



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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OFFICE OF
AIR QUALITY PLANNING
AND STANDARDS

MEMORANDUM

TO: EPA Docket # EPA-HQ-OAR-2007-0492

FROM: *JMK* for James Kelly, Mark Schmidt, Neil Frank, Brian Timin, Douglas Solomon, and Venkatesh Rao

THROUGH: Richard Wayland, Director, Air Quality Assessment Division *Richard Wayland*

RE: Technical Analyses to Support Surrogacy Policy for Proposed Secondary PM_{2.5} NAAQS under NSR/PSD Program

I. Overview

The Prevention of Significant Deterioration (PSD) program requires individual new or modified stationary sources to carry out an air quality analysis to demonstrate that their proposed emissions increases will not cause or contribute to a violation of any National Ambient Air Quality Standards (NAAQS). Such a demonstration for the proposed secondary PM_{2.5} visibility index NAAQS could require each PSD applicant to predict, via air quality modeling, the increase in visibility impairment that would result from the proposed source's emissions in conjunction with an assessment of existing air quality (visibility impairment) conditions. If this demonstration were to be attempted using the six-step procedure that the EPA is proposing to use for calculating PM_{2.5} visibility index design values from monitored air concentrations of PM_{2.5} components, significant technical issues with the modeling procedures could arise.

Recognizing these difficult technical issues, the EPA believes that there is an essential need to provide alternative approaches to enable prospective PSD sources to demonstrate that they will not cause or contribute to a violation of the secondary PM_{2.5} visibility index NAAQS, if finalized as proposed. To meet this need, this memorandum documents the technical analyses conducted to provide the basis for a surrogacy approach that could

be used by prospective PSD sources to facilitate the transition to a workable PSD permitting approach under the proposed secondary PM_{2.5} visibility index NAAQS. As described here, the EPA conducted a two-pronged technical analysis of the relationships between the proposed PM_{2.5} visibility index standard and the 24-hour PM_{2.5} standard. Based on this technical analysis, the EPA currently believes that there is sufficient evidence that a demonstration that a source does not cause or contribute to a violation of the mass-based 24-hour PM_{2.5} NAAQS serves as a suitable surrogate for demonstrating that a source does not cause or contribute to a violation of the proposed secondary 24-hour PM_{2.5} visibility index NAAQS under the PSD program. As such, many or all sources undergoing PSD review for PM_{2.5} could rely upon their analysis for demonstrating that they do not cause or contribute to a violation of the mass-based 24-hour PM_{2.5} NAAQS to also show that they do not cause or contribute to a violation of the proposed secondary PM_{2.5} visibility index NAAQS, if finalized.

II. Policy Background

PSD applicants are currently required to demonstrate that they do not cause or contribute to a violation of the existing annual and 24-hour PM_{2.5} NAAQS. To assist sources and permitting authorities in carrying out the required air quality analysis for PM_{2.5} under the existing standards, the EPA issued, on March 23, 2010, a guidance memorandum that recommends certain interim procedures to address the fact that compliance with the 24-hour PM_{2.5} NAAQS is based on a particular statistical form and that there are technical complications associated with the ability of existing models to estimate the impacts of secondarily formed PM_{2.5} resulting from emissions of PM_{2.5} precursors.¹ To provide more detail and to address potential issues associated with the modeling of direct and precursor emissions of PM_{2.5}, the EPA is now developing additional permit modeling guidance that will recommend appropriate technical approaches for conducting a PM_{2.5} NAAQS compliance demonstration for the existing PM_{2.5} NAAQS, which includes a more adequate accounting for contributions from secondary formation of ambient PM_{2.5} resulting from a proposed new or modified source's precursor emissions. To this end, the EPA discussed this draft guidance in March 2012 at the EPA's 10th Modeling Conference.² Based on its review of public comments received and further technical analyses, the EPA intends to issue final guidance by the end of calendar year 2012.

The EPA is proposing a distinct secondary NAAQS for PM_{2.5} that will provide protection against visibility

¹ U.S. EPA (2010) Modeling procedures for demonstrating compliance with PM_{2.5} NAAQS. Stephen D. Page Memorandum, dated March 23, 2010. U.S. Environmental Protection Agency, Research Triangle Park, NC.

² The presentation on this draft guidance is posted on the EPA website at: <http://www.epa.gov/ttn/scram/10thmodconf.htm>.

impairment, measured in terms of a visibility index using a calculated PM_{2.5} light extinction indicator. The PM_{2.5} visibility index values are determined using a six-step procedure involving 24-hour speciated PM_{2.5} concentration data together with climatological relative humidity factors. The EPA plans to calculate design values for the proposed secondary PM_{2.5} visibility index NAAQS using this procedure with ambient PM_{2.5} speciation measurement data (available through the Chemical Speciation Network, CSN, and the Interagency Monitoring of Protected Visual Environments, IMPROVE, network) and climatological relative humidity (RH) data.

As noted in the overview section, certain technical issues currently prevent modeled determinations of the visibility impairment that would result from a new or modified source. The relevant technical difficulties include the current limitations on speciated source-specific emissions data for model input; the lack of an EPA-approved air quality model with the capability to address the atmospheric chemistry associated with secondary formation of PM_{2.5}; and the lack of PSD screening tools for streamlining the air quality analysis process. In addition, due to the limited monitoring network for speciated PM_{2.5}, some sources may not be able to rely on existing speciated monitoring data to adequately represent the background air quality and thereby satisfy preconstruction monitoring requirements. Consequently, some prospective PSD sources could be required to collect new data in order to determine the representative background concentrations of the PM_{2.5} species required for calculating the PM_{2.5} visibility index values.

Recognizing these difficult technical issues, the EPA believes that there is an essential need to provide alternative approaches to enable prospective PSD sources to demonstrate that they will not cause or contribute to a violation of the secondary PM_{2.5} visibility index NAAQS, if finalized as proposed. To meet this need, the EPA believes that it is reasonable to allow the use of a surrogacy approach for at least the interim period while technical issues are being resolved, but which could potentially be continued beyond such time if shown to be appropriate. The EPA believes that following this approach will facilitate the transition to a workable PSD permitting approach under the proposed secondary PM_{2.5} visibility index NAAQS.

To support consideration of alternative approaches that could be used by prospective PSD sources, the EPA conducted a two-pronged technical analysis of the relationships between the proposed PM_{2.5} visibility index NAAQS and the 24-hour PM_{2.5} NAAQS. The first prong of the analysis addressed aspects of a PSD significant impact analysis by evaluating whether an individual source's impact resulting in a small increase in PM_{2.5} concentration would produce a comparably small increase in visibility impairment. This analysis included estimates of PM_{2.5} speciation profiles based on direct PM_{2.5} emission profiles for a broad range of source categories and for

theoretical upper and lower bound scenarios. The analysis indicated that small increases in ambient PM_{2.5} concentrations caused by individual sources produce similarly small changes in visibility impairment for ambient conditions near the proposed standard level of either 30 or 28 deciviews (dv). This result indicates that a significant impact level (SIL) defined in the context of the 24-hour PM_{2.5} NAAQS would also be suitable for use as a SIL in the context of the proposed secondary PM_{2.5} visibility index NAAQS. The second prong of the analysis addressed aspects of a PSD cumulative impact analysis by exploring the relationship between the three-year design values for the existing 24-hour PM_{2.5} NAAQS and coincident design values for the proposed PM_{2.5} visibility index NAAQS based on recent air quality data. This aspect of the analysis indicated that increases in 24-hour PM_{2.5} design values generally correspond to increases in visibility index design values, and vice-versa. The analysis further explored the appropriateness of using a demonstration that a source does not cause or contribute to a violation of the 24-hour PM_{2.5} NAAQS as a surrogate for a demonstration that a source does not cause or contribute to a violation of the proposed secondary PM_{2.5} visibility index NAAQS. This analysis is based on 2008 to 2010 air quality data and the proposed level of 35 µg/m³ for the 24-hour PM_{2.5} standard and for illustrative purposes an alternative standard level of 12 µg/m³ for the annual PM_{2.5} standard together with the proposed levels of 28 or 30 dv for the secondary PM_{2.5} visibility index standard in conjunction with 24-hour averaging time and a 90th percentile form. The results indicate that all (for the 30 dv level) or nearly all (for the 28 dv level) areas in attainment of the 24-hour PM_{2.5} standard would also be in attainment of the proposed secondary PM_{2.5} visibility index standard.³

Note that the surrogacy approach is not intended to replace or otherwise undermine the validity of the analytical techniques employed for air quality related value assessments (AQRVs), including visibility, required under 40 CFR Part 51.166(p) and 40 CFR Part 52.21(p). The federal land managers (FLMs)—the federal officials with direct responsibility for management of Federal Class I parks and wilderness area—have an affirmative responsibility to protect the AQRVs of such lands and to provide the appropriate procedures and analysis techniques for assessing AQRVs (Appendix W to 40 CFR Part 51, Sections 6.1(b) and 6.2.3(a)). The FLMs have developed specific modeling approaches for AQRV assessments that are not specifically governed under the requirements set forth in 40 CFR Part 51.166(l)(1) and 40 CFR Part 52.21(l)(1). Thus the surrogacy approach is not applicable to the AQRV assessments under the PSD program.

³ The relationships between design values as characterized here are dependent on the specific level and form of each of the standards

III. Technical Background

The IMPROVE equation used here for calculating the light extinction coefficient, b_{ext} ⁴, from speciated $PM_{2.5}$ concentration is as follows:

$$\begin{aligned} b_{ext} = & 3 \times f(RH) [\text{Sulfate}] + \\ & 3 \times f(RH) [\text{Nitrate}] + \\ & 4 \times [\text{Organic Mass}] + \\ & 10 \times [\text{Elemental Carbon}] + \\ & 1 \times [\text{Fine Soil}], \end{aligned} \quad (1)$$

where [Sulfate] is the mass of ammonium sulfate under the assumption of fully-neutralized sulfate ion (i.e., [Sulfate] = $1.375 \times SO_4^{2-}$ concentration), [Nitrate] is the mass of ammonium nitrate under the assumption of fully-neutralized nitrate ion (i.e., [Nitrate] = $1.29 \times NO_3^-$ concentration), [Organic Mass] is calculated as $1.4 \times$ the organic carbon concentration, [Elemental Carbon] is elemental carbon concentration, [Fine Soil] is a sum of the fine soil-derived elements (Al, Si, K, Ca, Ti, Fe) along with their normal oxides (Al_2O_3 , SiO_2 , CaO , K_2O , FeO , Fe_2O_3 , TiO_2), and $f(RH)$ is a relative humidity adjustment factor that accounts for enhanced light extinction due to water uptake by hygroscopic particle components. For a given $PM_{2.5}$ composition and RH, increases in b_{ext} are linear with respect to increases in $PM_{2.5}$ concentration. The visibility index (VI) is a logarithmic transformation of the light extinction coefficient and is calculated as follows:

$$VI = 10 \ln \left(\frac{b_{ext} + 10}{10} \right), \quad (2)$$

where units are in dv . Increases in VI are logarithmic with respect to increases in b_{ext} such that changes in VI are approximately linear with respect to perceived visibility changes. Equation 2 ensures that increases or decreases in light extinction coefficient always produce, respectively, increases or decreases in visibility index.

While Equations 1 and 2 provide clear relationships between speciated $PM_{2.5}$ concentrations and visibility impairment, the impact of variable particle composition and RH on the relationships under ambient conditions is not obvious from the expressions. To explore the relationships for ambient conditions, calculated light extinction (b_{ext}) and visibility index (VI) values are plotted as functions of 24-hour $PM_{2.5}$ concentration for $PM_{2.5}$ measurements from 2008 to 2010 at 199 locations in Figure 1. Following the trend expected from Equation 1, calculated light extinction

⁴ b_{ext} is the attenuation of light per unit distance due to scattering and absorption by gases and particles in the atmosphere and is expressed in Mm^{-1} (inverse megameter) units.

increases roughly linearly with $PM_{2.5}$ concentration (Figure 1a) with correlation coefficients for U.S. regions defined in Figure 2 ranging from 0.81 to 0.95 and equaling 0.92 over all sites (Table 1). The scatter in results in Figure 1a is due to differences in RH and $PM_{2.5}$ composition for the different measurements. The results shown in Figure 1b indicate that the calculated visibility index tends to increase logarithmically with increasing $PM_{2.5}$ concentration for the ambient $PM_{2.5}$ data as expected based on Equation 2. Similar to the light extinction case, the scatter in the results for the visibility index is due to differences in $PM_{2.5}$ composition and RH for the different measurements. The strong relationship between 24-hour $PM_{2.5}$ concentration and visibility impairment for the ambient data in Figure 1 provides the foundation for the analysis described below that focuses on demonstrating surrogacy in the context of the NSR/PSD program.

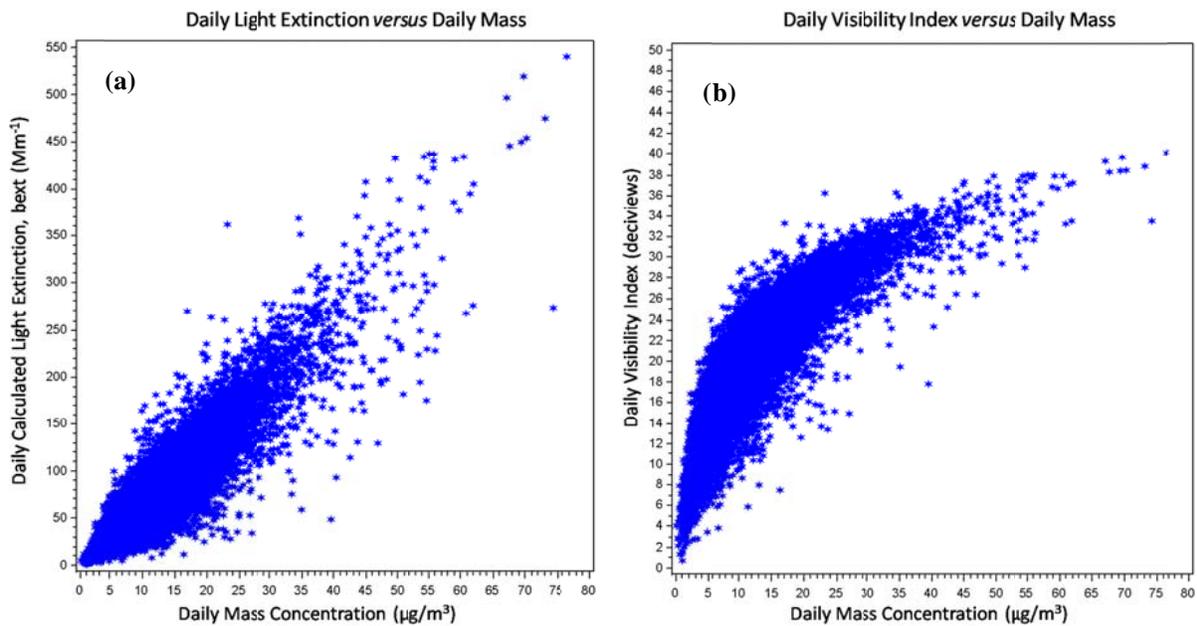


Figure 1. Daily calculated (a) light extinction coefficient and (b) visibility index as a function of measured daily average $PM_{2.5}$ concentration



Figure 2. Definition of U.S. regions⁵ considered in this analysis.

⁵ U.S. EPA (1996) Air Quality Criteria for Particulate Matter. Volume I of III. EPA/600/P-95/001aF <http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=2832>

Table 1. Correlation of daily calculated light extinction and 24-hour PM_{2.5} concentration for U.S. observational sites. Note: values correspond to results shown in Figure 1a; regions are defined in Figure 2.

Region	n daily values	n sites	Correlation of daily calculated light extinction, bext (in Mm ⁻¹) vs. daily mass concentration (in µg/m ³)
Northeast	7,204	35	0.93
Southeast	7,039	41	0.88
Ind. Midwest	9,770	66	0.93
Upper Midwest	2,258	11	0.93
Southwest	967	7	0.81
Northwest	4,859	31	0.93
So. California	1,917	8	0.95
U.S.	34,014	199	0.92

IV. Technical Analyses

This section examines the use of analyses related to the 24-hour PM_{2.5} NAAQS as a surrogate for analyses related to the proposed secondary PM_{2.5} visibility index NAAQS in the context of two aspects of the NSR/PSD program. First, the topic of whether a SIL defined for the 24-hour PM_{2.5} NAAQS would correspond to a comparably small value in terms of visibility impairment is examined. The NSR/PSD air quality impact analysis uses a SIL in determining whether a source's modeled impact on air quality for a particular pollutant is considered significant⁶. If a source's impact exceeds the SIL, then a cumulative impact analysis is required for that source to determine if its emissions cause or contribute to potential NAAQS violations. The second component of the analysis explores the suitability of using a surrogate approach in a cumulative impact analysis by considering whether violation status based on recent air quality data would be similar under the proposed secondary PM_{2.5} visibility index NAAQS and under the 24-hour PM_{2.5} NAAQS.

A Small Increase in PM_{2.5} Concentration Produces a Comparably Small Increase in Visibility Impairment

For a SIL developed in the context of the 24-hour PM_{2.5} NAAQS to be suitable for the proposed secondary visibility index NAAQS, a small increase in PM_{2.5} concentration relative to the 24-hour PM_{2.5} NAAQS should produce a comparably small increase in visibility index relative to the secondary visibility index NAAQS. In this analysis, the changes in visibility index associated with increases in PM_{2.5} concentration of around 1 µg m⁻³ are evaluated. The PM_{2.5} speciation profiles listed in Table 2 are used with Equation 1 in examining the relationship between corresponding increases in ambient PM_{2.5} concentration and visibility index values for ambient conditions

⁶ The EPA defined SILs for PM_{2.5} in a final rule issued on October 20, 2010. See, 75 FR 64864. SILs for other pollutants are defined at 40 CFR 51.165(b)(2).

near the proposed standard levels of 28 or 30 dv under low- and high-RH conditions. The profiles in Table 2 are based on direct-PM_{2.5} emission source profiles as described in Appendix A. Cases where PM_{2.5} is assumed to be composed of a single component are also considered to provide theoretical upper- and lower-bound values. For instance, the upper-bound change in visibility index occurs under high-RH conditions when PM_{2.5} is composed entirely of a hygroscopic component such as sulfate.

The increases in visibility index values associated with a 1 µg m⁻³ increase in PM_{2.5} concentration for low- and high-RH conditions are shown in Figure 3 as a function of the background ambient visibility index for PM_{2.5} with the concentration profiles in Table 2. Curves for the theoretical upper and lower bounds are based on calculations for 1 µg m⁻³ of single-component PM_{2.5} without hydration⁷. Although the upper-bound composition may not be realized in practice, it is included here as a reference to address the potential concern that the secondary component of PM_{2.5} concentration resulting from SO₂ and NO_x emissions is not directly considered in the concentration profiles in Table 2. In this discussion, “low-RH” conditions correspond to a relative humidity adjustment factor, f(RH), of 1.51, and “high-RH” conditions correspond to f(RH)=4.16. These values occur at the lower and upper end of the climatological monthly average f(RH) distributions shown in Figure A.1 in Appendix A. In terms of relative humidity, the RH adjustment factors correspond to RHs of 55% and 90% based on the scale used in Regional Haze Rule guidance documents (see Appendix A). Visibility impairment by PM_{2.5} is greatest under high-RH conditions due to water uptake by hygroscopic particle components (i.e., sulfate and nitrate) with increasing RH. Therefore, results in Figure 3b for profiles with large sulfate fractions are an extreme test of the visibility impacts associated with a 1 µg m⁻³ increase in PM_{2.5} concentration.

For a background ambient visibility index of 27 dv, the addition of 1 µg m⁻³ of PM_{2.5} produces a median increase in visibility impairment of 0.2 dv with a range of 0.09-0.44 dv under low-RH conditions based on the profiles in Table 2 (Figure 3a). Elemental carbon (EC) has the greatest light extinction per unit mass for low-RH conditions, and so the Natural Gas Combustion profile (43.9% EC) produces the greatest visibility impairment in Figure 3a. The theoretical upper-bound of 0.65 dv is given in this case by single-component EC PM_{2.5}, and the theoretical lower bound of 0.07 dv is given by single-component fine soil PM_{2.5}. Under high-RH conditions (Figure 3b), the median increase in visibility index for the profiles for an increase of 1 µg m⁻³ of PM_{2.5} concentration is 0.36 dv and the range is 0.11-0.78 dv at a background ambient visibility index of 27 dv. [Sulfate] and [Nitrate] have the

⁷For instance, the upper-bound dashed curve in Figure 3b is based on calculations with Equation 1 using a value of 1 µg m⁻³ for [Sulfate].

greatest light extinction per unit mass for high-RH conditions, and so the Residential Oil Combustion profile (95.2% [Sulfate]) produces the greatest visibility impairment of the source profiles in Figure 3b. The theoretical upper-bound of 0.81 dv is given in this case by single-component [Sulfate] $PM_{2.5}$, and the theoretical lower bound of 0.07 dv is given by single-component fine soil $PM_{2.5}$. Considering that median changes in the visibility index for the profiles is less than 0.5 dv and the theoretical maximum change is less than 1 dv even under conditions of high RH, results in Figure 3 indicate increases in the visibility index are comparably small to a $1 \mu\text{g m}^{-3}$ increase in $PM_{2.5}$ concentration for ambient conditions near the proposed secondary standard levels of 28 or 30 dv.

The increase in visibility impairment with an increase in $PM_{2.5}$ concentration for ambient conditions with a background visibility index of 27 dv is shown as a function of $PM_{2.5}$ concentration increase (0.8 to $1.2 \mu\text{g m}^{-3}$) in Figure 4 for low- and high-RH conditions. For the highest $PM_{2.5}$ concentration increase considered, the median increase in visibility impairment under low-RH conditions is 0.24 dv with a range of 0.11-0.53 dv (Figure 4a) for the profiles in Table 2, with theoretical upper- and lower-bound values of 0.78 dv and 0.08 dv, respectively. The median increase in visibility impairment under high-RH conditions for the source profiles is 0.43 dv with a range of 0.13-0.93 dv (Figure 4b), and the theoretical upper- and lower-bound values are 0.96 dv and 0.08 dv, respectively. Results in Figure 4 indicate that visibility index changes associated with an increase of $PM_{2.5}$ concentration of up to $1.2 \mu\text{g m}^{-3}$ are comparably small for ambient conditions near the proposed levels of 28 or 30 dv.

For readers so interested, the increases in light extinction coefficient associated with increases in $PM_{2.5}$ concentration (0.8 to $1.2 \mu\text{g m}^{-3}$) are shown in Figure 5 for low- and high-RH conditions. Note that changes in the light extinction coefficient associated with changes in $PM_{2.5}$ concentration do not depend on the background amount of light extinction as do changes in the visibility index. Under low-RH conditions, a $1 \mu\text{g m}^{-3}$ increase in $PM_{2.5}$ concentration produces a median increase in light extinction of 3.06 Mm^{-1} with a range of 1.31 - 6.72 Mm^{-1} for the source profiles in Table 2 (Figure 5a). The median increase in light extinction coefficient in this case is 1.9% of the total light extinction coefficient at 28 dv (i.e., $b_{\text{ext}+10}=164.4 \text{ Mm}^{-1}$; Equation 2) and 1.5% of the value at 30 dv (i.e., 200.9 Mm^{-1} ; Equation 2). The theoretical upper-bound of 10 Mm^{-1} for a $1 \mu\text{g m}^{-3}$ increase in $PM_{2.5}$ concentration is given in this case by single-component EC $PM_{2.5}$, and the theoretical lower bound of 1 Mm^{-1} is given by single-component soil $PM_{2.5}$. Under high-RH conditions, a $1 \mu\text{g m}^{-3}$ increase in $PM_{2.5}$ concentration produces a median increase in light extinction coefficient for the source profiles of 5.43 Mm^{-1} with a range of 1.6 - 12.13 Mm^{-1} (Figure 5b). The median increase in light extinction coefficient in this case is 3.3% of the total light extinction coefficient at

28 dv and 2.7% of the value at 30 dv. Under high-RH conditions, single-component [Sulfate] $PM_{2.5}$ gives a theoretical upper-bound change in light extinction coefficient of $12.48 Mm^{-1}$ for a $1 \mu g m^{-3}$ increase in $PM_{2.5}$ concentration, and soil $PM_{2.5}$ gives a theoretical lower bound of $1 Mm^{-1}$. Results in Figure 5 indicate that changes in light extinction associated with a small increase in $PM_{2.5}$ concentration would be comparably small relative to total light extinction at the proposed levels of either 28 or 30 dv⁸.

Overall, results in Figures 3–5 suggest that a small increase in $PM_{2.5}$ concentration relative to the 24-hour $PM_{2.5}$ NAAQS produces a comparably small increase in visibility index and light extinction coefficient relative to the proposed secondary visibility index NAAQS. Thus the results provide support for using the 24-hour $PM_{2.5}$ NAAQS as a surrogate for the proposed secondary visibility index NAAQS in the air quality analysis for NSR/PSD applications. Specifically, the results indicate that a SIL defined in the context of the 24-hour $PM_{2.5}$ NAAQS would be suitable for use as a SIL in the context of the secondary $PM_{2.5}$ visibility index NAAQS.

⁸ In the context of AQRV protection including Class I visibility relative to natural background conditions, similar changes in light extinction could approach or exceed thresholds of concern to FLMs.

Table 2. Profiles of PM_{2.5} concentration used in visibility calculations with Equation 1 (see Appendix A for details on the development of the profiles).

Category	EC	OM	[Nitrate]	[Sulfate]	Soil
Aluminum Production	2.9%	6.9%	0.7%	7.7%	81.8%
Asphalt Manufacturing	7.9%	8.3%	0.2%	1.3%	82.4%
Asphalt Roofing	0.0%	98.9%	0.0%	0.1%	0.9%
Bituminous Combustion	2.9%	6.3%	0.5%	29.8%	60.5%
Cast Iron Cupola	0.9%	8.8%	0.6%	8.5%	81.1%
Catalytic Cracking	0.1%	0.0%	0.0%	44.0%	55.9%
Cement Production	2.9%	17.6%	6.0%	24.1%	49.4%
Construction Dust	0.0%	10.8%	0.1%	2.4%	86.7%
Distillate Oil Combustion	13.8%	48.4%	0.0%	36.1%	1.6%
Electric Arc Furnace	0.4%	4.8%	0.3%	3.3%	91.1%
Industrial Manufacturing - Avg	3.6%	41.0%	1.5%	53.9%	0.0%
Lignite Combustion	1.4%	38.8%	0.5%	10.1%	49.2%
Lime Kiln	2.1%	8.3%	0.6%	45.1%	43.9%
Natural Gas Combustion	43.9%	39.5%	3.1%	13.5%	0.0%
Open Hearth Furnace	0.0%	27.3%	0.7%	53.6%	18.5%
Petroleum Industry - Avg	0.0%	13.0%	0.9%	86.0%	0.0%
Process Gas Combustion	14.7%	42.5%	3.1%	22.9%	16.8%
Pulp & Paper Mills	0.1%	0.0%	0.0%	65.3%	34.6%
Residential Coal Combustion	24.0%	62.8%	0.4%	4.6%	8.2%
Residential Natural Gas Combustion	6.4%	65.1%	4.2%	16.5%	7.9%
Residual Oil Combustion	1.6%	2.2%	0.0%	95.2%	1.0%
Solid Waste Combustion	2.2%	17.1%	2.7%	13.5%	64.5%
Sub-Bituminous Combustion	6.5%	6.7%	0.1%	21.2%	65.5%
Wood Fired Boiler	3.6%	48.0%	0.0%	8.8%	39.6%

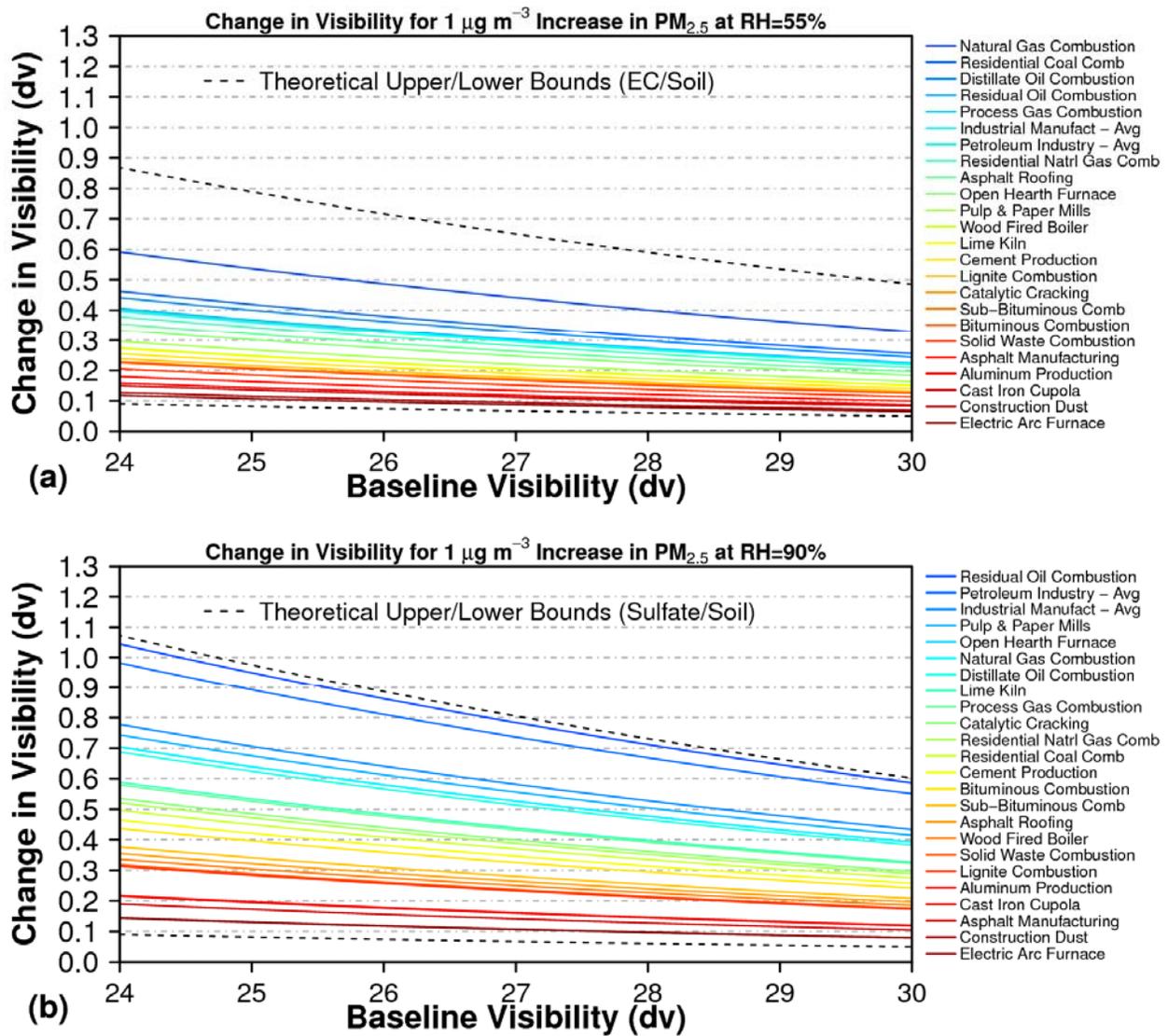


Figure 3. Change in visibility index in deciview units for a $1 \mu\text{g m}^{-3}$ increase in $\text{PM}_{2.5}$ under (a) low-RH and (b) high-RH conditions. The order of emission sources in the legend matches that of the curves.

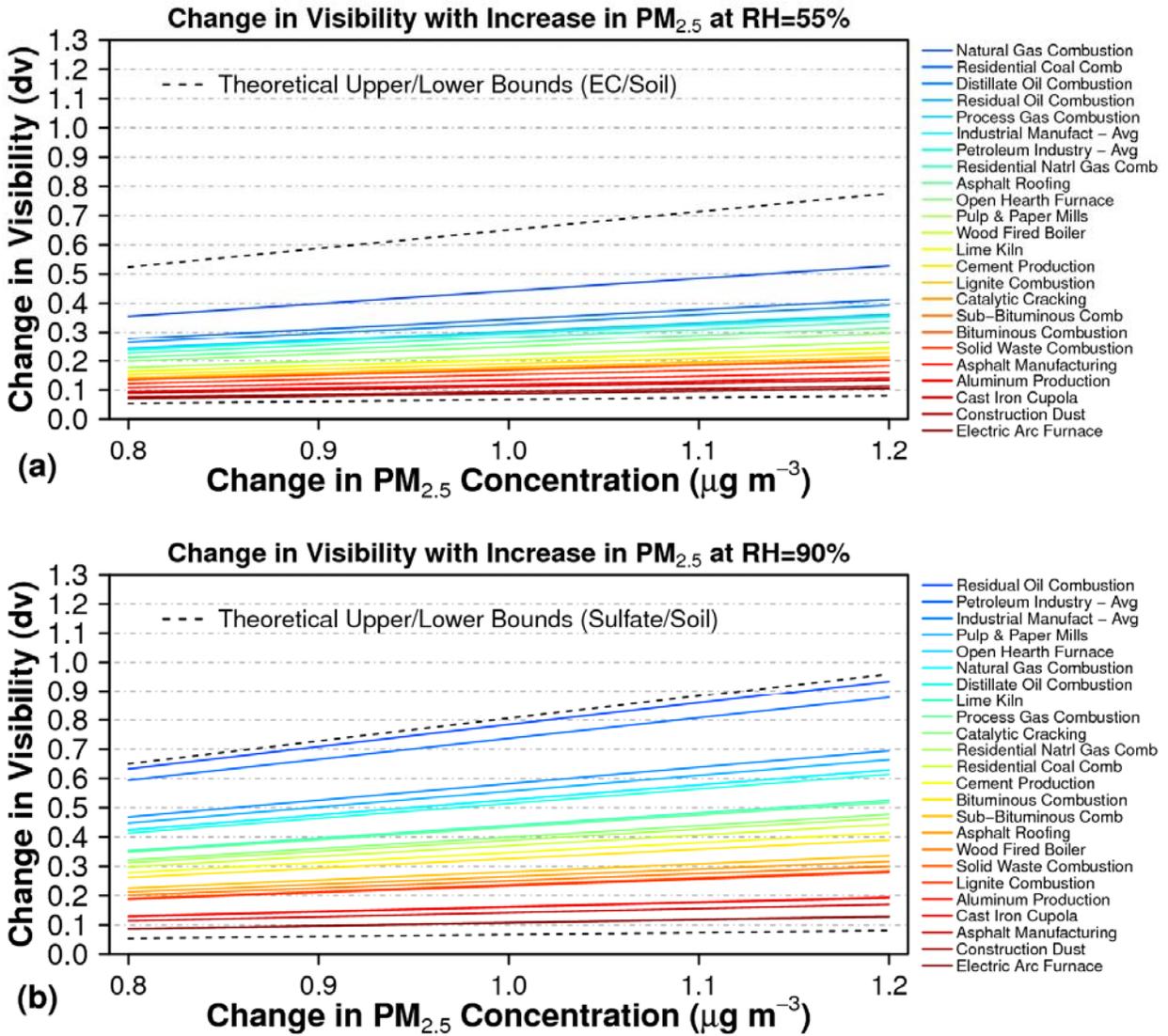


Figure 4. Change in visibility index in deciview units for an increase in PM_{2.5} concentration at ambient conditions of 27 dv under (a) low-RH and (b) high-RH conditions. The order of emission sources in the legend matches that of the curves.

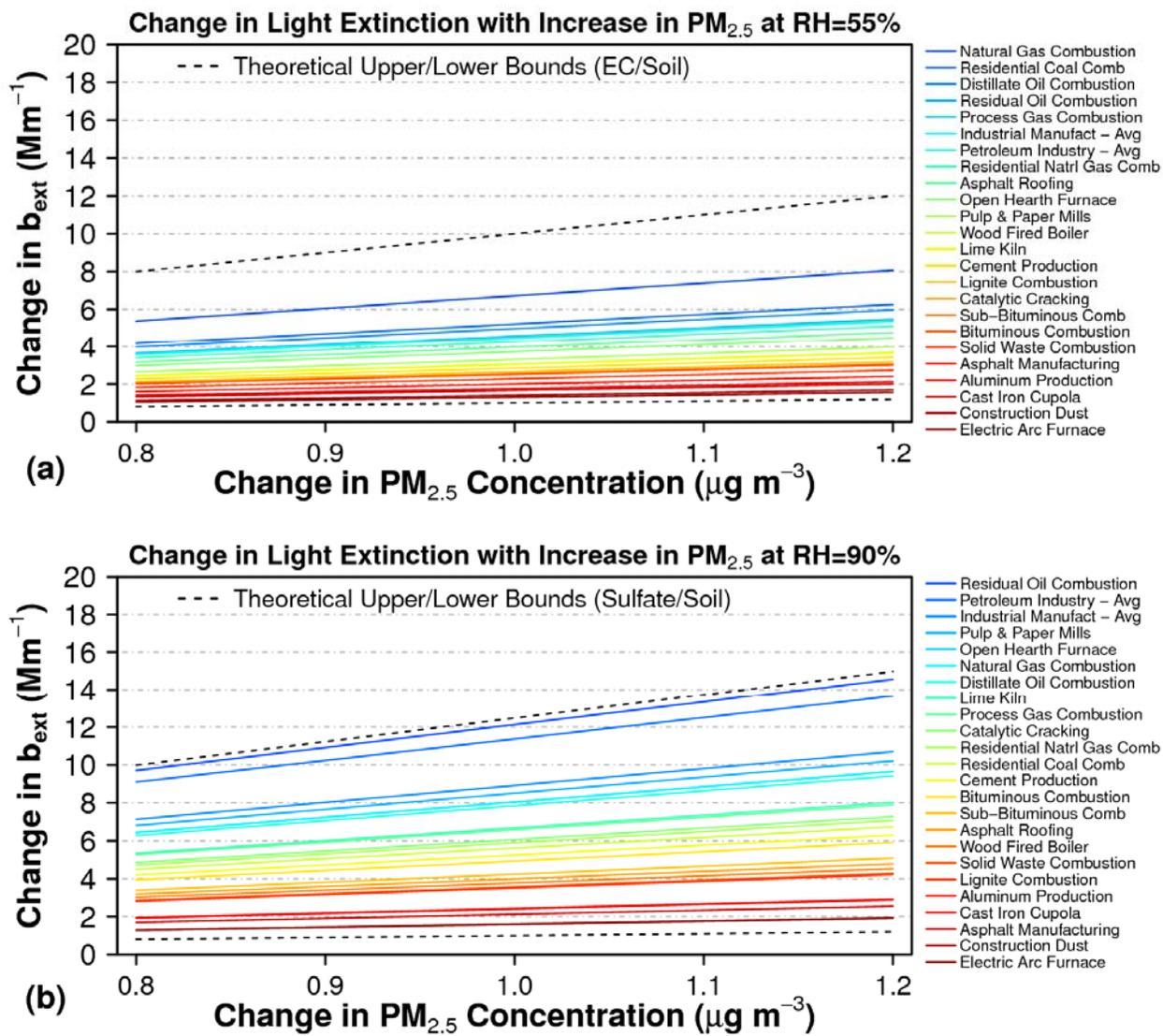


Figure 5. Change in light extinction for an increase in PM_{2.5} concentration under (a) low-RH and (b) high-RH conditions. The order of emission sources in the legend matches that of the curves.

Areas that Attain the 24-hour PM_{2.5} NAAQS Generally Attain the Proposed Secondary Visibility Index NAAQS

In this section, the relationship between 24-hour PM_{2.5} design values and visibility index design values is examined along with violation status under the 24-hour PM_{2.5} NAAQS and the secondary visibility index NAAQS. While the relationship between PM_{2.5} concentration and visibility index has been described above, the relationship between design values for the 24-hour PM_{2.5} NAAQS and secondary visibility index NAAQS is not obvious *a priori* because of differences in design value calculations for the standards.

Design values for the 24-hour PM_{2.5} NAAQS and the secondary PM_{2.5} visibility index NAAQS based on PM_{2.5} measurements from 2008 to 2010 are shown in Figure 6. The 102 sites represented in Figure 6 are those with data that meet the current and/or proposed data completeness criteria of 40 CFR Part 50, Appendix N, for the 24-hour PM_{2.5} NAAQS and a possible visibility index NAAQS level of 28 dv. Data markers are color-coded according to the U.S. regions defined in Figure 2 and are shape-coded according to location in the eastern or western U.S. The data suggest that increases or decreases in 24-hour PM_{2.5} design values correspond, respectively, to increases or decreases in visibility index design values. Although some curvature is indicated by the data for the relationship between 24-hour PM_{2.5} design values and visibility index design values, linear correlations were calculated and range from 0.65 to 0.98 for the U.S. regions and equal 0.75 over all U.S. sites (Figure 6). The curvature in the data arises from the logarithmic relationship between PM_{2.5} concentration and visibility index (i.e., Equation 2) that persists to some degree through the design value calculation⁹.

The four quadrants demarcated by solid grey lines in Figure 6 identify zones of exceedance for the 24-hour PM_{2.5} NAAQS and the proposed secondary visibility index NAAQS level of 28 dv. Note that these quadrants are based on design values of 35.5 µg m⁻³ and 28.5 dv (rather than 35 µg m⁻³ and 28 dv) in the Figure 6 to reflect rounding conventions. Similarly, the dashed horizontal line at 30.5 dv corresponds to the proposed secondary NAAQS level of 30 dv. The majority of the design values in Figure 6 fall into the lower-left quadrant where neither the 24-hour nor the secondary NAAQS level is exceeded. For design values in the upper-right quadrant, where both NAAQS levels are exceeded, a question arises on whether the visibility index levels of 28 or 30 dv would be attained if the 24-hour PM_{2.5} design values were reduced to the level of 35 µg m⁻³ through emission controls. Based on trends in the figure, the secondary standard level of 30 dv would likely be attained at sites that violate both the 24-hour level and the secondary visibility index 30 dv level if PM_{2.5} concentrations were reduced such that the 24-

⁹ The relationship between annual PM_{2.5} design values and visibility index design values (Figure A.2 in Appendix A) is similar to that for the 24-hour PM_{2.5} design values but with generally higher linear correlations (i.e., 0.72 to 0.96 for U.S. regions and 0.87 over all U.S. sites).

hour level was attained. For the Southern California (red circles) and Northwest (blue circles) design values that exceed the 24-hr NAAQS and the secondary 28 dv level, a roughly 2-3 dv decrease in visibility index design value with a roughly 13-27 $\mu\text{g m}^{-3}$ decrease in 24-hour $\text{PM}_{2.5}$ design value would provide for attainment of both standards. Such behavior is consistent with the overall trend of design values for the Southern California and Northwest regions in Figure 6. No design value for these regions occurs in the upper-left quadrant, where the proposed visibility index NAAQS is exceeded and the 24-hour $\text{PM}_{2.5}$ NAAQS is attained. For the Industrial Midwest marker (grey star) in the upper-right quadrant, a roughly 3 dv decrease in visibility index design value with a roughly 13 $\mu\text{g m}^{-3}$ decrease in 24-hour $\text{PM}_{2.5}$ design value would provide for attainment of both the 24-hour level and secondary level of 28 dv. For this case, attainment of the 24-hour $\text{PM}_{2.5}$ NAAQS may lead to attainment of the proposed secondary level of 28 dv, although behavior for Industrial Midwest sites is more complicated because four values for this region occur in the upper-left quadrant.

Design values in the upper-left and lower-right quadrants of Figure 6 correspond to cases where either the 24-hour $\text{PM}_{2.5}$ NAAQS or the secondary visibility index NAAQS is exceeded (but not both). Of the design values in these quadrants, values for sites in Southern California and the Northwest occur in the lower-right quadrant where both secondary visibility index NAAQS levels are attained despite exceedance of the 24-hour $\text{PM}_{2.5}$ NAAQS level, while values for sites in the Industrial Midwest occur in the upper-left quadrant where the secondary visibility index NAAQS level of 28 dv is exceeded despite attainment of the 24-hour $\text{PM}_{2.5}$ NAAQS level. No design value exists where the secondary NAAQS level of 30 dv is exceeded but the 24-hour $\text{PM}_{2.5}$ NAAQS level is attained. However, the design values for Industrial Midwest sites that exceed the secondary visibility index NAAQS level of 28 dv but attain the 24-hour $\text{PM}_{2.5}$ NAAQS level indicate that attainment of the 24-hour $\text{PM}_{2.5}$ NAAQS does not guarantee attainment of the proposed visibility index NAAQS level of 28 dv.

A map of exceedance counties for the 24-hour $\text{PM}_{2.5}$ NAAQS and secondary visibility index NAAQS level of 28 dv based on 24-hour average $\text{PM}_{2.5}$ measurements from 2008 to 2010 is shown in Figure 7. Note that 132 counties are represented in Figure 7 while only 102 sites are represented in Figure 6 due to data completeness considerations. For instance, a county is represented in Figure 7 if complete data exists for calculating a 24-hour design value and a secondary standard design value for the county from a combination of monitors in the county, whereas a site is represented in Figure 6 if complete data exists for calculating both the 24-hour and secondary standard design values at the individual monitoring site. The Industrial Midwest counties in Indiana (i.e., Elkhart and Clark) and Ohio (i.e., Cuyahoga and Jefferson) shown in red in Figure 7 exceed the secondary NAAQS level of

28 dv but do not exceed the 24-hour PM_{2.5} NAAQS. The Industrial Midwest is characterized by PM_{2.5} with relatively high nitrate and sulfate fractions (Figure 8a) as well as instances of high RH (Figure 8b) that can combine to produce relatively high visibility impairment per unit mass of PM_{2.5}. This region also tends to experience a relatively large number of days with moderate PM_{2.5} levels such that the 90th percentile PM_{2.5} concentration (relevant to visibility index design value calculations) is relatively close to the 98th percentile PM_{2.5} concentration (relevant to 24-hour PM_{2.5} design value calculations). This behavior is evident in the comparison of the ratios of 90th-to-98th percentiles of PM_{2.5} concentration distributions in Figure 8c. The combination of high nitrate and sulfate fractions, substantial RH adjustment factors, and PM_{2.5} distribution characteristics leads to relatively high visibility index design values for a given 24-hour PM_{2.5} design value for counties in the Industrial Midwest. Regional reductions in sulfate PM_{2.5} due to emission controls planned as part of national rules as well as emission reductions associated with potential annual standard violations¹⁰ are expected to improve visibility in this region.

The design value trends in Figure 6 for U.S. regions suggest that the 24-hour PM_{2.5} NAAQS level of 35 µg m⁻³ would generally be controlling of violation status compared with the secondary visibility index levels of 28 or 30 dv. For instance, moving from left to right in the figure, the red and blue circles pass from the quadrant of attaining both standards to the quadrant of exceeding the 24-hour PM_{2.5} NAAQS before entering the quadrant where the secondary visibility index NAAQS level of 28 dv is exceeded. Such a trend indicates that a source would trigger a violation of the 24-hour PM_{2.5} NAAQS before triggering a violation of the secondary visibility index NAAQS if it caused a 24-hour PM_{2.5} concentration increase above the SIL in an area attaining both standards. Emissions from a single source would be unlikely to alter the trends apparent in Figure 6, particularly for background PM_{2.5} conditions near the levels of the standards. Therefore trends in Figure 6 generally support the use of the surrogacy approach in a NSR/PSD cumulative impact analysis. For Industrial Midwest counties, the trend of design values in Figure 6 indicates that the secondary visibility index level of 28 dv may be controlling compared with the 24-hour PM_{2.5} level in some cases. However, the main driver of the behavior in the Industrial Midwest (i.e., large amounts of sulfate PM_{2.5}) is projected to be substantially reduced in coming years due to emissions controls associated with planned national rules.

Overall, design values based on 2008-2010 data suggest that counties that attain the 24-hour PM_{2.5} NAAQS would attain the proposed secondary PM_{2.5} visibility index NAAQS level of 30 dv and generally attain the level of

¹⁰ For instance, PM_{2.5} design values for the annual standard for Cuyahoga, Jefferson, and Clark counties exceed the alternative standard level of 12 µg m⁻³ and Elkhart has an annual design value equal to 12 µg m⁻³

28 dv. The Industrial Midwest counties where this behavior does not hold at the lower secondary standard level of 28 dv will experience visibility improvements due to regional emission controls planned as part of national rules and due to potential annual PM_{2.5} NAAQS violations. Therefore the comparison of design values for the 24-hour and proposed secondary PM_{2.5} NAAQS provides support for using the 24-hour PM_{2.5} NAAQS as a surrogate for the proposed secondary visibility index NAAQS in NSR/PSD applications. Specifically, the results indicate that a cumulative impact analysis that demonstrated that a source does not cause or contribute to a violation of the 24-hour PM_{2.5} NAAQS would generally be suitable for demonstrating that a source does not cause or contribute to a violation of the secondary visibility index NAAQS under current conditions.

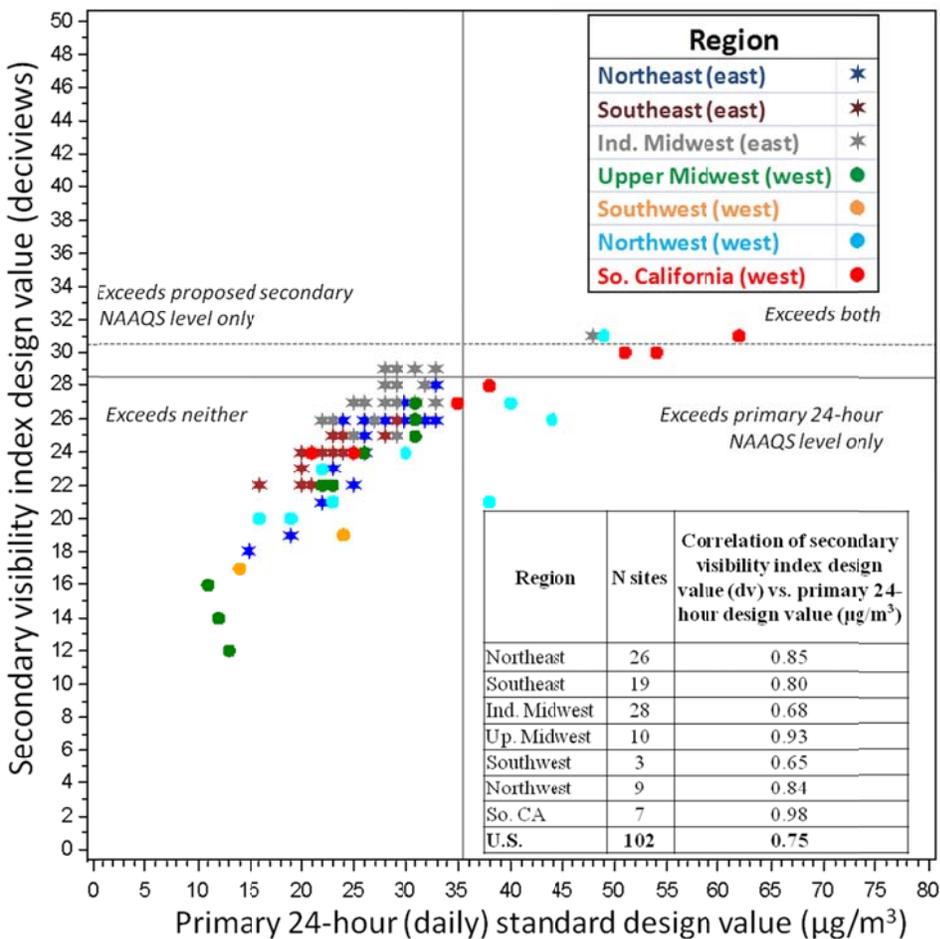


Figure 6. Design values for 24-hour PM_{2.5} NAAQS and secondary visibility index NAAQS based on 24-hour average PM_{2.5} measurements from 2008 to 2010 for sites that meet the current and/or proposed data completeness criteria of 40 CFR Part 50, Appendix N, for the 24-hour PM_{2.5} NAAQS and the 28-dv visibility index NAAQS.¹¹

¹¹ Quadrants in the figure are based on design values of 35.5 µg m⁻³, 28.5 dv, and 30.5 dv (rather than 35 µg m⁻³, 28 dv, and 30 dv, respectively) to reflect rounding conventions.



Figure 7. Map of exceedance counties for the 24-hour $PM_{2.5}$ NAAQS and secondary visibility index NAAQS level of 28 dv based on 24-hour average $PM_{2.5}$ measurements from 2008 to 2010.

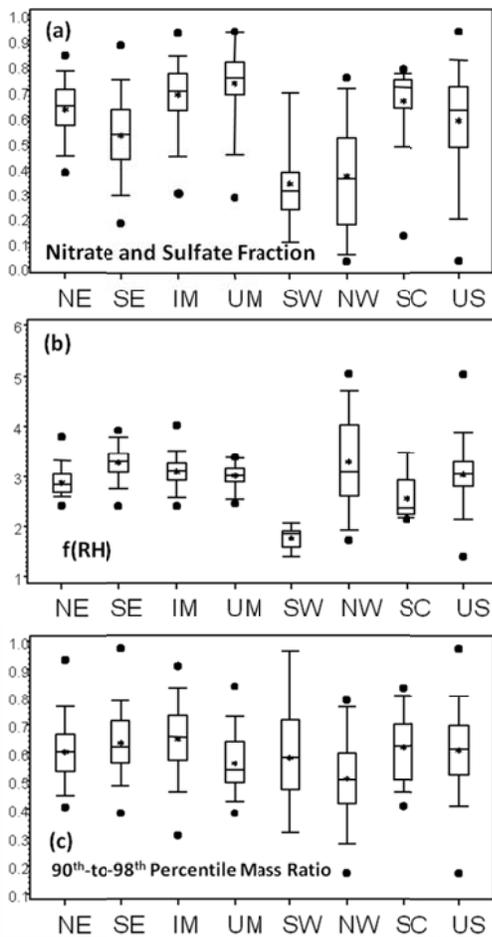


Figure 8. Distributions of the (a) fraction of $PM_{2.5}$ composition that is nitrate and sulfate, (b) RH adjustment factor, and (c) 90th-to-98th percentile mass ratios for U.S. regions defined in Figure 2 (NE=Northeast, SE=Southeast, IM=Industrial Midwest, UM=Upper Midwest, SW=Southwest, NW=Northwest, SC=Southern California, U.S.=all U.S. regions).

Appendix A. Development of PM_{2.5} Concentration Profiles from Emission Source Profiles, Distributions of RH Adjustment Factors, and Annual Design Values.

To estimate PM_{2.5} concentration profiles that could potentially correspond to direct-PM_{2.5} emissions, PM_{2.5} emission source profiles developed by Reff et al. (2009)¹² were used. Stationary sources relevant to PSD regulations include coal fired boilers, coal fired EGUs, refineries, pulp and paper operations, biomass boilers, and other potentially large emission sources. Median profiles for these and other sources that emit significant amounts of PM_{2.5} and primary sulfates were selected from Reff et al. (2009) to represent a wide range of possible direct-PM_{2.5} emissions. Emission source profiles for the 24 categories considered are given in Table A.1. Note that controlled and uncontrolled EGUs/boilers are not distinguished because the compositing process used by Reff et al. (2009) tends to lump this information together in arriving at a median value.

In Table A.1, organic mass (OM) is 1.4 times the organic carbon (OC) proportion of the PM_{2.5} source profile. “Crustal” represents the sum of all non-sulfur elements plus the estimated oxides of the metals (Reff et al., 2009). “Other” represents unmeasured components and/or measurement uncertainty and includes water and ammonium. The “other” category is a significant percentage of the total PM_{2.5} for many of the source categories in Table A.1. Primary emissions of elemental carbon, sulfate, and nitrate are represented by labels “pec”, “pso4”, and “pno3”, respectively.

To perform source-specific visibility calculations, characteristic direct-PM_{2.5} concentration profiles were developed using the emission source profiles in Table A.1. First, the fractions of primary sulfate and nitrate emissions were scaled by factors of 1.375 and 1.29, respectively, under the assumption that they are fully neutralized by ammonium. Next, the resulting component fractions for pec, OM, pso4, pno3, and Crustal were normalized by dividing by a total fraction, which was the sum of these component fractions. The component percentages resulting from this procedure are listed in Table 2. Note that hydration of the pso4 and pno3 components was not considered in developing the profiles in Table 2 even though PM_{2.5} would contain some adsorbed water in a PM_{2.5} Federal Reference Method measurement.¹³ Hydration was excluded for the sake of clarity, and this exclusion enhances the conservative nature of the visibility calculations. For instance, if hydration of pno3 and pso4 had been considered, the PM_{2.5} component percentages in Table 2 would sum to less than 100%, and visibility impairment for a given amount of PM_{2.5} would be reduced accordingly. Finally, note that the normalization procedure effectively allocates

¹² Reff A., Bhave P.V., Simon H., Pace T.G., Pouliot G.A., Mobley J.D., and Houyoux M. (2009) Emissions inventory of PM_{2.5} trace elements across the United States. *Environmental Science & Technology* **43**, 5790-5796.

¹³ Frank N. (2006) Retained nitrate, hydrated sulfates, and carbonaceous mass in Federal reference method PM_{2.5} for six eastern US cities. *Journal of the Air and Waste Management Association* **56**, 500-511.

unknown PM_{2.5} emissions proportionally among the five components: pec, OM, pso4, pno3, and Crustal. Therefore PM_{2.5} concentration profiles for categories with large “other” emissions (e.g., industrial manufacturing, petroleum industry, and residual oil combustion) tend to have large sulfate fractions and are large contributors to visibility impairment under high-RH conditions based on this approach.

Table A.1. Stationary source profiles of directly-emitted PM_{2.5}.

Species	pec	OM	pno3	pso4	Crustal	PM2.5	other
Aluminum Production	2.3%	5.5%	0.4%	4.4%	64.4%	78.0%	22.0%
Asphalt Manufacturing	5.7%	6.1%	0.1%	0.7%	60.0%	72.9%	27.1%
Asphalt Roofing	0.0%	84.4%	0.0%	0.1%	0.8%	85.8%	14.2%
Bituminous Combustion	1.7%	3.7%	0.2%	12.7%	35.3%	56.4%	43.6%
Cast Iron Cupola	0.9%	8.9%	0.5%	6.3%	81.9%	100.0%	0.0%
Catalytic Cracking	0.1%	0.0%	0.0%	32.7%	57.0%	98.1%	1.9%
Cement Production	2.9%	17.7%	4.7%	17.7%	49.8%	100.0%	0.0%
Construction Dust	0.0%	6.5%	0.0%	1.1%	51.9%	59.8%	40.2%
Distillate Oil Combustion	10.0%	35.0%	0.0%	19.0%	1.2%	65.2%	34.9%
Electric Arc Furnace	0.4%	4.5%	0.2%	2.2%	85.1%	92.5%	7.5%
Industrial Manufacturing - Avg	0.9%	10.3%	0.3%	9.9%	0.0%	23.7%	76.3%
Lignite Combustion	1.4%	39.8%	0.4%	7.6%	50.4%	100.0%	0.0%
Lime Kiln	2.3%	9.3%	0.6%	37.0%	49.5%	98.7%	1.3%
Natural Gas Combustion	38.4%	34.6%	2.1%	8.6%	0.0%	83.7%	16.3%
Open Hearth Furnace	0.0%	28.0%	0.6%	40.0%	19.0%	87.5%	12.5%
Petroleum Industry - Avg	0.0%	4.9%	0.3%	23.5%	0.0%	34.3%	65.7%
Process Gas Combustion	14.6%	42.2%	2.4%	16.6%	16.7%	100.0%	0.0%
Pulp & Paper Mills	0.1%	0.0%	0.0%	50.6%	36.8%	87.4%	12.6%
Residential Coal Combustion	24.0%	62.8%	0.3%	3.3%	8.2%	100.0%	0.0%
Residential Natural Gas Combustion	6.7%	68.6%	3.4%	12.6%	8.3%	100.0%	0.0%
Residual Oil Combustion	1.0%	1.4%	0.0%	44.0%	0.7%	47.1%	52.9%
Solid Waste Combustion	1.5%	11.8%	1.4%	6.8%	44.5%	74.3%	25.7%
Sub-Bituminous Combustion	4.3%	4.4%	0.1%	10.2%	43.2%	62.5%	37.5%
Wood Fired Boiler	3.7%	49.2%	0.0%	6.5%	40.6%	100.0%	0.0%

In visibility calculations with the “original” IMPROVE algorithm (Equation 1), relative humidity adjustment factors, f(RH), are used to convert dry extinction values for sulfate and nitrate to ambient extinction values.^{14,15} Distributions of monthly average climatological f(RH) are given in Figure A.1. In Figure A.2, a comparison of annual PM_{2.5} design values with secondary visibility index design values is provided.

¹⁴ http://vista.cira.colostate.edu/improve/Tools/humidity_correction.htm

¹⁵ <http://vista.cira.colostate.edu/improve/Publications/GuidanceDocs/guidancedocs.htm>

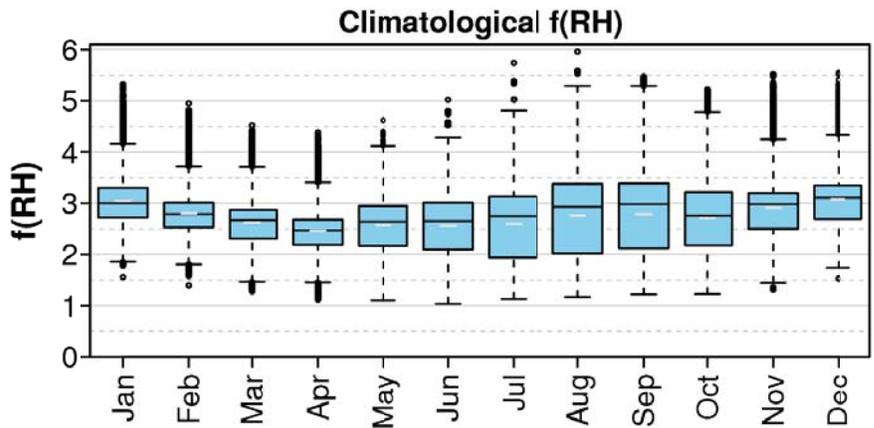


Figure A.1. Distributions of climatological monthly average RH adjustment factor, $f(RH)$

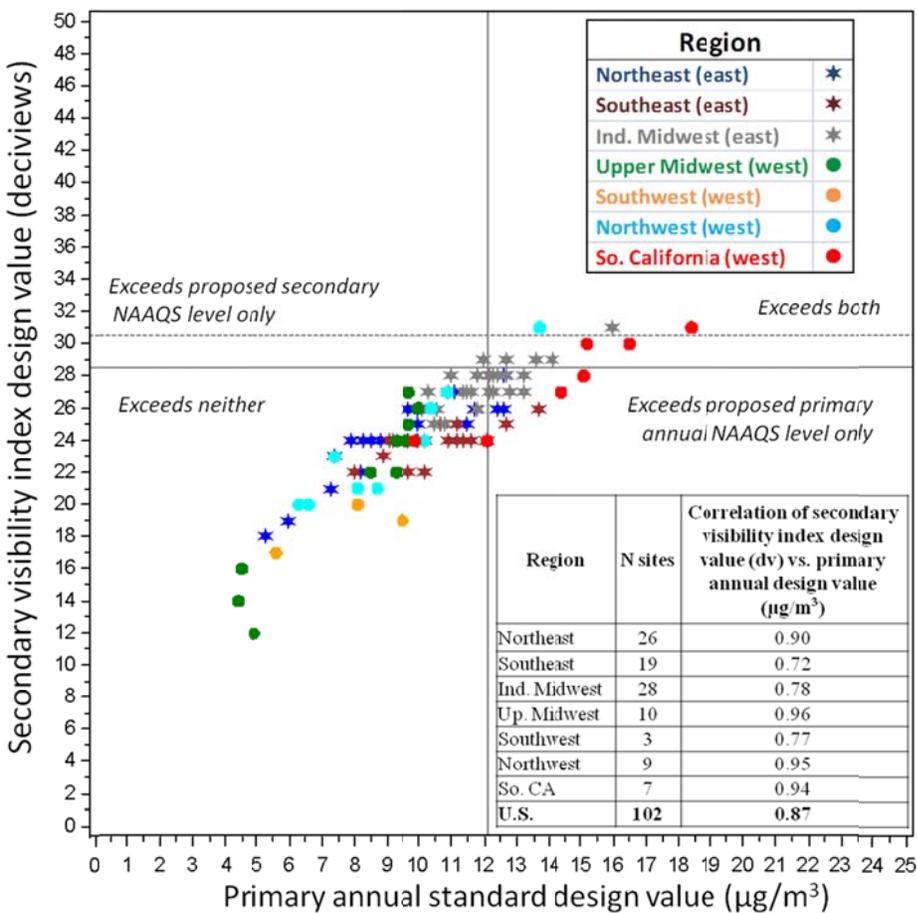


Figure A.2. Three-year design values for annual $\text{PM}_{2.5}$ NAAQS and secondary visibility index NAAQS based on $\text{PM}_{2.5}$ measurements from 2008 to 2010 for sites that meet the current and/or proposed data completeness criteria of 40 CFR Part 50, Appendix N, for the annual $\text{PM}_{2.5}$ NAAQS and the 28-dv visibility index NAAQS.