progress goals (RPGs) for those Class I areas. To set the RPGs, the Regional Haze Rule requires states to project visibility conditions to end of the implementation period that reflect the long-term strategy and other enforceable measures in place. This means that Minnesota must determine the 2028 RPGs for Boundary Waters and Voyageurs, based on the long-term strategy and other enforceable measures.

The requirement to establish these RPGs is specified in 40 CFR § 51.308(f)(3)(i).

> ***Reasonable progress goals.*** *A state in which a mandatory Class I Federal area is located must establish reasonable progress goals (expressed in deciviews) that reflect the visibility conditions that are projected to be achieved by the end of the applicable implementation period as a result of those enforceable emissions limitations, compliance schedules, and other measures required under [40 CFR § 51.308 (f)(2)] that can be fully implemented by the end of the applicable implementation period, as well as the implementation of other requirements of the CAA. The long-term strategy and the reasonable progress goals must provide for an improvement in visibility for the most impaired days since the baseline period and ensure no degradation in visibility for the clearest days since the baseline period.*

U.S. EPA provides additional information regarding the relationship between a state's long-term strategy and the RPGs set for Class I areas located within their borders in its August 2019 Guidance.[99] Briefly, U.S. EPA reiterates that the RPGs are a projected outcome based on the content of the long-term strategy. Meeting the RPGs is not an enforceable requirement of the Regional Haze Rule, but RPGs do provide a useful metric for evaluating progress. The Regional Haze Rule identifies the intended use of the RPGs in 40 CFR § 51.308(f)(3)(iii).

> *The reasonable progress goals established by the State are not directly enforceable but will be considered by the Administrator in evaluating the adequacy of the measures in the implementation plan in providing for reasonable progress towards achieving natural visibility conditions at that area.*

U.S. EPA also clarifies that while states are required to determine the RPGs, there are no requirements in the Regional Haze Rule regarding the method and tools used to do so. U.S. EPA suggests that states will typically project visibility conditions through photochemical air quality modeling. U.S. EPA goes on to identify that many details associated with the U.S. EPA-recommended modeling process for

[99] *USEPA 2019 August*

projecting RPGs are explained in further detail within U.S. EPA's November 29, 2018 modeling guidance.[100]

MPCA has followed the U.S. EPA guidance for using a photochemical model to estimate future visibility in Boundary Waters and Voyageurs and to establish RPGs.

4.8.2. Reasonable Progress Goals for Boundary Waters and Voyageurs

Recognizing the intense resources required to conduct modeling analyses of this nature, U.S. EPA guidelines for regional haze do not suggest modeling the multiple years comprising the 5-year baseline period (2014 – 2018), but discuss modeling one full year (i.e. 2016) as a "logical goal". The methodology in the U.S. EPA guidelines attempts to take into account the year-to-year variability of the meteorology in the monitored baseline. The middle year (2016) will have more weight because the 2016 emissions and meteorology are used in the modeling to develop the RRF applied to the baseline conditions. This application of the model results intends to balance the resource limitations of conducting multiple years of modeling, and to "help reduce the impact of possible over-or under-estimations by the dispersion model due to emissions, meteorology, or general selection of other model input parameters"[101].

Relative Response Factors. MPCA used the CAMx model with the inputs described in Section 4 to simulate the future visibility conditions that will result from future emissions estimates. U.S. EPA guidelines require model simulations of emissions from a "base" or known, year (e.g. 2016) representing the baseline period and from a year in the future (e.g. 2028). The model results are used to estimate the air concentration change from base year to future year. These air concentration changes are in the form of ratios of the future year air concentrations to the base year concentrations predicted near a monitor location and averaged over the same 20 percent most impaired and 20 percent clearest days in the base year that were used to establish baseline visibility conditions. A ratio is developed for each specie comprising $PM_{2.5}$ (sulfate, nitrate, organic carbon, elemental carbon, fine soil [≤2.5 µm diameter], and coarse particulate matter [>2.5 µm, but ≤10 µm diameter]). The ratio, called a Relative Response Factor (RRF), is calculated as follows:

$$RRF_{[X]} = \text{Modeled Future Mean}_{[X]} / \text{Modeled Base Year Mean}_{[X]}$$

Where: RRF is the relative response factor (unitless);

Future Mean and Base Year Mean are the modeled base year (2016) and the future year (2028) concentrations at the Class I area monitor location averaged for the 20 percent most impaired days (and 20 percent clearest days) as determined by the base year (2016) monitor data; and

[X] is the species concentration sulfate, nitrate, organic carbon, elemental carbon, fine soil and coarse particulate matter

Applying the RRFs to baseline monitoring conditions, for each species comprising $PM_{2.5}$, provides the estimate of future visibility conditions. Applying the methodology with future emission estimates that reflect reasonable controls provides the RPG based on modeling. These steps are bulleted below.

- Multiply each species specific RRF by the corresponding measured species concentrations for all of the 20 percent most impaired (and 20 percent clearest) days over the 5-year baseline period to obtain the future projected estimate based on modeling

$$\text{Future}_{[X]} = RRF_{[X]} * \text{Baseline}_{[X]} \text{ daily value}$$

[100] *USEPA 2018*
[101] *USEPA 2018*

where: [X] is the species concentration sulfate, nitrate, organic carbon, elemental carbon, fine soil and coarse particulate matter

- Estimate the extinction coefficient (b_{ext}) for $Future_{[X]}$ using the IMPROVE algorithm and converting to units of deciview
- Calculate the future visibility projection estimate, which may also be the RPG, over the 20 percent most impaired (and 20 percent clearest) days
  - Calculate the annual arithmetic mean for each year in the baseline period
  - Calculate a 5-year mean from the annual values

MPCA has set the 2028 RPGs for Boundary Waters and Voyageurs at the deciview levels, 13.4 dv for Boundary Waters and 13.6 dv for Voyageurs, shown in Table 25. The 2028 model projection for the clearest days, 4.5 dv for Boundary Waters and 5.3 dv for Voyageurs, ensures "no degradation" from baseline visibility, 6.5 dv for Boundary Waters and 7.2 dv for Voyageurs. The Table also includes the 2018 RPGs set in the first implementation period, for reference. In the first implementation period, the 2028 projection on the clearest days at Boundary Waters was 6.6 dv, 0.1 dv above the goal of no degradation, 6.5 dv.

Table 25. Reasonable progress goals (RPG) at Boundary Waters and Voyageurs

Intermediate goal year	Boundary Waters		Voyageurs	
	Most impaired RPG	Clearest no degradation	Most impaired RPG	Clearest No degradation
Period 1: 2018 (dv)	17.2	6.6	17.5	7.2
Period 2: 2028 (dv)	13.4	4.5	13.6	5.3

Factors impacting the RPG. Not all measures in the long-term strategy are reflected in the RPGs because they were not available at the time the 2016 model platform was developed. Table 26 lists all the facilities and emission units MPCA considered for the long-term strategy and how they are reflected in the emissions projections.

All the emission unit retirements at the electric generation facilities are included in the long-term strategy. However, the ERTAC emissions projection model shifts power generation to other emission units, including at facilities with emission unit retirements. The power generation shift occurs primarily to natural gas to offset lost generation capacity from coal unit retirements. There are no new coal units.

- Xcel Energy – Sherburne units 1 and 2 are retired in the modeling, but emissions increase at unit 3 which is scheduled to retire in 2030
- Minnesota Power – Boswell Energy Center units 1 and 2 are retired in the modeling, but emissions increase at units 3 and 4
- Hibbing Public Utilities Commission is not scheduled to retire and has NO_X emission reductions scheduled for implementation through emission limits, but the ERTAC model increases emissions at three of the units considered in the four-factor analysis

Measures that did not make it into the modeling, and therefore are not reflected in the RPG are:

- Hibbing Taconite Company requirements in the taconite FIP for the first implementation period
- Cleveland Cliffs Minorca Mine requirements in the taconite FIP for the first implementation period

Table 26. Long term strategy measures reflected in the RPGs for Boundary Waters and Voyageurs

Facility name	Emission unit	Action	Reflected in RPG	Modeled emission change			
				ΔNO_X		ΔSO_2	
				Tons	%	Tons	%
American Crystal Sugar - Crookston	Boiler 1	-	-	-	-	-	-
	Boiler 2	-	-	-	-	-	-
	Boiler 3	-	-	-	-	-	-
American Crystal Sugar - East Grand Forks	Boiler 1	-	-	-	-	-	-
	Boiler 2	-	-	-	-	-	-
Boise White Paper	Recovery Furnace	-	-	-	-	-	-
	Boiler 1	-	-	-	-	-	-
	Boiler 2	-	-	-	-	-	-
Cleveland Cliffs Minorca Mine Inc.	Indurating Machine	Low NO_X burners	No	-2,102	-65%	-	-
Hibbing Public Utilities Commission	Boiler No. 1A	ERTAC	Yes	+6	+4%	+198	+133%
	Boiler No. 2A	ERTAC	Yes	+125	+315%	+311	+830%
	Boiler No. 3A	ERTAC	Yes	-30	-15%	+179	+106%
	Wood Fired Boiler	-	-	-	-	-	-
Hibbing Taconite Company	Indurating Furnace Line 1	Low NO_X burners	No	-730	-61%	-	-
	Indurating Furnace Line 2	Low NO_X burners	No	-846	-48%	-	-
	Indurating Furnace Line 3	Low NO_X burners	No	-731	-54%	-	-
Minnesota Power - Boswell Energy Center	Unit 1	Retired 2018	Yes	-540	-100%	-1,560	-100%
	Unit 2	Retired 2018	Yes	-456	-100%	-1,391	-100%
	Unit 3	ERTAC	Yes	+88	+12%	+17	+12%
	Unit 4	ERTAC	Yes	+265	+10%	+56	+10%
Minnesota Power - Taconite Harbor Energy	Boiler 1	Retirement 2023	Yes	-219	-100%	-525	-100%
	Boiler 2	Retirement 2023	Yes	-187	-100%	-407	-100%
Northshore Mining - Silver Bay	Power Boiler 1	Idled to 2031	Yes	-377	-100%	-609	-100%
	Power Boiler 2	Idled to 2031	Yes	-1,011	-100%	-782	-100%
	Furnace 11	-	-	-	-	-	-
	Furnace 12	-	-	-	-	-	-

Facility name	Emission unit	Action	Reflected in RPG	Modeled emission change			
				ΔNO_X		ΔSO_2	
				Tons	%	Tons	%
Sappi Cloquet LLC	Power Boiler #9	-	-	-	-	-	-
	Recovery Boiler #10	-	-	-	-	-	-
Southern Minnesota Beet Sugar Coop	Boiler 1	-	-	-	-	-	-
United Taconite LLC - Fairlane Plant	Line 1 Pellet Induration	Low NO_X burners	Yes	-22	-2%	-	-
	Line 2 Pellet Induration	Low NO_X burners	Yes	-549	-23%	-	-
US Steel Corporation - Keetac	Grate Kiln	Low NO_X burners	Yes	-3,654	-73%		
US Steel Corporation - Minntac	Line 3 Rotary Kiln	Low NO_X burners	Yes	-405	-36%	-	-
	Line 4 Rotary Kiln	Low NO_X burners	Yes	-630	-33%	-	-
	Line 5 Rotary Kiln	Low NO_X burners	Yes	-410	-34%	-	-
	Line 6 Rotary Kiln	Low NO_X burners	Yes	-337	-33%	-	-
	Line 7 Rotary Kiln	Low NO_X burners	Yes	-398	-37%	-	-
Virginia Department of Public Utilities	Boiler 7	Retirement 2025	Yes	-23	-100%	-39	-100%
	Boiler 9	Retirement 2021	Yes	-214	-100%	-247	-100%
	Boiler 11	-	-	-	-	-	-
Xcel Energy - Allen S. King	Boiler 1	Retirement 2028	Yes	-1,380	-100%	-1,505	-100%
Xcel Energy - Sherburne	Unit 1	Retirement 2026	Yes	-3,057	-100%	-451	-100%
	Unit 2	Retirement 2023	Yes	-1,929	-100%	-306	-100%
	Unit 3	Retirement 2030 / ERTAC	No / Yes	+525	+15%	+1,168	+15%

Overall, MPCA believes the RPGs at Boundary Waters and Voyageurs appear to be somewhat conservative estimates of visibility improvements due to the long-term strategy for the second implementation period. Not all emission reduction measures could be reflected in the modeling, and some emissions increase projections reflected in the modeling are unlikely to occur, suggesting visibility conditions will improve more than predicted.

RPG comparison to uniform rate of progress. After states with Class I areas within their borders establish RPGs for their Class I area(s), the Regional Haze Rule requires a comparison of the RPGs to the baseline period visibility conditions and to the URP glidepath. This means that Minnesota must provide this comparison for the 2028 RPGs for Boundary Waters and Voyageurs.

In its August 2019 Guidance, U.S. EPA summarizes the needed information for the progress, degradation, and URP glidepath checks that states must provide for Class I areas within their borders:

- Demonstrate that there will be an improvement on the 20% most impaired days in 2028 compared to 2000-2004 conditions
- Demonstrate that there will be no degradation on the 20% clearest days in 2028 compared to 2000-2004 conditions
- Determine the URP that would achieve natural conditions in 2064 (may be adjusted for certain international impacts and wildland prescribed fires subject to U.S. EPA approval)
- Compare the 2028 RPGs for the most impaired days to the 2028 point on the URP glidepath (with additional demonstrations required if the RPG is above the glidepath)

Minnesota Class I areas show marked improvement on the 20% most impaired days and show no degradation on the 20% clearest days in 2028 compared to 2000-2004 conditions.

Table 27 shows the values at each milestone and placement of the 2028 RPGs on the URP glidepath. Since 2004 baseline an estimated visibility improvement of 5.1 dv at Boundary Waters and 4.3 dv at Voyageurs is projected in 2028 on the most impaired days.

Table 27. Progress, degradation, and glidepath checks at Boundary Waters and Voyageurs

Days	Milestone	Boundary Waters	Voyageurs
Most impaired	2004 Baseline	18.5	17.9
	2028 Projection	13.4	13.6
	Progress (2028 – 2004)	-5.1	-4.3
	Uniform rate of progress	14.7	14.5
	Glidepath check (2028 – URP)	-1.3	-0.9
Clearest	2004 Baseline	6.5	7.2
	2028 Projection	4.5	5.3
	No degradation check (2028 – 2004)	-2.0	-1.9

Achieving natural conditions in 2064 looks promising even without adjusting for international impacts and wildland prescribed fires. Should those adjustments be made in future implementation periods, meeting natural conditions might occur earlier than 2064. While Minnesota does not seek U.S. EPA approval to adjust the 2064 end point this implementation period, readily available information suggests an earlier end point.

The 2028 RPGs for the most impaired days at Boundary Waters and Voyageurs are below the 2028 point on the URP glidepath. No additional demonstrations are required.

Figure 21 for Boundary Waters and Figure 22 for Voyageurs illustrate the marked projected progress toward unadjusted natural conditions. Similar to the first implementation period, the 2028 model projected RPGs show a relatively flat estimated visibility reduction from baseline. In the first implementation period, the 2018 RPG from baseline 2004 reflected a 1.3 dv reduction at Boundary Waters and 0.5 dv reduction at Voyageurs. In the second implementation period, the 2028 RPG from baseline 2016 reflects a 1.1 dv reduction at Boundary Waters and a 1.3 dv reduction at Voyageurs.

Measurements of actual visibility progress indicate the modeled estimates underpredict in both implementation periods. In the first implementation period, measurements from 2004 to 2018 show a

4.7 dv reduction at Boundary Waters and 3.9 dv reduction at Voyageurs. In the second implementation period, the RPGs for 2028 have already been met in 2019. This equates to a 1.1 dv (14.5 – 13.4 dv) reduction at Boundary Waters and 1.4 dv (14.9 – 13.5 dv) reduction at Voyageurs from 2016 to 2019.

Figure 21. Progress, degradation, and glidepath checks at Boundary Waters

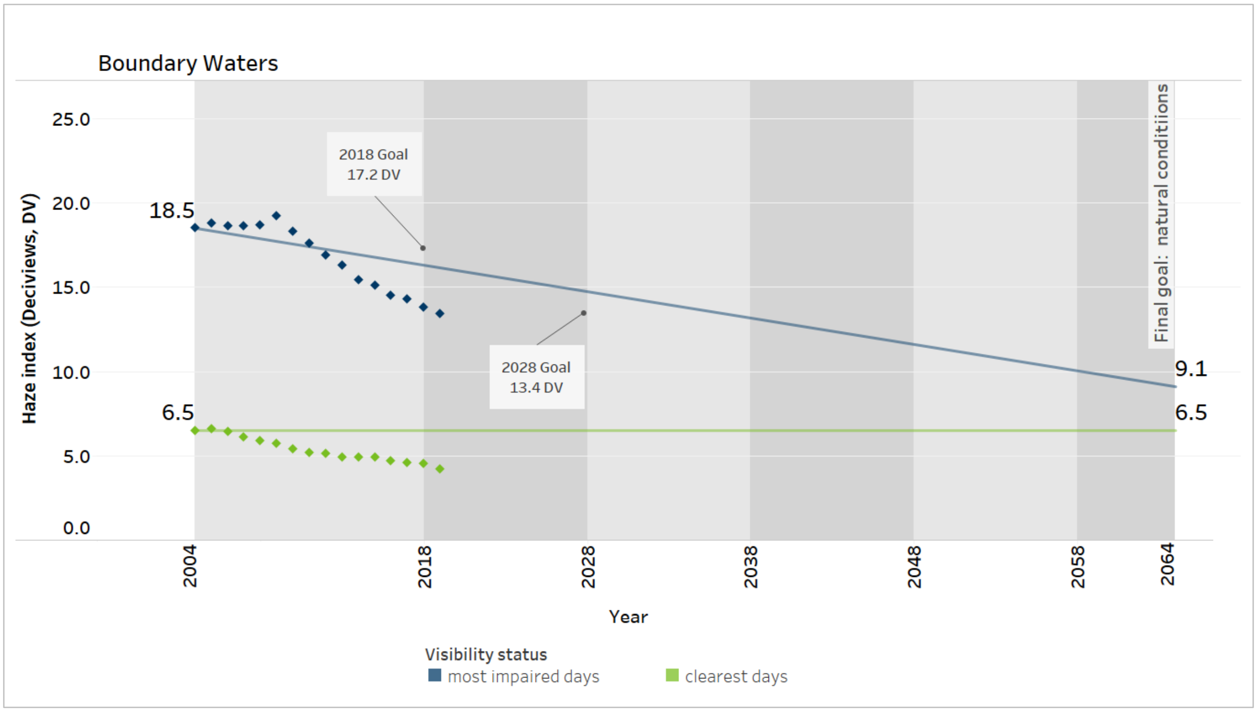
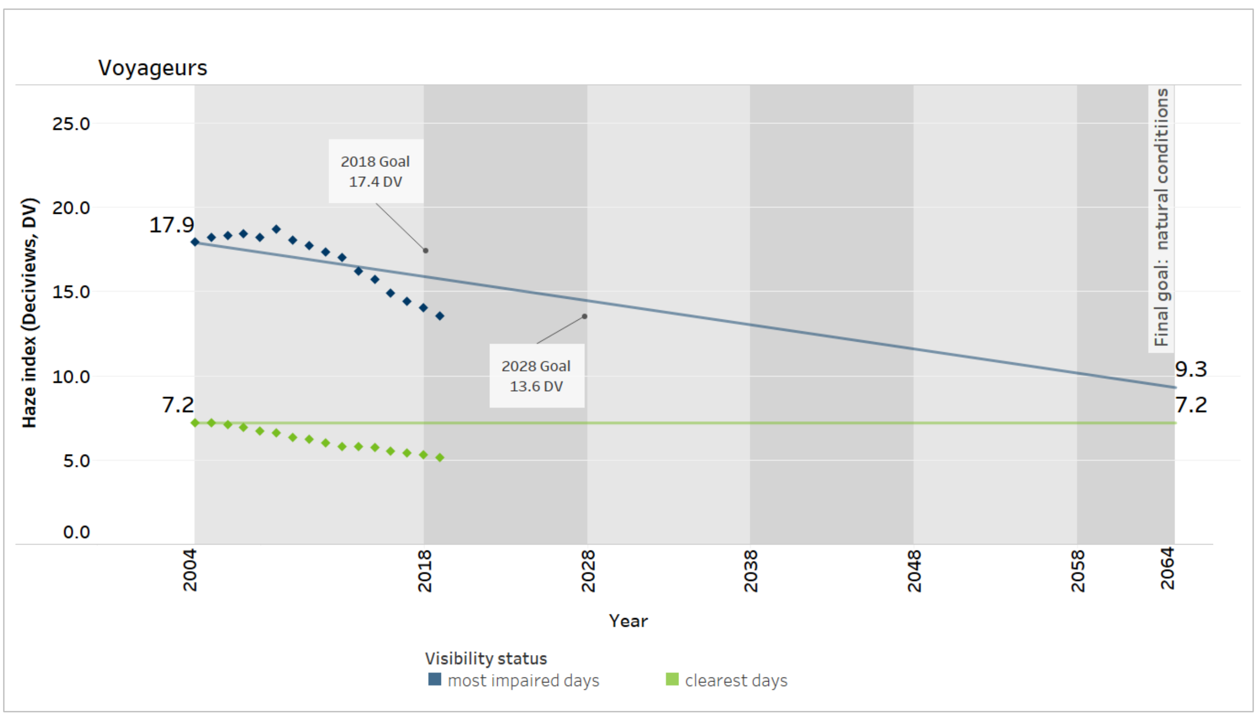


Figure 22. Progress, degradation, and glidepath checks at Voyageurs



4.8.3. Contributions to the 2028 RPG for Boundary Waters and Voyageurs

The Regional Haze Rule requires states to determine which Class I area(s) may be affected by emissions from within the state. States that host Class I areas within their borders are required to develop a long-term strategy that addresses visibility impairment for those Class I areas. All states, including those without Class I areas, are required to develop a long-term strategy to address visibility impairment for Class I areas in other states "that may be affected by emissions from the state."

This means that Minnesota must develop a long-term strategy that addresses visibility impairment for:

- The Boundary Waters and Voyageurs located within Minnesota
- Other Class I areas affected by emissions from within Minnesota

The requirement to determine which Class I areas in other states may be affected by a state's own emissions is a part of the requirement to develop a long-term strategy specified in 40 CFR § 51.308(f)(2).

> ***Long-term strategy for regional haze.*** *Each State must submit a long-term strategy that addresses regional haze visibility impairment for each mandatory Class I Federal area within the State and for each mandatory Class I Federal area located outside the State that may be affected by emissions from the State.*

U.S. EPA provides additional information regarding how a state determines which Class I area in other states may be affected by emissions from within the state in its August 2019 Guidance.[102] The guidance describes that each state is responsible for making its determination of what Class I areas may be affected by its emissions, a state has the flexibility to use any reasonable method for quantifying the impact of its own emissions on out-of-state Class I areas, and a state may use any reasonable assessment for this determination.

U.S. EPA also provides two examples of how a state might make this determination:

- A state may retain determinations of affected Class I areas previously made in the first regional haze implementation period but should consider if assumptions from the first period have changed since those original assessments.
- A state may reassess determinations of affected Class I areas using a reasonable approach to assess which out-of-state Class I areas may be affected by aggregate emissions from within the state. This determination may be based on recent emissions or anticipated emissions in 2028 and must include all anthropogenic emission sources or be based on total statewide emissions.

U.S. EPA identifies the most common approach in the first regional haze implementation period was to use a photochemical transport model to track the contribution due to emissions from whole states to specific Class I areas. U.S. EPA offers that this approach may also be used in the second implementation period, or a state may use another reasonable method such as a back trajectory-based approach.

First implementation period.

In the first implementation period, MPCA used a photochemical transport model to track the contribution of whole states or regions to Boundary Waters and Voyageurs. The November 2009 technical support document[103] identified Minnesota as the largest contributor to visibility impacts at Boundary Waters and Voyageurs, as shown in Table 28, followed by sources located outside the boundary of the modeling domain, North Dakota, Wisconsin, Iowa, Missouri, Illinois, and Canada, respectively.

[102] *USEPA 2019 August*
[103] *MPCA 2009*

The modeling domain in the first implementation period was relatively small, effectively cutting off the western portion of the contiguous United States. Boundary conditions enter and depart the modeling domain through the top, north, south, east, and west of the domain, making it difficult to pinpoint the source of visibility impacts entering from the boundary.

The model year was 2002 with projections to 2018 in the first implementation period. Monitoring data in the base year showed the majority of "worst" visibility days at Boundary Waters was due to sulfate. Although sulfate is formed all year round, most is formed in the warmer months of the year. Prevailing winds during warmer months are generally from the Southeast, which supported the conclusion Boundary Waters benefited from emissions reductions occurring in states to the East and Southeast. Monitoring data showed the majority of "worst" visibility days at Voyageurs were equally split between sulfate and nitrate. Nitrate forms in the cooler months (nitric acid in warmer months) when prevailing winds are from the West and Northwest, which supported the conclusion that Voyageurs would not benefit as much as Boundary Waters from emissions reductions occurring in states to the East and Southeast. Nitrate and sulfate need time to form in the atmosphere and are understood to travel large distances.

Table 28. State contributions in first implementation period to ammonium nitrate and sulfate at Boundary Waters and Voyageurs in 2018

Region name	Boundary Waters	Voyageurs
	Region contribution to visibility (%)	Region contribution to visibility (%)
Minnesota[104]	28	31
Boundary of model domain	11	15
North Dakota	6	13
Wisconsin	10	6
Iowa	8	7
Missouri	6	4
Illinois	6	3
Canada	3	5
All others	22	16

MPCA focused the contribution analysis on Boundary Waters and Voyageurs in the first implementation period, concluding any future emissions reductions in the State made to improve visibility in Boundary Waters and Voyageurs should have a commensurate effect on any other Class I areas impacted by Minnesota.

Second implementation period.

While the determination of affected Class I areas in the first implementation period are informative, important assumptions changed between the first and second implementation period. The form of the tracking metrics changed to moderate the effects of fire on the chosen 20% most impaired visibility days. As described in Section 4.7, the new metrics show many fewer most impaired days in the warmer months for both the first and second implementation periods.

In the second implementation period, the timing for the 2016 modeling platform development was not conducive to guide the direction of the long-term strategy through air quality modeling. Instead, MPCA

[104] Six counties in Northeast Minnesota contributed more than half of the State impact to Boundary Waters and just under half of the impact to Voyageurs.

used a surrogate analysis of emissions divided by distance (Q/d) to screen potential individual facility contributors to visibility impairment. The Q/d process was completed in late 2019. The surrogate approach and the long-term strategy are fully described in the Regional Haze SIP and are not discussed further herein.

In the second implementation period, the title of this section “control strategy development” is somewhat of a misnomer for the modeled contribution analysis begun in January 2021. Rather than direct the path of the long-term strategy, MPCA has used a photochemical transport model to serve as weight-of-evidence in general support of the long-term strategy and to foster interstate consultation.

Based on knowledge gained from the first implementation period, along with that learned from visibility trends with the revised tracking metrics (Section 4.7), MPCA became quite certain that photochemical modeling would show:

- Emissions changes in Minnesota and other states and regions that contribute to visibility at Boundary Waters and Voyageurs continue to result in measured reasonable progress toward natural visibility conditions
- Minnesota would continue to be the largest State contributor to visibility impairment at Boundary Waters and Voyageurs
- NO_X controls would be needed, with observed data trends increasingly showing nitrate dominating most impaired visibility days
- Boundary Waters and Voyageurs may not benefit as much from control measures in states located to the East and Southeast due to prevailing winds from the West and Northwest during periods of high nitrate production

MPCA conducted the contribution assessment with version 7.10 of the CAMx photochemical model, described in Section 4, applying the Particulate Source Apportionment Technology (PSAT) module to track the original source of particulate species by geographic region and source category. MPCA intended to use the same version of the CAMx model (version 7.00) as that used to establish the RPG, but a bug in the source apportionment module of that version pushed the state to use the newer version just publicly released at the start of the study. All other aspects of the modeling approach are the same.

Available high performance computational resources, time and the goal of the study, dictate the configuration of the PSAT simulation. MPCA’s configuration includes:

- The entire 12US2 12 km domain (described in Section 4)
- Sulfur and nitrogen tracer families resulting in output of particulate sulfate (from primary emissions plus secondarily formed), particulate nitrate (from primary emissions plus secondarily formed), and particulate ammonium
- 16 geographic regions: Minnesota, North Dakota, Nebraska, Iowa, Wisconsin, Michigan, Missouri, Illinois, Indiana, Texas, Central Midwest, Northeast, Southeast, West, Canada/Mexico, and Water bodies shown in Figure 23
    - Central Midwest region comprised of Arkansas, Kansas, Louisiana, and Oklahoma
    - West region comprised of Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, South Dakota, Utah, Washington, and Wyoming
    - Southeast region comprised of Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia
    - Northeast region comprised of Connecticut, Delaware, District of Columbia, Maine, Massachusetts, Maryland, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, and Vermont
- 11 sector groups: Agriculture, Area, Dust, Electric Generating Units, Industry, Off-road, On-road, Oil/Gas, Residential Wood Combustion (RWC), Natural and Fire as described in Section 4.3

Figure 23. Geographic regions for contribution analysis with PSAT

MPCA only included sulfur and nitrogen tracer families in the contribution analysis because monitored and modeled extinction for the 20 percent most impaired visibility days at Boundary Waters and Voyageurs are predominantly associated with sulfate and nitrate. MPCA determined species contribution using an approach similar to that taken by U.S. EPA in its updated 2028 regional haze modeling conducted to inform state implementation plan development in the second implementation period.[105] The process mimics that used to develop RRFs and RPGs.

- Calculate an RRF from the air quality model output files. Assign the "bulk" overall average concentration output for 2028 to "modeled base year" and the 2028 PSAT concentration output for each geographic region to "modeled future".
- Assign the 2028 future visibility conditions used in the development of the RPG to "baseline monitoring conditions".
- Apply each sector group RRF to the newly defined "baseline monitoring conditions", for each specie to estimate the contribution of each sector group. The extinction value of each sector group divided by the total extinction multiplied by 100 provides the percent contribution of each geographic region (and sector group).

The newly assigned baseline monitoring conditions for Boundary Waters and Voyageurs are the same as those used in the RPG calculations. The baseline monitoring conditions for Class I areas in other states were calculated using measurement data obtained from CIRA[106].

MPCA calculated an RRF for particulate sulfate and particulate nitrate concentration for each geographic region and sector in the PSAT model simulation averaged over the 20% most impaired days at each Class I area assessed. The form of the RRF in the PSAT contribution analysis is as follows.

$$RRF_{[X,Y,Z]} = \text{Modeled PSAT Mean}_{[X,Y,Z]} / \text{Modeled 2028 Mean}_{[X]}$$

Where: RRF is the relative response factor (unitless)

[105] *USEPA 2019 September*

[106] *Scott Copeland (CIRA) file sia_impairment_daily_budgets_2_22.csv (February 2022) value headers: site, s_date, amm_so4, amm_no3, impairment_grp = '90', year in (2014, 2015, 2016, 2017, 2018)*

PSAT Mean and 2028 Mean are the modeled year (2028) total concentrations and the PSAT geographic and sector concentrations for 2028 projection year at the Class I area monitor location averaged for the 20 percent most impaired days (and 20 percent clearest days) as determined by the base year (2016) monitor data

[X] is the species concentration sulfate and nitrate

[Y] is the geographic region (16 listed above)

[Z] is the sector group (11 listed above)

Applying the RRFs to projected 2028 monitored visibility conditions, for each PSAT geographic and sector grouping provides the estimate of the contribution of each geographic and sector grouping to future (2028) visibility conditions. The steps for applying the RRFs are similar to those described in Section 4.7, however, extinction results are not converted to the deciview index because extinction values less than 10 Mm^{-1} would be negative in deciviews and confusing to interpret. The steps are bulleted below.

- Multiply each species-geographic-sector specific RRF by the corresponding measured nitrate and sulfate concentrations for all of the 20 percent most impaired days over the 5-year baseline period projected to the future year 2028

$$Future_{[X,Y,Z]} = RRF_{[X,Y,Z]} * Future_{[X]} \text{ daily value}$$

where: Future is the projected estimate based on modeling

[X] is the species concentration sulfate and nitrate

[Y] is the geographic region (16 listed above)

[Z] is the sector group (11 listed above)

- Calculate the difference between the $Future_{[X]}$ daily value and $Future_{[X,Y,Z]}$ to obtain $Contribution_{[X,Y,Z]}$
- Estimate extinction coefficient (b_{ext}) for $Contribution_{[X,Y,Z]}$ using the relevant parts of the IMPROVE algorithm

$$b_{ext} = 2.2 * f_S(RH) * [\text{small sulfate}] + 4.8 * f_L(RH) * [\text{large sulfate}]$$
$$+ 2.4 * f_S(RH) * [\text{small nitrate}] + 5.1 * f_L(RH) * [\text{large nitrate}]$$

- Calculate the contribution to light extinction over the 20 percent most impaired days
  - Calculate the annual arithmetic mean light extinction for each year in the projected baseline period
  - Calculate a 5-year mean light extinction from the annual values

Overall contributions to visibility impairment.

The revised tracking metrics in the second implementation period are designed to moderate the effects of fire and dust storms in the selection of the 20 percent most impaired (and clearest) days through adjustments to measured carbon and dust species. Moderating the effects of fire focuses more attention on sulfate and nitrate from anthropogenic sources as shown in Figure 24. In the contribution analysis, fire accounts for nearly 3% and for 1% of light extinction due to sulfate and nitrate at Boundary Waters and Voyageurs, respectively. Natural sources account for about 6% of light extinction at both Class I Areas. Boundary conditions account for 38% and 40% of light extinction at Boundary Waters and Voyageurs, respectively. Anthropogenic sources account for nearly 54% and for 53% of light extinction due to sulfate and nitrate at Boundary Waters and Voyageurs, respectively. MPCA will not address fire further in the contribution assessment.

Figure 24. Total light extinction (nitrate and sulfate) percent contributions from outside model boundary (BC) and from total anthropogenic, natural and fire sectors within the model domain at Boundary Waters (left) and Voyageurs (right)

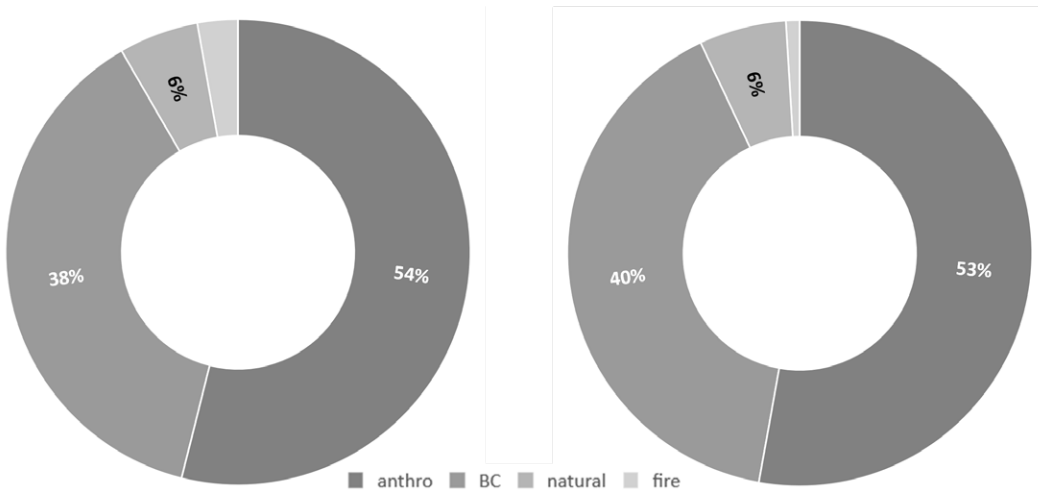


Table 29 contains the breakdown of light extinction into sulfate and nitrate overall contribution to Boundary Waters and Voyageurs. The modeling supports the MPCA hypothesis that NO_X controls are increasingly important. It also provides information on the continued role of SO_2 emissions contributing to visibility impairment.

At Boundary Waters, 47 percent of the sulfate extinction comes from anthropogenic sources and 50 percent comes from outside the model boundary. Fifty-nine percent of the nitrate extinction at Boundary Waters comes from anthropogenic sources and 28 percent comes from outside the model boundary.

At Voyageurs, 55 percent of the sulfate extinction comes from anthropogenic sources and 44 percent comes from outside the model boundary. Fifty-one percent of the nitrate extinction at Voyageurs comes from anthropogenic sources and 37 percent comes from outside the model boundary.

In the third implementation period, MPCA expects to focus more attention on the source and make up of the visibility impacts entering through the model boundary. Sulfate and nitrate contribution from the model boundary warrants equal attention. In the second implementation period, like in the first, MPCA mainly focuses attention on the largest, anthropogenic fraction, within the model domain.

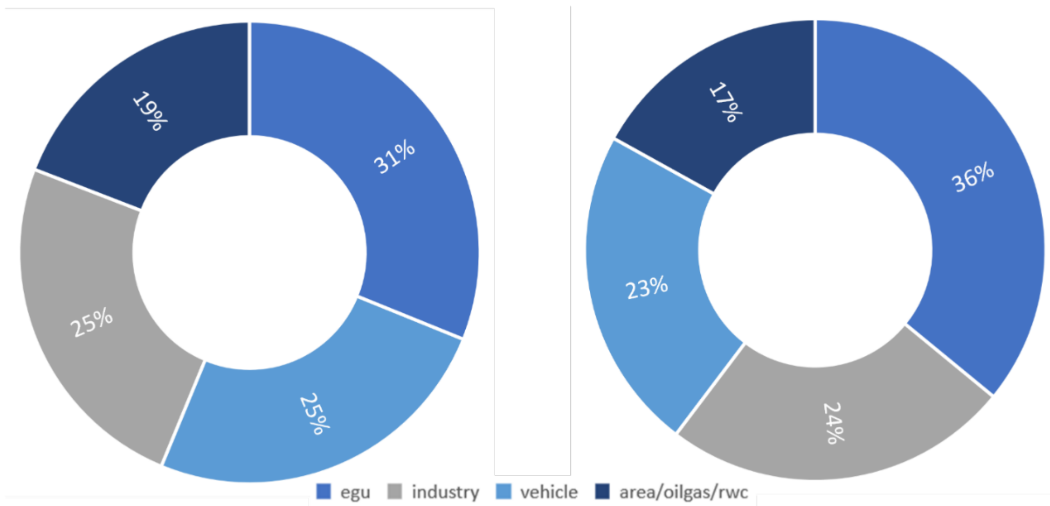
Table 29. Light extinction (nitrate, sulfate and total) percent contributions from outside model boundary and from anthropogenic, natural and fire sources at Boundary Waters and Voyageurs

Overall grouping	Boundary Waters			Voyageurs		
	$Sulfate_{ext}$ (%)	$Nitrate_{ext}$ (%)	$Total_{ext}$ (%)	$Sulfate_{ext}$ (%)	$Nitrate_{ext}$ (%)	$Total_{ext}$ (%)
Anthropogenic	47	59	54	55	51	53
Model boundary	50	28	38	44	37	40
Natural	0	10	6	0	10	6

Overall grouping	Boundary Waters			Voyageurs		
	$Sulfate_{ext}$ (%)	$Nitrate_{ext}$ (%)	$Total_{ext}$ (%)	$Sulfate_{ext}$ (%)	$Nitrate_{ext}$ (%)	$Total_{ext}$ (%)
Fire	2	3	3	1	1	1
Total[107]	100	100	100	100	100	100

The 54% total anthropogenic contribution to sulfate and nitrate extinction at Boundary Waters and 53% total anthropogenic contribution to sulfate and nitrate extinction at Voyageurs are further dissected into the sector groupings electric generating units, industrial facilities, vehicles, residential wood combustion and the aggregated sector grouping comprised of area, oil & gas. Figure 25 illustrates the overall percentage sulfate and nitrate contribution from each anthropogenic sector grouping.

Figure 25. Total light extinction (nitrate and sulfate) percent contributions from anthropogenic sectors groups at Boundary Waters (left) and Voyageurs (right)



Overall sector contributions to sulfate and nitrate visibility impairment at Boundary Waters and Voyageurs from the contiguous United States are mainly attributable to electric generating units, industrial facilities and vehicle sector groups. The contribution from the industry and vehicle groups are nearly evenly split at 25% each at Boundary Waters, and at 23% vehicle, 24% industry at Voyageurs. Electric generating units contribute 31% and 36% to visibility impairment at Boundary Waters and Voyageurs, respectively.

Of all the anthropogenic sulfate extinction most by far is emitted by electric generating units at 62% (Boundary Waters) and 64% (Voyageurs), with industry following at 26% at both Class I areas. Anthropogenic nitrate extinction is weighted toward vehicles at 38% at both Class I areas with industry and the aggregate sector "area + oil & gas + residential wood combustion" both at 24% (Boundary Waters and Voyageurs). Electric generating units comprise 14% at Boundary Waters and 15% at Voyageurs of anthropogenic nitrate extinction. Table 30 shows the breakdown of overall visibility impairment by anthropogenic sector grouping.

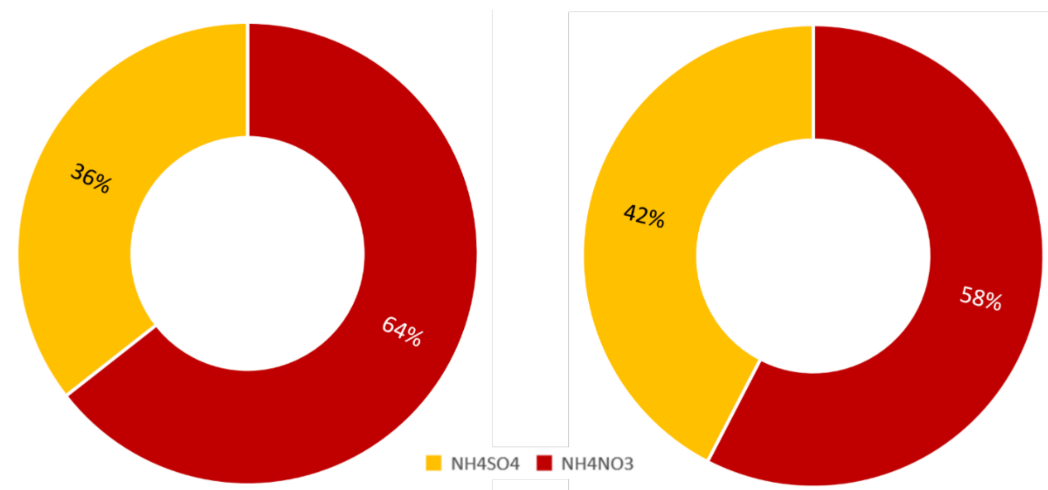
[107] *Rounding results in values not totaling 100 percent in some cases*

Table 30. Light extinction (nitrate, sulfate and total) percent contributions from anthropogenic sector groupings at Boundary Waters and Voyageurs

Sector grouping	Boundary Waters			Voyageurs		
	$Sulfate_{ext}$ (%)	$Nitrate_{ext}$ (%)	$Total_{ext}$ (%)	$Sulfate_{ext}$ (%)	$Nitrate_{ext}$ (%)	$Total_{ext}$ (%)
EGU	62	14	31	64	15	36
Industry	26	24	25	26	23	24
Vehicles	2	38	25	2	38	23
Area + oil & gas + RWC	10	24	19	9	23	17
Total[108]	100	100	100	100	100	100

Considering overall results pointing to electric generating units contributing most to light extinction at the Minnesota Class I areas, and that sector contribution mostly due to sulfate, one might conclude sulfate extinction due to electric generating units should be the primary focus of any future control strategies. While important, electric generating units as a sector grouping likely stand out because of its dominance over the sulfate portion of the light extinction. The preferential formation of sulfate over nitrate in the atmosphere likely has a role in the non-linear contribution of sulfate from electric generating units. The nitrate portion of the light extinction is distributed more evenly among the various sectors. At both Boundary Waters and Voyageurs visibility impairment from anthropogenic sources overall is predominantly due to nitrate at 64% at Boundary Waters and 58% at Voyageurs. The remainder is due to sulfate at 36% at Boundary Waters and 42% at Voyageurs. Figure 26 illustrates the overall importance of nitrate and sulfate extinction at the Minnesota Class I areas.

Figure 26. Sulfate (NH4SO4) and nitrate (NH4NO3) percent contribution from anthropogenic sector groups to light extinction at Boundary Waters (left) and Voyageurs (right)



Regional contributions to visibility impairment. What follows is apportioning the light extinction contributions to formal geographical regions—countries, states and groups of states. The modeling tracks the contribution of whole states or regions to Boundary Waters and Voyageurs. In addition to identifying whole states and regions contributing visibility impacts to Boundary Waters and Voyageurs,

[108] *Rounding results in values not totaling 100 percent in some cases*

unlike in the first implementation period, MPCA assessed the contribution of Minnesota to some Class I areas in other states.

Michigan has two Class I areas located in the Upper Peninsula of Michigan; Isle Royale National Park, an island in Lake Superior, and Seney National Wildlife Refuge located in the eastern portion of the Upper Peninsula. For accessibility and maintenance reasons the IMPROVE monitor for Isle Royale is not located at the Class I area, but on the coast in the Upper Peninsula.

The remaining Class I areas assessed were chosen to capture those closest to the Minnesota border in each applicable direction of the compass. The Class I areas are Lostwood Wilderness and Theodore Roosevelt National Park in North Dakota, Badlands Wilderness in South Dakota, Hercules-Glades Wilderness Area and Mingo Wilderness Area in Missouri, and Mammoth Cave National Park in Kentucky.

Table 31 below contains descriptions of each Class I area assessed. Figure 27 shows the boundaries of the Class I areas with yellow stars depicting the location of the IMPROVE monitor representing each Class I area assessed. Isle Royale and Seney ambient monitors are closest to the Minnesota border at 117 kilometers (km) and 329 km, respectively. The remaining Class I areas assessed are between 381 km and 828 km from the Minnesota border.

Figure 27. Class I areas assessed for contribution to visibility impairment

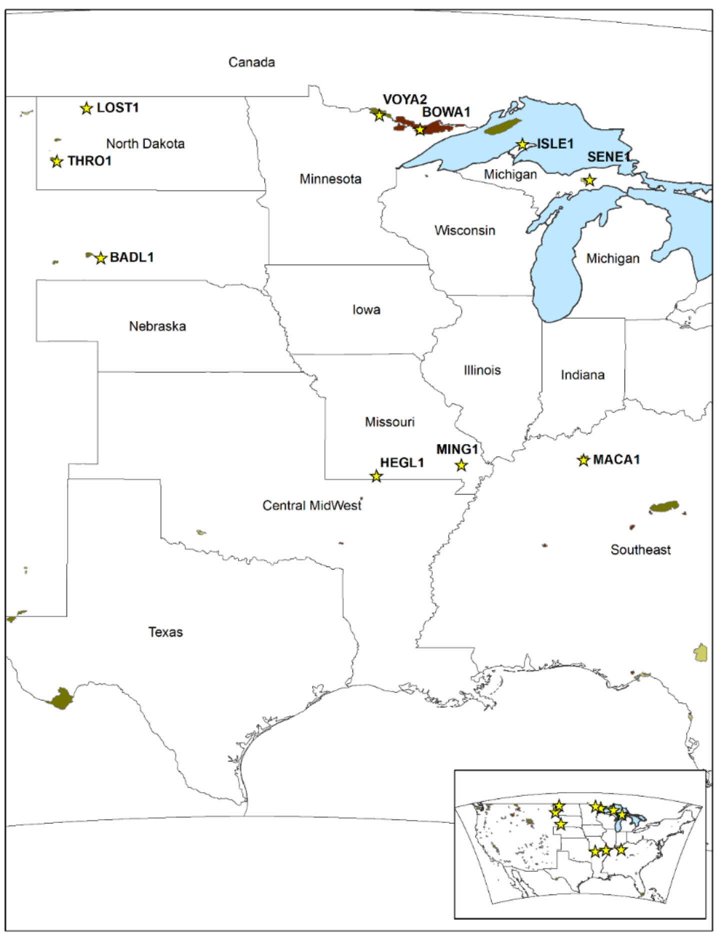


Table 31. Class I areas assessed for contribution to visibility impairment

Class I area	Acres	Affiliation	State located	Direction from Minnesota
Boundary Waters	747,840	U.S. DA - Forest Service	Minnesota	-
Voyageurs	114,964	U.S. DI - National Park Service	Minnesota	-
Isle Royale National Park	542,428	U.S. DI - National Park Service	Michigan	East
Seney Wilderness Area	25,150	U.S. DI - Fish & Wildlife Service	Michigan	East
Lostwood Wilderness	5,557	U.S. DI - Fish & Wildlife Service	North Dakota	West
Badlands Wilderness	64,250	U.S. DI - National Park Service	South Dakota	West
Theodore Roosevelt National Park	69,675	U.S. DI - National Park Service	North Dakota	West
Mingo Wilderness Area	8,000	U.S. DI - Fish & Wildlife Service	Missouri	South-Southeast
Hercules-Glades Wilderness Area	12,315	U.S. DA - Forest Service	Missouri	South
Mammoth Cave National Park	51,303	U.S. DI - National Park Service	Kentucky	Southeast

4.8.4. Minnesota's impact on Class I areas

As anticipated, Minnesota has the greatest visibility impact on the Class I areas within the State—Boundary Waters and Voyageurs—with lesser visibility impact on the two Michigan Class I areas, Isle Royale and Seney. Visibility impacts to the Class I areas in other states are unremarkable, except it is interesting that Minnesota has slightly more than 2.5 percent visibility impact at Mammoth Cave in Kentucky. Mammoth Cave is the furthest distance (828 km) from Minnesota of all the Class I areas assessed. It is located to the southeast of Minnesota and perhaps more of the impaired days due to nitrate and sulfate at Mammoth Cave are in the cooler months this implementation period than in the first implementation period.

MPCA concludes Minnesota is culpable over the 3.5% contribution threshold to visibility impairment, described in Section 4.8.5, at Minnesota Class I areas Boundary Waters and Voyageurs, and at Michigan Class I areas Isle Royale and Seney. Table 32 contains MPCA estimates of Minnesota's projected contribution to nitrate and sulfate at select Class I areas.

Table 32. Minnesota contribution to 2028 nitrate and sulfate extinction at select Class I areas[109]

Class I area	Monitor site abbreviation	Monitor location		Distance of monitor from Minnesota boundary (km)	Minnesota contribution to visibility (%)
		Latitude	Longitude		
Boundary Waters	BOWA1	47.9466	-91.4955	0	16.2
Voyageurs	VOYA2	48.4126	-92.8286	0	17.6
Isle Royale National Park	ISLE1	47.4596	-88.1491	117	8.2
Seney Wilderness Area	SENE1	46.2889	-85.9503	329	4.3
Lostwood Wilderness	LOST1	48.6419	-102.4022	381	0.5

[109] *Does not include contribution from fire.*

Class I area	Monitor site abbreviation	Monitor location		Distance of monitor from Minnesota boundary (km)	Minnesota contribution to visibility (%)
		Latitude	Longitude		
Badlands Wilderness	BADL1	43.7435	-101.9412	442	1.2
Theodore Roosevelt National Park	THRO1	46.8948	-103.3777	489	1.7
Mingo Wilderness Area	MING1	36.9717	-90.1432	731	1.6
Hercules-Glades Wilderness Area	HEGL1	36.6138	-92.9221	765	1.8
Mammoth Cave National Park	MACA1	37.1318	-86.1479	828	2.6

Given that Minnesota is a major contributor to visibility impairment at its own Class I areas, MPCA believes that the measures taken to reach the 2028 reasonable progress goals set for the Boundary Waters and Voyageurs, detailed in the Regional Haze SIP, are sufficient to account for Minnesota's share of emissions reductions needed to meet the reasonable progress goal at any other Class I area that Minnesota may impact. Specifically, Isle Royale and Seney.

4.8.5. Whole states and regions impacting Minnesota's Class I areas

Emissions sources located outside the boundary of the modeling domain, from the direction of Canada, carry a very significant portion of the visibility impact at Boundary Waters (37.7%) and Voyageurs (40.2%). This is a much higher percentage than the first implementation period at Boundary Waters (11%) and Voyageurs (15%) shown in Table 28. The portion of Canada within the modeling domain is significant contributor at Boundary Waters (7%) and Voyageurs (10%). The remainder of Canada falls outside the boundary of the modeling domain.

Source apportionment techniques can only account for the total contribution of boundary conditions to the overall visibility conditions, which accounts for the conservation of mass in the apportionment modeling. Broadly assuming all the impacting sources are in Canada, total impact estimates from Canada would be Boundary Waters 45% (37.7% plus 7.0%) and Voyageurs 50% (40.2% plus 10.0%). While that can't be determined without further study, the U.S. EPA and EPRI estimates of international contributions in Section 4.7, Table 24, can provide a sense of scale. Some of the contribution from outside the boundary could be from global sources and from U.S. air traveling outside the boundary then re-entering.

Minnesota along with other states are still culpable for visibility impacts at Boundary Waters and Voyageurs. Table 33 contains the percent contribution to visibility impairment in terms of light extinction due to nitrate and sulfate at Boundary Waters and Voyageurs for each region in the assessment.

Table 33. Region contribution to visibility impairment in 2028 due to nitrate and sulfate extinction at Minnesota Class I areas[110]

Region name	Boundary Waters		Voyageurs	
	Distance of region boundary to monitor (km)	Region contribution to visibility impairment (%)	Distance of region boundary to monitor (km)	Region contribution to visibility impairment (%)
Boundary of model domain	432	37.7	385	40.2

[110] Does not include contribution from fire (2.8 % at Boundary Waters and 1.0 % at Voyageurs)

Region name	Boundary Waters		Voyageurs	
	Distance of region boundary to monitor (km)	Region contribution to visibility impairment (%)	Distance of region boundary to monitor (km)	Region contribution to visibility impairment (%)
Minnesota	0	16.2	0	17.6
Canada/Mexico[111]	12 / 2,190	7.0	10 / 2,176	10.0
North Dakota	404	4.8	314	5.9
Central Midwest[112]	934	4.6	955	3.7
Iowa	494	4.3	546	4.1
Nebraska	715	3.9	706	3.5
West[113]	446	3.9	395	3.0
Wisconsin	113	3.6	194	1.5
Missouri	815	3.5	869	2.8
Illinois	608	2.6	678	1.7
Texas	1,451	1.5	1,447	1.3
Indiana	760	1.0	853	0.9
Southeast[114]	1,118	1.0	1,216	0.8
Northeast[115]	872	0.9	977	1.1
Michigan	170	0.4	274	0.8
Water bodies	64	0.2	170	0.2

In the first implementation period, MPCA chose a five percent contribution threshold for determining significant contribution to visibility impacts at each Class I area. For the second implementation period, MPCA has chosen a 3.5% contribution threshold.

A 3.5% contribution threshold accounts for roughly 80% of the total contribution to visibility impairment at Boundary Waters and Voyageurs. The figure was derived by sorting the region percent contributions in descending order and calculating the cumulative percent until reaching 80%. The boundary of the model domain is included in the cumulative percent. The Central Midwest and West regions are excluded from the cumulative percent because those regions are an aggregation of multiple states, and it would be unlikely for any one state individually to appear as high on the sorted list.

Minnesota, Canada, North Dakota, Iowa, Nebraska, Wisconsin and Missouri are identified as the most culpable regions contributing to visibility impairment in one or both Class I areas in Minnesota.

In the August 2019 Guidance, U.S. EPA says a state with a Class I area may advise another state that it considers its Class I area(s) to be affected by emissions from the other state[116]. While each state is responsible for its determination of what Class I areas may be affected by its emissions, U.S. EPA states that this is a potential area for interstate consultation. 40 CFR § 51.308(f)(2)(ii)(C) specifies the

[111] Contribution most likely attributed solely to Canada
*[112] **Central Midwest** region comprised of Arkansas, Kansas, Louisiana, and Oklahoma.*
*[113] **West** region comprised of Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, South Dakota, Utah, Washington, and Wyoming.*
*[114] **Southeast** region comprised of Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia.*
*[115] **Northeast** region comprised of Connecticut, Delaware, District of Columbia, Maine, Massachusetts, Maryland, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, and Vermont.*
[116] U.S. EPA August 2019

requirements for documenting interstate consultations and describing the actions taken to resolve any disagreements on the emission reduction measures needed to make reasonable progress:

> *In any situation in which a State cannot agree with another State on the emission reduction measures necessary to make reasonable progress in a mandatory Class I Federal area, the State must describe the actions taken to resolve the disagreement. In reviewing the State's implementation plan, the Administrator will take this information into account in determining whether the plan provides for reasonable progress at each mandatory Class I Federal area that is located in the State or that may be affected by emissions from the State. All substantive interstate consultations must be documented.*

Other than adjusting the 2064 endpoint of the glidepath to account for international impacts, MPCA has no recourse to address visibility impacts from Canada to Boundary Waters and Voyageurs. As discussed in Section 4.7, MPCA does not seek U.S. EPA approval to adjust the 2064 endpoint this implementation period in part because observation data for both Boundary Waters and Voyageurs are below the glidepath and well under way to meet the unadjusted 2064 end point at this time.

No states have notified MPCA that they have identified Minnesota emissions as reasonably anticipated to contribute to visibility impairment at Class I areas within their borders. No states have asked Minnesota to undertake specific emissions reductions to make reasonable progress. Further information regarding consultation with specific states is provided in the Regional Haze SIP, Section 2.9.1 Consultation with states.

Sector contributions to sulfate and nitrate visibility impairment by the most culpable regions (over 3.5% threshold) at Boundary Waters and Voyageurs

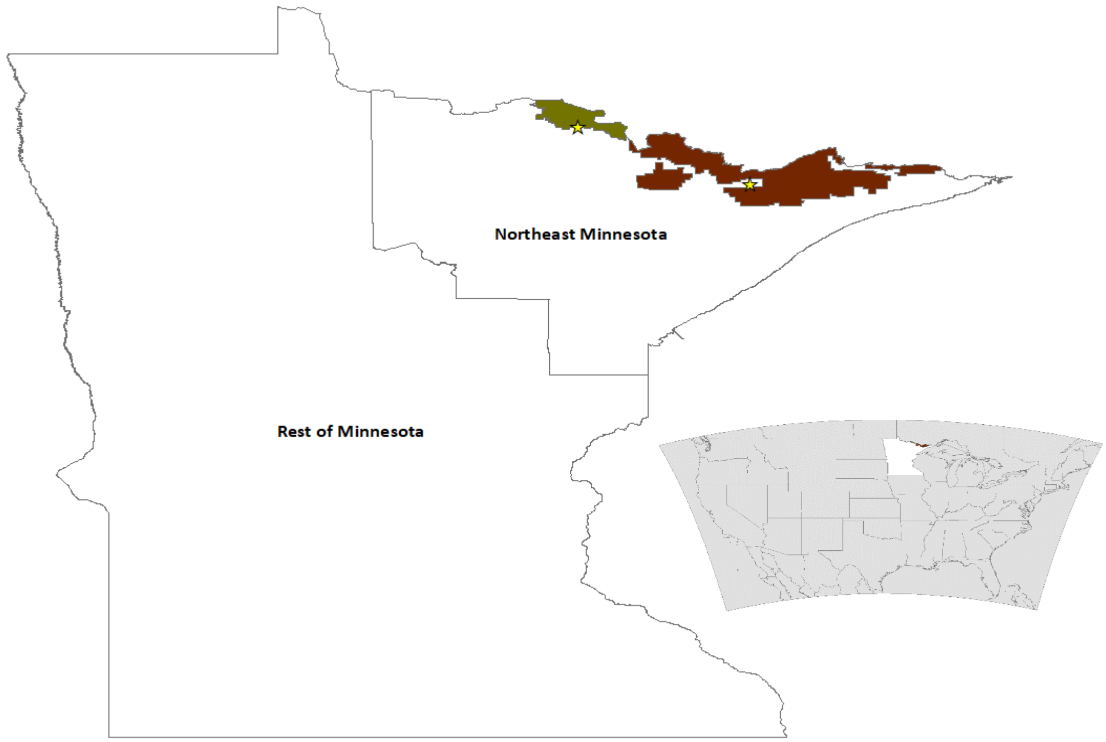
MPCA has more thoroughly assessed the contributions of whole states and regions over the 3.5% threshold to Minnesota Class I areas by evaluating the NO_X and SO_2 emissions from these regions and the resultant contributions by sector grouping. Minnesota, Canada, North Dakota, Iowa, Nebraska, Wisconsin, and Missouri are identified as the most culpable regions contributing to visibility impairment in one or both Class I areas in Minnesota. In addition to the anthropogenic contribution from each region, MPCA includes natural contribution for comparison.

Minnesota overall contributes mostly nitrate, roughly two-thirds, to visibility impairment at Boundary Waters and Voyageurs with the remainder due to sulfate. Corresponding statewide NO_X emissions are more than 6.5 times higher than statewide SO_2 emissions. In order of highest to lowest, contributing sector groups to visibility impairment from the region are industry, vehicles, electric generating units, the combination of area, oil & gas and residential wood combustion, and lastly natural sources. Each of the sector groups contribute mostly nitrate—between 65% to nearly 100% —to visibility impairment, except for electric generating units which contribute mostly sulfate—between 70-75% —to its portion of visibility impairment. Each of the other sector groups emit much more NO_X than SO_2, but electric generating units emit nearly identical amounts of NO_X and SO_2, about 12,000 tons, in 2016 v1b modeling projected to 2028. The preferential formation of sulfate over nitrate in the atmosphere likely has a role in the non-linear contribution of sulfate from electric generating units.

The top third of Table 34 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in Minnesota. It also contains the percent breakdown of sulfate and nitrate and the relevant 2028 NO_X and SO_2 emissions used in the analysis.

MPCA also separated contributions from "**Northeast Minnesota**" and the "**Rest of Minnesota**", shown in Figure 28. Northeast Minnesota comprises the six counties, Carlton, Cook, Itasca, Koochiching, Lake and St. Louis. These counties encompass the entire boundaries of both Boundary Waters and Voyageurs. In both the first and second implementation periods, MPCA has included in the Regional Haze SIP the "Northeast Minnesota Plan" for facilities in the Northeast Minnesota counties to assure no back-sliding on NO_X and SO_2 emissions in the region. The Regional Haze SIP, Section 2.5.7, describes the plan in more detail.[117] The contribution assessment continues below.

Figure 28. Northeast and Rest of Minnesota regions



The **Northeast Minnesota** region overall contributes mostly nitrate, roughly two thirds, to visibility impairment at Boundary Waters and Voyageurs with the remainder due to sulfate. Corresponding regionwide NO_X emissions are nearly six times higher than regionwide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are industry, electric generating units, vehicles, the combination of area, oil & gas and residential wood combustion, and natural sources. All sector groups contribute mostly nitrate—between 60% to nearly 100% —to visibility impairment, except for electric generating units which contribute mostly sulfate—between 56-66% —to its portion of visibility impairment. Each of the sector groups emit much more NO_X than SO_2. The preferential formation of sulfate over nitrate in the atmosphere likely has some role in the non-linear contribution of sulfate from electric generating units.

In Northeast Minnesota the most significant sector group contributing to visibility impairment is industry at 4.7% of the region total at both Class I areas (6.5% at Boundary Waters and 7.3% at Voyageurs). The EGU sector contributes 1.3% of the region total at Voyageurs. Each of the remaining sector groupings make up less than 1% of the region total at either Boundary Waters or Voyageurs.

The **Rest of Minnesota** region overall contributes mostly nitrate, roughly two thirds, to visibility impairment at Boundary Waters and Voyageurs with the remainder due to sulfate. Corresponding region total emissions of NO_X are nearly seven times higher than region total emissions of SO_2. In order of highest to lowest contributing sector groups to visibility impairment from the region are vehicles, the combination of area, oil & gas and residential wood combustion, electric generating units, industry, and natural sources. All sector groups contribute mostly nitrate—between 55% to nearly 100% —to visibility

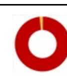
[117] *MPCA 2022*

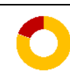
impairment, except for electric generating units which contribute mostly sulfate—between 77-81% —to its portion of visibility impairment. Each of the sector groups emit much more NO_X than SO_2. The preferential formation of sulfate over nitrate in the atmosphere likely has some role in the non-linear contribution of sulfate from electric generating units.

In the Rest of Minnesota vehicles are the most significant contributor to visibility impairment at around 3% of the region total at Boundary Waters and Voyageurs. The remaining anthropogenic sector groupings are close at from about 2.5% contribution for the combined area, oil & gas and residential wood combustion sector grouping, around 2.0% contribution for electric generating units, to about 1.5% contribution for industry. The industry sector grouping is close to the contribution of nitrate from natural sources at 0.9% and 1.2% at Boundary Waters and Voyageurs, respectively.

Table 34 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group, the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the associated 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 34. Minnesota Sector contribution to visibility impairment in 2028 due to nitrate and sulfate at Minnesota Class I areas

Minnesota Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) ■ NH4NO3 ■ NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Minnesota total						
Region total	16.2	17.6			180,940	27,219
Industry	6.2	6.3			36,000	10,000
Vehicle	3.5	3.7			62,200	907
EGU	2.6	3.5			12,200	12,000
Area + Oil/gas + RWC	2.9	2.7			28,040	4,312
Natural	1.0	1.4			42,500	--

Minnesota Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Northeast Minnesota Counties (Carlton, Cook, Itasca, Koochiching, Lake, and St. Louis)[118]						
Sub-region total	6.5	7.3			33,690	5,663
Industry	4.7	4.7			20,900	3,440
EGU	0.8	1.3			4,180	1,810
Vehicle	0.6	0.7			5,470	42.6
Area + Oil/gas + RWC	0.3	0.4			1,310	370
Natural	0.1	0.1			1,830	--
Rest of Minnesota[119]						
Sub-region total	9.7	10.3			148,120	21,600
Vehicle	2.9	3.1			57,200	880
Area + Oil/gas + RWC	2.5	2.4			26,700	3,950
EGU	1.8	2.2			8,020	10,200
Industry	1.5	1.5			15,200	6,570
Natural	0.9	1.2			41,000	--

In the first implementation period, Northeast Minnesota contributed more than half of the State total percent contribution of extinction at Boundary Waters and just under half of the percent contribution of extinction at Voyageurs. In the second implementation period, Northeast Minnesota contributes about 40% of the state total contribution to visibility impairment at both Boundary Waters and Voyageurs. With the remaining 60% of the state total contribution attributed to the rest of the state, the modeling suggests the need for additional focus on vehicles—the top contributing sector group in the Rest of Minnesota Region—in the third implementation period.

Table 35 contains a breakdown of the emissions into less aggregated sector groups for the second implementation period and includes the emissions change from baseline for the whole state. In

[118,81] *The sub-region emission totals from Northeast Minnesota and Rest of Minnesota do not exactly add-up to the total for the entire state due to rounding. d*

Minnesota large reductions in NO_X emissions of around 66,200 tons from vehicles—on-road and off-road—were accounted for between 2016 and 2028. Even so, vehicles make up about 62,200 tons of NO_X in 2028. In comparison, the EGU and industry sector groups combined make up about 48,200 tons of NO_X and 22,000 tons of SO_2 in 2028.

Table 35. Minnesota NO_X and SO_2 emissions change from baseline by sector group

Minnesota Sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Area	22,500	22,000	-577	3,010	3,000	-6.62
EGU	19,800	12,200	-7,570	16,900	12,000	-4,950
Industry	43,500	36,000	-7,500	11,500	10,000	-1,480
Oil/gas	2,840	2,690	-152	152	152	0.004
On-road	68,400	22,700	-45,700	403	198	-205
Off-road	60,000	39,500	-20,500	361	709	348
RWC	3,440	3,350	-96.1	1,360	1,160	-197
Fire	2,620	2,620	0.00	1,790	1,790	0.00
Natural	42,500	42,500	0.00	--	--	--

North Dakota's overall contribution to visibility impairment is 4.8% at Boundary Waters and 5.9% at Voyageurs. Most of that contribution is due to nitrate, 53% at Boundary Waters and 60% at Voyageurs, with the remainder due to sulfate. Corresponding statewide NO_X emissions are more than three times higher than statewide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are electric generating units, combination of area, oil & gas and residential wood combustion, and vehicles. Contribution from North Dakota industry sector falls below that of natural sources.

Each of the sector groups contribute mostly nitrate—between 61% to nearly 100% —to visibility impairment, except for electric generating units which contribute mostly sulfate—between 70-75% —to its portion of visibility impairment and for industry which contributes 50% of both sulfate and nitrate. Each of the other sector groups emit much more NO_X than SO_2, but electric generating units emit similar amounts of NO_X (33,600 tons) and SO_2 (38,000 tons), in 2016 v1b modeling projected to 2028. The preferential formation of sulfate over nitrate in the atmosphere likely has some role in the non-linear contribution of sulfate from electric generating units.

Table 36 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in North Dakota. It also contains the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the associated 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 36. North Dakota sector contribution to visibility impairment in 2028 due to nitrate and sulfate at Minnesota Class I areas

North Dakota Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Region total	4.8	5.9			151,228	49,629

North Dakota Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) ■ NH4NO3 ■ NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
EGU	2.4	2.5			33,600	38,000
Area + Oil/gas + RWC	1.1	1.4			34,048	9,444
Vehicle	0.7	1.0			29,470	165
Natural	0.4	0.6			50,500	--
Industry	0.2	0.3			3,610	2,020

Table 37 contains a breakdown of the emissions into less aggregated sector groups and includes the emissions change from baseline. In North Dakota large reductions in NO_X emissions of around 32,200 tons from vehicles—on-road and off-road—were accounted for between 2016 and 2028. Vehicles make up about 29,800 tons of NO_X in 2028. The electric generating unit and industry sector groups combined make up about 37,200 tons of NO_X and 40,000 tons of SO_2 in 2028. The oil and gas sector NO_X emissions in the modeling are projected to increase 12,500 tons to 32,700 tons in 2028. Oil and gas sector SO_2 emissions are also projected to increase nearly 3,000 tons to 9,240 tons in 2028. North Dakota actions to limit emissions from electric generating units and perhaps oil & gas are most likely to lessen visibility impacts at Boundary Waters and Voyageurs.

Table 37. North Dakota NO_X and SO_2 emissions change from baseline by sector group

North Dakota sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Area	1,210	1,210	1.32	174	174	0.293
EGU	38,400	33,600	-4,850	47,100	38,000	-9,170
Industry	3,640	3,610	-32.5	2,220	2,020	-204
Oil/gas	20,200	32,700	12,500	6,280	9,240	2,960
On-road	22,000	8,270	-13,700	75.2	54.3	-20.9
Off-road	39,700	21,200	-18,500	104	111	6.33
RWC	133	138	5.28	32.4	30.1	-2.25
Fire	2,470	2,470	0.00	1,170	1,170	0.00
Natural	50,500	50,500	0.00	--	--	--

Iowa's overall contribution to visibility impairment is 4.3% at Boundary Waters and 4.1% at Voyageurs. Most of that contribution is due to nitrate, 60% at Boundary Waters and 53% at Voyageurs, with the remainder due to sulfate. Corresponding statewide NO_X emissions are more than three times higher than statewide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are electric generating units and vehicles. Contribution from Iowa industry and combination of area, oil & gas and residential wood combustion sectors is similar to that of natural sources.

Each of the sector groups contribute mostly nitrate—between 46% to nearly 100% —to visibility impairment, except for electric generating units which contribute mostly sulfate—between 72-81% —to its portion of visibility impairment. Each of the other sector groups emit much more NO_X than SO_2, but electric generating units emit similar amounts of NO_X (22,300 tons) and SO_2 (28,500 tons) in the 2016 v1b modeling projected to 2028. The preferential formation of sulfate over nitrate in the atmosphere likely has some role in the non-linear contribution of sulfate from electric generating units and industry.

Table 38 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in Iowa. It also contains the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the associated 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 38. Iowa sector contribution to visibility impairment in 2028 due to nitrate and sulfate at Minnesota Class I areas

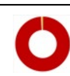
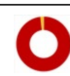
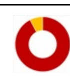
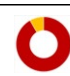
Iowa Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Region total	4.3	4.1			156,722	36,120
EGU	1.8	1.9			22,300	28,500
Vehicle	1.0	0.8			46,600	382
Natural	0.6	0.6			59,800	--
Industry	0.5	0.4			13,600	6,680
Area + Oil/gas + RWC	0.4	0.3			14,422	558

Table 39 contains a breakdown of the emissions into less aggregated sector groups and includes the emissions change from baseline. In Iowa large reductions in NO_X emissions of around 53,700 tons from vehicles—on-road and off-road—were accounted for between 2016 and 2028. Vehicles make up about 46,600 tons of NO_X in 2028. The electric generating unit and industry sector groups combined make up about 35,900 tons of NO_X and 35,200 tons of SO_2 in 2028. Emissions reductions between 2016 and 2028 from electric generating units are only 427 tons of NO_X and 4,050 tons of SO_2. Iowa actions to limit emissions from electric generating units and perhaps vehicles are most likely to lessen visibility impacts at Boundary Waters and Voyageurs.

Table 39. Iowa NO_X and SO_2 emissions change from baseline by sector group

Iowa sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Area	9,110	8,940	-173	422	428	6.11
EGU	22,700	22,300	-427	32,600	28,500	-4,050
Industry	15,200	13,600	-1,590	6,910	6,680	-227
Oil/gas	5,060	4,890	-178	5.30	5.30	0.00
On-road	52,100	18,400	-33,700	294	132	-162

Iowa sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Off-road	48,200	28,200	-20,000	138	250	111
RWC	594	592	-2.15	162	125	-37.1
Fire	1,420	1,420	0.00	749	749	0.00
Natural	59,800	59,800	0.00	--	--	--

Nebraska's overall contribution to visibility impairment is 3.9% at Boundary Waters and 3.5% at Voyageurs. Most of that contribution is due to sulfate, 51% at Boundary Waters and 60% at Voyageurs, with the remainder due to nitrate. Corresponding statewide NO_X emissions are 2.75 times higher than statewide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are electric generating units and vehicles. Contribution from Nebraska industry and combination of area, oil & gas and residential wood combustion sectors is similar to that of natural sources.

Each of the sector groups contribute mostly nitrate—between 65% to nearly 100% —to visibility impairment, except for electric generating units which contribute mostly sulfate—between 80-84% —to its portion of visibility impairment. Each of the other sector groups emit much more NO_X than SO_2, but electric generating units emit 23,200 tons of NO_X and 57,000 tons of SO_2 in the 2016 v1b modeling projected to 2028.

Table 40 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in Nebraska. It also contains the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the associated 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 40. Nebraska sector contribution to visibility impairment in 2028 due to nitrate and sulfate at Minnesota Class I areas

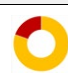
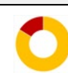
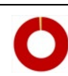
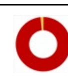
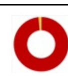
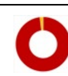
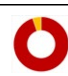
Nebraska Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Region total	3.9	3.5			163,169	59,187
EGU	2.4	2.4			23,200	57,000
Vehicle	0.8	0.5			51,200	204
Industry	0.2	0.2			7,270	1,840
Natural	0.4	0.2			74,700	--
Area + Oil/gas + RWC	0.2	0.1			6,799	143

Table 41 contains a breakdown of the emissions into less aggregated sector groups and includes the emissions change from baseline. In Nebraska large reductions in NO_X emissions of around 47,300 tons from vehicles—on-road and off-road—were accounted for between 2016 and 2028. Vehicles make up about 51,200 tons of NO_X in 2028. The electric generating unit and industry sector groups combined make up about 30,500 tons of NO_X and 68,800 tons of SO_2 in 2028. In the modeling, emissions increased between 2016 and 2028 from electric generating units by 2,400 tons of NO_X and 5,260 tons of SO_2. Nebraska actions to limit emissions from electric generating units are most likely to lessen visibility impacts at Boundary Waters and Voyageurs.

Table 41. Nebraska NO_X and SO_2 emissions change from baseline by sector group

Nebraska sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Area	2,830	2,830	1.92	87.7	88.0	0.333
EGU	20,800	23,200	2,400	51,700	57,000	5,260
Industry	7,270	7,270	-2.73	1,840	1,840	-6.83
Oil/gas	4,140	3,690	-445	3.66	3.64	-0.02
On-road	37,300	13,700	-23,600	194	92.4	-102
Off-road	61,200	37,500	-23,700	116	112	-3.84
RWC	277	279	1.98	66.5	51.7	-14.8
Fire	1,610	1,610	0.00	770	770	0.00
Natural	74,700	74,700	0.00	--	--	--

Wisconsin's overall contribution to visibility impairment is 3.6% at Boundary Waters and 1.5% at Voyageurs. Most of that contribution is due to nitrate, 76% at Boundary Waters and 65% at Voyageurs, with the remainder due to sulfate. Corresponding statewide NO_X emissions are nearly five times higher than statewide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are industry, vehicles and the combination of area, oil & gas and residential wood combustion. Contribution from Wisconsin electric generating units is similar to that of natural sources. Sector groups with emissions not routed through stacks contribute mostly nitrate—between 74% to nearly 100% —to visibility impairment. Electric generating units and industry contribute mostly nitrate to Boundary Waters—54% and 52%, respectively—and contribute mostly sulfate to Voyageurs—59% and 62%, respectively—to visibility impairment. Each of the sector groups emit more NO_X than SO_2 in the 2016 v1b modeling projected to 2028. The preferential formation of sulfate over nitrate in the atmosphere likely has a role in the non-linear contribution of sulfate from industry and electric generating units.

Table 42 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in Wisconsin. It also contains the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the associated 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 42. Wisconsin sector contribution to visibility impairment in 2028 due to nitrate and sulfate at Minnesota Class I areas

Wisconsin Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Region total	3.6	1.5			129,829	26,611

Wisconsin Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) ■ NH4NO3 ■ NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Industry	1.2	0.6			22,800	19,400
Vehicle	1.2	0.4			47,700	496
Area + Oil/gas + RWC	0.6	0.2			21,229	2,015
EGU	0.3	0.2			13,500	4,700
Natural	0.3	0.2			24,600	--

Table 43 contains a breakdown of the emissions into less aggregated sector groups and includes the emissions change from baseline. In Wisconsin large reductions in NO_X emissions of around 66,000 tons from vehicles—on-road and off-road—were accounted for between 2016 and 2028. Vehicles make up about 47,700 tons of NO_X in 2028. The EGU and industry sector groups combined make up about 36,300 tons of NO_X and 24,100 tons of SO_2 in 2028. In the modeling, emissions reductions between 2016 and 2028 from industrial facilities are only 307 tons of NO_X and 1,150 tons of SO_2. Wisconsin actions to limit emissions from industrial facilities and perhaps vehicles are most likely to lessen visibility impacts at Boundary Waters and Voyageurs.

Table 43. Wisconsin NO_X and SO_2 emissions change from baseline by sector group

Wisconsin sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Area	20,100	19,500	-652	1,730	1,750	21.4
EGU	16,100	13,500	-2,540	13,000	4,700	-8,260
Industry	23,100	22,800	-307	20,500	19,400	-1,150
Oil/gas	535	619	83.1	0.043	0.065	0.022
On-road	79,600	25,200	-54,400	410	227	-183
Off-road	34,100	22,500	-11,600	172	269	96.8
RWC	1,100	1,110	12.1	320	265	-54.5
Fire	765	765	0.00	407	407	0.00
Natural	24,600	24,600	0.00	--	--	--

Missouri's overall contribution to visibility impairment is 3.5% at Boundary Waters and 2.8% at Voyageurs. Most of that contribution is due to nitrate, about 56% at both Class I areas, with the remainder due to sulfate. Corresponding statewide NO_X emissions are less than two times higher than statewide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are electric generating units and vehicles. Contribution from Missouri industry and combination of area, oil & gas and residential wood combustion sectors are similar to that of natural sources.

Each of the sector groups contribute mostly nitrate—between 52% to nearly 100% —to visibility impairment, except for electric generating units which contribute mostly sulfate—80% —to its portion of visibility impairment. Each of the other sector groups emit much more NO_X than SO_2, but electric generating units emit 33,200 tons of NO_X and 95,600 tons of SO_2 in the 2016 v1b modeling projected to 2028.

Table 44 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in Missouri. It also contains the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the relevant 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 44. Missouri sector contribution to 2028 nitrate and sulfate at Minnesota Class I areas

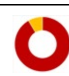
Missouri Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Region total	3.5	2.8			204,531	109,547
EGU	1.6	1.3			33,200	95,600
Vehicle	0.9	0.7			75,600	848
Industry	0.4	0.3			21,000	12,200
Natural	0.3	0.3			55,400	--
Area + Oil/gas + RWC	0.3	0.2			19,331	899

Table 45 contains a breakdown of the emissions into less aggregated sector groups and includes the emissions change from baseline. In Missouri large reductions in NO_X emissions of around 92,700 tons from vehicles—on-road and off-road—were accounted for between 2016 and 2028. Vehicles make up about 75,600 tons of NO_X in 2028. The EGU and industry sector groups combined make up about 54,200 tons of NO_X and 107,000 tons of SO_2 in 2028. Emissions reductions between 2016 and 2028 from electric generating units are 24,200 tons of NO_X and 4,130 tons of SO_2. Missouri actions to limit emissions from electric generating units and perhaps vehicles are most likely to lessen visibility impacts at Boundary Waters and Voyageurs.

Table 45. Missouri NO_X and SO_2 emissions change from baseline by sector group

Missouri sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Area	14,600	14,000	-569	671	670	-0.92
EGU	57,400	33,200	-24,200	99,800	95,600	-4,130
Industry	21,000	21,000	3.84	13,000	12,200	-738
Oil/gas	4,590	4,380	-212	4.33	4.31	-0.02
On-road	108,000	38,800	-69,300	588	309	-280

Missouri sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
Off-road	60,200	36,800	-23,400	260	539	279
RWC	949	951	1.62	276	225	-50.5
Fire	12,700	12,700	0.00	6,270	6,270	0.00
Natural	55,400	55,400	0.00	--	--	--

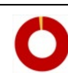
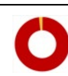
Canada emissions provided by U.S. EPA to MPCA did not distinguish between EGUs and industrial facilities, and MPCA decided to put them all in the industry sector group for source apportionment modeling. The vehicle sector group only includes on-road vehicles. Off-road vehicles came combined with area sources in the area sector group. Canada only has four sector groups, industry, area, natural and vehicle.

Overall Canada's contribution to visibility impairment is 7% at Boundary Waters and 10% at Voyageurs. Most of that contribution is due to sulfate, about 59% at Boundary Waters and 51% at Voyageurs, with the remainder due to nitrate. Corresponding region-wide NO_X emissions are more than 1.5 times higher than region-wide SO_2 emissions. In order of highest to lowest contributing sector groups to visibility impairment from the region are industry (including electric generating units) and area sources (including off-road vehicles). Contribution from Canada on-road vehicles is similar to that of natural sources.

Each of the sector groups contribute mostly nitrate—between 83% to nearly 100% —to visibility impairment, except for industry (including electric generating units) which contributes mostly sulfate—72% at Boundary Waters and 76% at Voyageurs—to its portion of visibility impairment. Each of the other sector groups emit much more NO_X than SO_2, but industry (including electric generating units) emits 199,000 tons of NO_X and 372,000 tons of SO_2 in the portion of Canada that falls within the 12US2 modeling domain.

Table 46 contains the percent contribution of total sulfate and nitrate visibility impairment for each sector group in Canada. It also contains the relative percent breakdown of the total visibility impairment into sulfate and nitrate, and the associated 2028 NO_X and SO_2 annual emissions used in the analysis.

Table 46. Canada sector contribution to visibility impairment in 2028 due to nitrate and sulfate at Minnesota Class I areas

Canada Sector group	Contribution to visibility impairment (%)		Pollutant contribution (%) NH4NO3 NH4SO4		Annual 2028 emissions (tons)	
	Boundary Waters	Voyageurs	Boundary Waters	Voyageurs	NO_X	SO_2
Region total	7.0	10.0			618,000	386,035
Industry (+ EGU)	5.3	6.8			199,000	372,000
Area (+ off-road)	0.9	1.7			190,000	13,500
Natural	0.4	0.8			114,000	--
Vehicle (on-road only)	0.4	0.7			115,000	535

Canada emissions are distributed across the entire northern border of the United States. To get a better understanding of the emissions impacting Boundary Waters and Voyageurs, MPCA divided the emissions summary into West Canada and East Canada. The border between Manitoba and Ontario north of Minnesota serves as the dividing line.

Table 47 contains a breakdown of the emissions into less aggregated sector groups and includes the emissions change from baseline. Canada experienced large reductions in NO_X emissions of around 157,000 tons (55,300 tons West, 102,000 tons East) from vehicles—on-road only—that were accounted for between 2016 and 2028. Vehicles make up about 115,000 tons (35,700 tons West, 79,300 tons East) of NO_X in 2028. The industry sector group (+ electric generating units) makes up about 199,000 tons (74,900 tons West, 124,000 tons East) tons of NO_X and about 372,000 tons (96,700 tons West, 275,000 tons East) of SO_2 in 2028. Emissions reductions between 2016 and 2028 from industry (+ electric generating units) are about 34,000 tons (43,500 tons reduction West, 9,610 tons increase East) of NO_X and about 140,000 tons (28,600 tons West, 111,000 tons East) of SO_2. The area (+ off-road) sector group makes up about 190,000 tons NO_X in 2028. Emissions reductions between 2016 and 2028 from area (+ off-road) are about 74,500 tons (31,600 tons West, 42,900 tons East) of NO_X. Canada actions to limit emissions from industry (+ electric generating units) and perhaps area sources are most likely to lessen visibility impacts at Boundary Waters and Voyageurs.

Table 47. Canada split into west and east NO_X and SO_2 emissions change from baseline by sector group

Canada sector group	NO_X emissions (tons)			SO_2 emissions (tons)		
	2016	2028	Difference	2016	2028	Difference
West Canada						
Area (+ off-road)	95,600	64,000	-31,600	6,410	6,280	-125
Industry (+ EGU)	118,000	74,900	-43,500	125,000	96,700	-28,600
On-road	91,100	35,700	-55,400	238	113	-125
Fire	2,920	2,920	0.00	1,490	1,490	0.00
Natural	78,300	78,300	0.00	--	--	--
East Canada						
Area (+ off-road)	169,000	126,000	-42,900	7,460	7,220	-238
Industry (+ EGU)	114,000	124,000	9,610	386,000	275,000	-111,000
On-road	182,000	79,300	-102,000	974	422	-553
Fire	4,580	4,580	0.00	1,940	1,940	0.00
Natural	35,700	35,700	0.00	--	--	--

The region and sector contribution analysis of sulfate and nitrate at Boundary Waters and Voyageurs supports the main statements MPCA posited at the beginning of the section, before examining the model contribution data, with a few modifications.

- Minnesota continues to be the largest state contributor to visibility impairment at Boundary Waters and Voyageurs
- NO_X emission reductions are needed
- Boundary Waters and Voyageurs may benefit from emission reductions in other regions or states located to the West and Northwest but also from other directions, in the following order of importance: Canada, North Dakota, Iowa, Nebraska, Wisconsin and Missouri

After examining the results, MPCA adds that SO_2 emission reductions especially from electric generating units in other states likely may lesson visibility impacts at Boundary Waters and Voyageurs. In this scenario, reductions of both species should occur together. The preferential formation of sulfate over nitrate in the atmosphere likely has a role in the non-linear contribution of sulfate to visibility impairment. Reductions of sulfate could free up ammonia to interact with available NO_X to form additional nitrate.

Most non-Minnesota state contributors over 3.5% threshold—North Dakota, Iowa, Nebraska and Missouri—contribute most from electric generating units, except for Wisconsin. Like Minnesota, Wisconsin's top two sector contributors to sulfate and nitrate extinction at Boundary Waters and Voyageurs, in order of importance, are industry and vehicles.

5. Data access

All data files used to support this TSD and the accompanying SIP are archived in the MPCA computer system and a provision has been made to maintain them. The files are generated and read on a Linux operating platform. Model output is processed with a series of Python programs. To obtain files used in the analysis contact Margaret McCourtney at margaret.mccourtney@state.mn.us .

6. References

Boylan, J. W. and A. G. Russell, 2006. PM and Light Extinction Model Performance Metrics, goals and Criteria for Three-Dimensional Air Quality Models. Atmospheric Environment, Environment, 40, 4946–4959.

Copeland 2008. Copeland, S.A, M. Pitchford, R. Ames, August 2008. Regional Haze Rule Natural Level Estimates Using the Revised IMPROVE Aerosol Reconstructed Light Extinction algorithm (http://vista.cira.colostate.edu/improve/Publications/GrayLit/032_NaturalCondIIpaper/Copeland_etal_NaturalConditionsII_Description.pdf)

Emery, C., Liu, Z., Russell, A. G., Odman, M. T., Yarwood, G., and Kumar, N., 2017. Recommendations on statistics and benchmarks to assess photochemical model performance, Journal of the Air & Waste Management Association, 67(5), pp. 582–598.

EPRI. Electric Power Research Institute, September 2020. Regional Haze Modeling to Evaluate Progress in Improving Visibility. (https://www.epri.com/research/programs/113141/results/3002016531)

Hand 2006. Hand,J, W.C. Malm, 2006 March. Review of the IMPROVE Equation for Estimating Ambient Light Extinction Coefficients. (http://vista.cira.colostate.edu/improve/Publications/GrayLit/016_IMPROVEeqReview/IMPROVEEquationReview.pdf)

Hand 2021. Hand, J, et al. Preview of the IMPROVE VI Report, presented at IMPROVE Steering Committee meeting, November 9-10, 2021. (http://vista.cira.colostate.edu/improve/wp-content/uploads/2021/11/03_Hand_IMP21_preview_short.pdf)

LADCO 2021. Lake Michigan Air Directors Consortium, June 2021. Modeling and Analysis for Demonstrating Reasonable Progress for the Regional Haze Rule 2018 – 2028 Planning Period, Technical Support Document. (https://www.ladco.org/wp-content/uploads/Projects/Regional-Haze/Round2/LADCO_RegionalHaze_Round2_TSD_17June2021_Final.pdf)

Malm 1999. Malm, W.C., Introduction to Visibility, May 1999. (https://www.epa.gov/sites/default/files/2016-07/documents/introvis.pdf)

MPCA 2009. Minnesota Pollution Control Agency, 2009 November 9. Technical Support Document for the Minnesota State Implementation Plan for Regional Haze (https://www.pca.state.mn.us/sites/default/files/aq-sip2-13.pdf)

MPCA 2022. Minnesota Pollution Control Agency, 2022. Minnesota's State Implementation Plan for Regional Haze, Comprehensive update for the second implementation period (2018 – 2028)

Simon, H., K.R. Baker, and S.B. Phillips, 2012. Compilation and Interpretation of Photochemical Model Performance Statistics Published between 2006 and 2012, Atmospheric Environment, 61, 124-139.

USEPA 2003 September-a. U.S. Environmental Protection Agency, 2003 September. Guidance for Tracking Progress Under the Regional Haze Rule, Research Triangle Park, NC [EPA-454/B-03-004] (https://www.regulations.gov/document/EPA-HQ-OAR-2015-0531-0006)

USEPA 2003 September-b. U.S. Environmental Protection Agency, 2003 September. Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Rule, Research Triangle Park, NC [EPA-454/B-03-005] (https://www.regulations.gov/document/EPA-HQ-OAR-2015-0531-0005)

USEPA 2018 November. U.S. Environmental Protection Agency, 2018 November 29. Modeling Guidance for Demonstrating Air Quality Goals for Ozone, $PM_{2.5}$, and Regional Haze, Research Triangle Park, NC. (https://www.epa.gov/sites/default/files/2020-10/documents/o3-pm-rh-modeling_guidance-2018.pdf)

USEPA 2018 December. U.S. Environmental Protection Agency, 2018 December 20. Technical Guidance on Tracking Visibility Progress for the Second Implementation Period of the Regional Haze Program, Research Triangle Park, NC (https://www.epa.gov/sites/default/files/2018-12/documents/technical_guidance_tracking_visibility_progress.pdf)

USEPA 2019 July. U.S. Environmental Protection Agency, 2019 July. Meteorological model performance for annual 2016 simulation with WRF v3.8, Research Triangle Park, NC [EPA-454/R-19-010] (https://www.epa.gov/sites/default/files/2020-10/documents/met_model_performance-2016_wrf.pdf)

USEPA 2019 August. U.S. Environmental Protection Agency, 2019 August 20. Guidance on Regional Haze State Implementation Plans for the Second Implementation Period, Research Triangle Park, NC. (https://www.epa.gov/sites/default/files/2019-08/documents/8-20-2019_-_regional_haze_guidance_final_guidance.pdf)

USEPA 2019 September. Technical Support Document for EPA's Updated 2028 Regional Haze Modeling, U.S. EPA, September 2019. (https://www.epa.gov/visibility/technical-support-document-epas-updated-2028-regional-haze-modeling)

USEPA 2021 March. Technical Support Document, Preparation of Emissions Inventories for the 2016v1 North American Emissions Modeling Platform, U.S. EPA, March 2021. (https://www.epa.gov/sites/default/files/2020-11/documents/2016v1_emismod_tsd_508.pdf)

Philip, S., R.V. Martina, J.R. Pierce, J.L. Jimenez, Q. Zhang, M.R. Canagaratna, D.V. Spracklen, C.R. Nowlan, L.N. Lamsal, M.J. Cooper, N.A. Krotkovi, 2014. Spatially and seasonally resolved estimate of the ration of organic mass to organic carbon, Atmospheric Environment, 87, 34-40.

Pitchford 1994. Pitchford, Marc L., Malm, William C., Development and Application of a Standard Visual Index. Atmospheric Environment, Volume 28: pp. 1049-1054

Pitchford 2007. Pitchford, M., W. Malm, B. Schichtel, N. Kumar, D. Lowenthal & J. Hand (2007). Revised Algorithm for Estimating Light Extinction from IMPROVE Particle Speciation Data, Journal of the Air & Waste Management Association, 57:11, 1326-1336, DOI: 10.3155/1047-3289.57.11.1326