1. Introduction to Visibility Issues

The national visibility goal, established in section 169A of the Clean Air Act (CAA) Amendments of 1977, requires the "prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Federal Class I areas which impairment results from manmade air pollution." Under section 169B of the Act, the U.S. Environmental Protection Agency (EPA) was required to issue a report to Congress estimating the visibility improvement expected in Mandatory Federal Class I areas[1] from implementation of the 1990 Clean Air Act Amendments (CAAA). In October 1993, EPA issued its report entitled *Effects of the 1990 Clean Air Act Amendments on Visibility in Class I Areas: An EPA Report to Congress* (Document EPA 452/R-93-014). The Act also requires that EPA provide Congress with regular assessments of the actual progress and improvements in visibility in the mandatory Federal Class I areas. This report was prepared to meet these requirements for the period 1994 through 1998.

Under the 1990 CAAA, the EPA promulgated the Regional Haze Rule to protect visibility in 156 mandatory Federal Class I areas (Regional Haze Regulations, Final Rule, 1999). Two of the 158 mandatory Federal Class I areas created by the 1997 CAAA (Rainbow Lake Wilderness Area, Wisconsin and Bradwell Bay Wilderness Area, Florida) were determined not to have visibility as an important value. Therefore, these two areas are not subject to the final rule. In addition, five Native American tribes have re-designated Class II lands under their jurisdiction as Class I. Since these areas were not identified as mandatory Federal Class I areas in 1977, these (and lands re-designated in the future) are not subject to the final rule. The final rule calls for states to establish goals aimed at improving visibility in the mandatory Federal Class I areas (Appendix A) and also to develop long-term plans for reducing pollutant emissions that contribute to visibility degradation. The rule gives states the flexibility to develop cost-effective strategies for pollution reductions and encourages states to coordinate through regional planning efforts.

This chapter first describes the concept of visibility and visibility impairment. The five common pollutant species that contribute to visibility impairment (degradation) are described, along with their emission sources. Common measurements used to quantify visibility impairment (visibility metrics) are then discussed. The five pollutant species are routinely sampled at IMPROVE monitoring locations. The last section of this chapter details the geographic distribution of the monitors that operated from 1994 through 1998.

A. Description of Visibility Impairment

The term visibility, when used in the context of scenic vistas at mandatory Federal Class I areas, refers to the clarity with which distant objects are perceived. Visibility is affected by pollutant concentrations, the viewing angle, relative humidity, cloud characteristics, and other physical factors such as color contrast between objects. Without the effects of manmade air pollution, a natural visual range would be nearly 140 miles (225 km) in western areas and 90 miles (145 km) in eastern areas.

[1] The Clean Air Act defines mandatory Federal Class I areas as certain national parks (over 6,000 acres), wilderness areas (over 5,000 acres), national memorial parks (over 5,000 acres), and international parks that were in existence as of August 7, 1977.

Clear Day Hazy Day

Figure 1–1. Visibility Impairment (Haze) in Glacier National Park, Montana

Clear Day Hazy Day

Figure 1–2. Visibility Impairment (Haze) in Shenandoah National Park, Virginia

The natural visual range is limited because atmospheric gases and aerosols absorb and scatter the light traveling from the vista to the observer. Absorbed light is converted into heat, and the scattered light is redirected from its straight-line approach. The natural light scattered from air molecules is referred to as Rayleigh scattering and causes the blue appearance of the sky. Visibility is impaired beyond the Rayleigh scattering as additional gases and particles are introduced into the air. Figures 1–1 and 1–2 show real examples of visibility impairment (haze) in Glacier National Park, Montana and Shenandoah National Park, Virginia.

In mandatory Federal Class I areas (EPA, 1993), the atmospheric pollutants that most often affect visibility exist as aerosols (tiny particles dispersed in the air). An aerosol particle is made of solid and/or liquid molecules that are held together by intermolecular or adhesive forces and act as a single unit. Fogs and mists are common examples of aerosols formed primarily from water vapor. Particulate matter refers to the nonwater particles that form solid or liquid aerosols in the atmosphere. The next section discusses the five most common particulate matter species, classified according to chemical analyses.

Light scattering and absorption by aerosols are the most important contributors to visibility impairment in mandatory Federal Class I areas. The absorption and scattering by the suspended particulate matter is dependent on the particle size, shape, and composition as well as factors such as humidity (which affects the amount of water condensing as liquid on the particles). The suspended particles may originate as emissions from natural sources (e.g., sea salt entrainment and wind-blown dust) or from

manmade sources (e.g., automobile exhaust and mining activities). Aerosol particles may also form in the atmosphere as gases condense or react with one another. The origins of the major particulate matter species are discussed briefly below.

B. Relevant Pollutants and Their Sources

As stated previously, visibility impairment in the mandatory Federal Class I areas usually results from light scattering and absorption by particulate matter. The particulate matter that most greatly affects visibility in mandatory Federal Class I areas has an aerodynamic diameter less than 2.5 microns. (For comparison, a human hair has a diameter of about 70 microns.) The individual aerosol particles (composed of both solid particles and liquid droplets) cannot be seen in the atmosphere, but they scatter and absorb light to impair the view.

Although particulate matter less than 2.5 microns ($PM_{2.5}$) is often composed of numerous chemical species, chemical analyses have been used to identify and group five key contributors to visibility impairment:

- sulfate,
- nitrate,
- organic carbon,
- elemental carbon, and
- crustal material.

The concentrations of these five species are measured regularly in many mandatory Federal Class I areas, and the light extinction coefficients and deciview visibility indices are calculated from these values (Appendix C). The emission sources for the five major constituents of $PM_{2.5}$ (including precursors) appear in the first six rows of Table 1–1 (ammonia is a chemical contained in sulfate and nitrate aerosols). The emission sources are divided into four columns: 1) natural processes that emit the pollutant directly as particulate matter (primary particulate), 2) manmade (or controlled) sources that emit primary particulate, 3) natural processes that emit gaseous pollutants that are converted in the atmosphere to particulate matter (secondary particulate), and 4) manmade sources of secondary particulate matter. The species are described briefly below.

Sulfates most often exist as ammonium sulfate [$(NH_4)_2SO_4$] and ammonium bisulfate [NH_4HSO_4]. When ammonia availability is low, sulfates occur as sulfuric acid [H_2SO_4]. The primary sources of sulfate emissions are sea spray and sulfate particles formed during the combustion of fossil fuels (mainly coal).

Sulfates form in the atmosphere when sulfur gases, such as sulfur dioxide [SO_2] and hydrogen sulfide [H_2S], oxidize to sulfuric acid and then combine with ammonia [NH_3] to create ammonium sulfate particles. Sulfur gases may be emitted from natural sources such as volcanoes, oceans, wetlands, and forest fires, or from manmade sources such as fossil fuel combustion. Sulfate particles are relatively stable in the atmosphere and are removed by settling and precipitation.

The ammonia that combines with the sulfate to form sulfate PM is generated from both natural and manmade sources. Wild animals produce ammonia, and ammonia is also generated by microbial

processes beneath undisturbed soil. Sources of ammonia controlled by man include animal husbandry and dairy operations, sewage treatment, ammonia slip during selective catalytic reduction (SCR) control of NO_x, and the introduction of ammonia to soil through fertilizers.

Nitrate particulate matter exists in the atmosphere mainly as ammonium nitrate [NH_4NO_3] but may take the form of nitric acid [HNO_3] when ammonia is not available. Nitrogen oxides (NO and NO_2,

Table 1–1. Atmospheric Fine Particles (< 2.5 μm) and Their Major Emission Sources

Atmospheric Pollutant	Primary Sources		Secondary Sources	
	Natural	Manmade	Natural	Manmade
Sulfate ($SO_4^{=}$)	Sea spray	Fossil fuel combustion	Oxidation of sulfur gases (SO_2 and H_2S) emitted by volcanoes, oceans, wetlands, and forest fires	Oxidation of sulfur dioxide (SO_2) emitted from fossil fuel combustion
Nitrate (NO_3^-)	Not Applicable	Motor vehicle exhaust	Oxidation of NO_x produced by soils, forest fires, and lightning	Oxidation of NO_x emitted from fossil fuel combustion, motor vehicle exhaust, and prescribed burning
Ammonia (NH_3)	Not Applicable	Motor vehicle exhaust	Wild animals and undisturbed soils	Animal husbandry, sewage treatment, and fertilized land
Organic Carbon	Wildfires	Open burning, wood burning, prescribed burning, cooking, motor vehicle exhaust, incineration, and tire wear	Oxidation of hydrocarbons (e.g., terpenes and waxes) emitted by vegetation and wildfires	Oxidation of hydrocarbons emitted by motor vehicles, open burning, wood burning, fuel storage and transport, and solvent usage (E. H. Pechan and Associates, 1994)
Elemental Carbon	Wildfires	Motor vehicle exhaust, wood burning, prescribed burning, and cooking	Not Applicable	Not Applicable
Crustal Material	Wind erosion and re-entrainment of deposited particles	Fugitive dust from paved and unpaved roads, agricultural operations, and forestry	Not Applicable	Not Applicable
Metals	Volcanic activity	Fossil fuel combustion, smelting, and brake wear	Not Applicable	Not Applicable
Bioaerosols	Viruses, bacteria	Not Applicable	Not Applicable	Not Applicable

Reference: USEPA, 1997a (Note: Prescribed burning of forests and agricultural fields was added to the list of sources in the cited reference)

collectively referred to as NO_x) are emitted from high-temperature combustion processes and life processes of certain soil microbes. The nitrogen oxides are converted into nitrate in the atmosphere. Natural sources of NO_x include forest fires (wildfires), lightning, and certain soil microbes. The major manmade sources include fossil fuel combustion and motor vehicle exhaust. The nitrogen oxides and ammonia emitted by motor vehicles sometimes combine in the exhaust system to create nitrate aerosols. These nitrate aerosols are primary sources of nitrate particulate matter.

Organic carbon represents the accumulation of all organic compounds existing in atmospheric aerosol particles. Organic carbon may rise into the atmosphere under the buoyant forces of processes such as forest and range wildfires, open burning, wood burning, cooking, incineration, and automobile exhaust. The organic carbon aerosols rise into the air during incomplete combustion and represent the major primary sources of organic carbon emissions. Tire wear is another potential source of primary organic carbon emissions, but these particles are usually larger than 2.5 microns in aerodynamic diameter.

Organic carbon may also be released into the atmosphere as off-gases from a number of different sources: vegetation, wildfires, motor vehicles, open burning, wood burning, fuel storage and transport, and solvent usage. In the atmosphere, these gases are partially oxidized and converted into products with lower saturation pressures. The organic carbon products then condense as secondary organic aerosol particles in the atmosphere.

Elemental carbon is often referred to as light-absorbing carbon and represents the soot from combustion practices. Elemental carbon is emitted directly into the atmosphere and therefore has only primary emission sources. The natural source of elemental carbon is wildfire activity, and the manmade sources include prescribed forest and range fires, motor vehicle exhaust (especially diesel exhaust), wood burning, and cooking operations. Industrial processes can prevent the escape of elemental carbon to the atmosphere with control devices such as fabric filters and cyclones.

Crustal material is composed of the particulate matter entrained in the atmosphere by various physical processes and therefore has only primary emission sources. Crustal material is composed of two measured fractions of particulate matter: fine soil and coarse mass. The fine soil particles have aerodynamic diameters less than 2.5 microns and the coarse mass particles have a diameter between 2.5 and 10 microns. Wind erosion of the soil introduces particulate matter into the atmosphere, as does the wind's re-entrainment of previously deposited particles. Manmade physical processes that introduce crustal material to the atmosphere include fugitive dust from industrial processes, entrainment of dust from vehicular traffic over paved and unpaved roads, construction and demolition activities, and agricultural tilling activities. These processes also introduce considerable quantities of large, visible particles to the atmosphere; however, the larger particles quickly settle out of the air when the winds calm.

C. Visibility Measurements

Three metrics are typically used to describe visibility: visual range, light extinction coefficient, and the deciview visibility index (USEPA, 1993; Sisler, 1996). They can be calculated from IMPROVE particulate sample data. ***Visual range*** is the most commonly used visibility metric and is defined as the greatest distance at which a large dark object can be seen against the background sky. To measure visual range, an observer looks at a series of visibility markers (e.g., lights at night) and determines the distance to the furthest visible object. Visual range has been measured at airports since 1919 and has been recorded on computers since 1940.

Visual range is likely to remain a common metric for visibility because it is easily characterized by sighted individuals without instrumentation and is reported in the common units of miles or kilometers. However, its simple measurement of distance sighted to an object does not express any information about the clarity of the perception. The clarity affects the scenic enjoyment, and noticeable degradation of scenic appearance (including the disappearance of some features) occurs on some objects as near as within 10 percent of the visual range.

The ***light extinction coefficient*** is a visibility metric used by scientists to describe reduced visibility. It represents the attenuation of light per unit distance due to the scattering and absorption by gases and aerosols between the source and receptor. As a reference, the light extinction from Rayleigh scattering by air is uniformly set at 10 inverse megameters (Mm^{-1}) (USDOE, 1984). The light extinction coefficient can be calculated directly from the concentrations of gas and aerosol species and therefore serves as a convenient measure for relating ambient air quality to visibility impairment. The use of calculated light extinction coefficients as measures of visibility impairment also allows improvements in ambient air quality to be related directly to visibility improvement.

In this report, the light extinction coefficients were calculated directly from concentration measurements of particle samples. Appendices B and C describe the methods used for these calculations. The total light extinction coefficient is the sum of the Rayleigh scattering and light extinction from aerosol particles. Since Rayleigh scattering is constant at any location (assuming constant atmospheric pressure) and represents pristine atmospheric visibility conditions, only the calculated aerosol light extinction coefficients are reported in the subsequent chapters. Adding 10 Mm^{-1} to the calculated aerosol light extinction coefficients will yield the calculated total light extinction coefficient.

The inverse distance units used to describe light extinction coefficients are difficult to interpret as humanly perceptible changes in visibility. Therefore, the ***deciview haze index*** (*dv*) was developed and is calculated directly from the total light extinction coefficient (b_{ext} expressed in Mm^{-1}):

$$dv = 10 \ln (b_{ext} / 10\ Mm^{-1})$$

The deciview scale is nearly zero for a pristine atmosphere (*dv* equals zero for Rayleigh scattering at approximately 1.8 km elevation), and each deciview change corresponds to a small but perceptible scenic change that is observed under either clean or polluted conditions. Like the decibel scale for

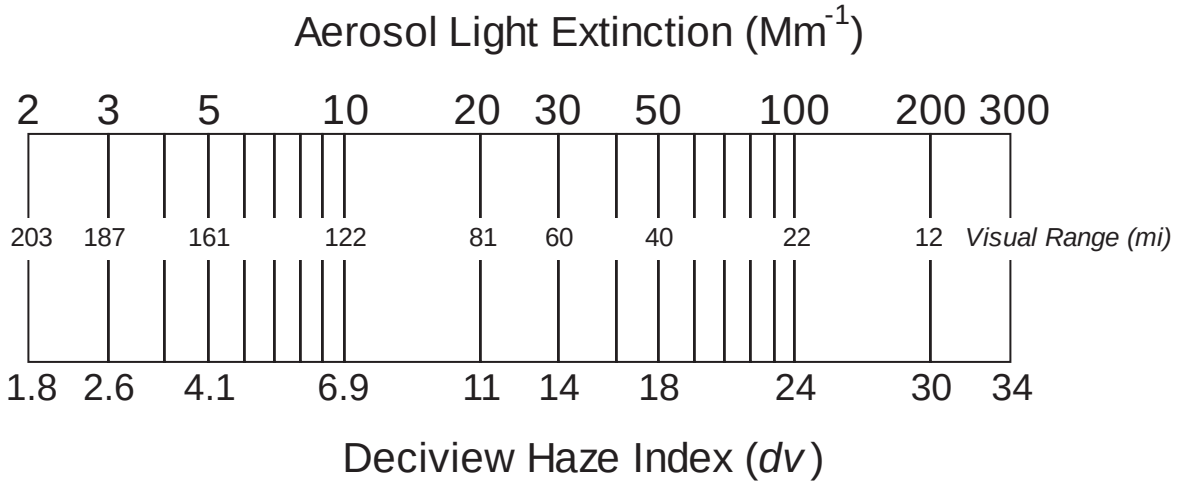

Figure 1–3. Relationship Between the Light Extinction, Deciview, and Visual Range Scales

sound, similar changes in deciviews are perceived as equal. This report includes many trends expressed as deciview changes. Each deciview decrease approximates a perceptible improvement in visibility. Figure 1–3 shows the relationship between the light extinction, deciview, and visual range scales.

D. National Programs to Improve Visibility

In July 1999, EPA promulgated the Regional Haze Rule to address visibility impairment in mandatory Federal Class I areas caused by numerous manmade air pollution sources located over broad regions. The proposed program takes into consideration scientific findings and policy recommendations from a number of sources, including the National Academy of Sciences (NAS), the Grand Canyon Visibility Transport Commission (GCVTC), and a Federal Advisory Committee on Ozone, Particulate Matter, and Regional Haze Implementation Programs (FACA). The proposal lays out a framework within which states can conduct regional planning and develop implementation plans to achieve "reasonable progress" toward the national visibility goal of no human-caused impairment in the 156 mandatory Federal Class I areas where visibility has been deemed an important value (USEPA, 1998).

Because of the common precursors and the regional nature of the ozone, PM, and regional haze problems, EPA is developing the implementation programs for these pollutants simultaneously in order to integrate future planning and control strategy efforts to the greatest extent possible. Implementation of the PM and Ozone National Ambient Air Quality Standards (NAAQS) in conjunction with the regional haze program is expected to improve visibility in urban as well as rural areas across the country. Other air quality programs are expected to lead to emissions reductions that will improve visibility in certain regions of the country.

The Interim Air Quality Policy on Wildland and Prescribed Fires is also intended to improve visibility conditions by reducing particulate matter emissions from managed burning in the wildlands. The EPA has been working with the Agricultural Air Quality Task Force set up by the U.S. Department of Agriculture (USDA) to develop a set of recommendations for a similar policy related to managed burning of agricultural lands. Once these recommendations are approved by the USDA and passed on to EPA, the Agency will consider them carefully in developing a policy to address the emissions from this source category.

Full implementation of the Acid Rain Program will achieve significant regional reductions in the emissions of sulfur dioxide, which is expected to reduce sulfate haze, particularly in the eastern United States. The recent NO_x State Implementation Plan (SIP) Call to reduce formation of ozone by reducing emissions from manmade sources of NO_x should also improve regional visibility conditions to some degree. In addition, the NAAQS, mobile source, and woodstove programs to reduce fuel combustion and soot emissions can benefit areas that have experienced visibility impairment from sources of organic and elemental carbon species.

Figure 1–4. Locations of IMPROVE Particulate Matter Samplers Operating Continuously from 1994–1998 (Green Shaded Areas Represent Mandatory Federal Class I Areas)

E. IMPROVE Monitoring Systems in and near the Mandatory Federal Class I Areas

Section 169(A) of the 1977 CAA Amendments established a national goal of protecting visibility from manmade air pollution in 158 specific areas, designated as mandatory Federal Class I areas (Figure 1–4).[3] Visibility was subsequently determined to not be an important value in two areas (Federal Register, Vol. 44, No. 232, pages 69122-7). Four Federal land management agencies are responsible for the remaining 156 mandatory Federal Class I areas and the land surrounding them: National Park Service, USDA-Forest Service, U.S. Fish and Wildlife Service, and the Bureau of Land Management. Interested readers should refer to Appendix A for a list of the 156 mandatory Federal Class I areas where visibility is an important value.

These agencies joined the EPA in 1985 to establish a collaborative monitoring program known as the Interagency Monitoring of Protected Visual Environments (IMPROVE) (Air Resource Specialists, 1992). In 1991, three other organizations were formally added to the IMPROVE Steering Committee: State and Territorial Air Pollution Program Administrators (STAPPA), Western States Air Resources Council (WESTAR), and Northeast States for Coordinated Air Use Management (NESCAUM). In

[3] The reader will note that the mandatory Federal Class I areas in Figure 1–4 are divided into a western region (greater than 100°W) and an eastern region (less than 100°W). A discussion of results based upon the regional site locations is found in Chapter 3, Section D.

Table 1–2. IMPROVE and IMPROVE Protocol Sites Collecting Data from 1994 through 1998

IMPROVE Site	State	Latitude (ºN)	Longitude (ºW)	Elevation (ft)
Sipsey Wilderness	Alabama	34.33	87.33	600
Denali National Park	Alaska	63.45	148.97	2,100
Chiricahua National Monument	Arizona	32.02	109.35	5,400
Grand Canyon National Park (South Rim)[1]	Arizona	36.07	112.15	7,100
Grand Canyon National Park (Indian Garden)	Arizona	36.07	112.13	3,800
Petrified Forest National Park	Arizona	35.07	109.77	5,500
Tonto National Monument	Arizona	33.65	111.10	2,600
Upper Buffalo Wilderness	Arkansas	35.83	93.22	2,300
Lassen Volcanic National Park	California	40.53	121.57	5,900
Pinnacles National Monument	California	36.49	121.17	1,000
Point Reyes National Seashore	California	38.12	122.90	125
Redwood National Park	California	41.55	124.08	760
San Gorgonio Wilderness	California	34.20	116.92	5,600
Sequoia National Park	California	36.50	118.82	1,800
Yosemite National Park	California	37.70	119.70	5,300
Great Sand Dunes National Monument	Colorado	37.73	105.50	8,200
Mesa Verde National Park	Colorado	37.20	108.48	7,200
Rocky Mountain National Park	Colorado	40.38	105.57	7,900
Weminuche Wilderness	Colorado	37.65	107.80	9,050
Washington (DC)[2]	District of Columbia	38.88	77.50	30
Chassahowitzka National Wildlife Refuge	Florida	28.75	82.57	10
Okefenokee National Wildlife Refuge	Georgia	30.73	82.12	50
Mammoth Cave National Park	Kentucky	37.22	86.07	750
Acadia National Park	Maine	44.38	68.27	420
Boundary Waters Canoe Area	Minnesota	47.95	91.52	1,700
Glacier National Park	Montana	48.50	113.98	3,200
Great Basin National Park[2]	Nevada	39.00	114.20	6,800
Jarbidge Wilderness	Nevada	41.88	115.42	6,200
Brigantine Wilderness - E.B. Forsythe National Wildlife Refuge	New Jersey	39.47	74.45	50
Bandelier National Monument	New Mexico	35.78	106.27	6,500
Crater Lake National Park	Oregon	42.88	122.13	6,500
Three Sisters Wilderness	Oregon	44.28	122.05	2,850
Badlands National Park	South Dakota	43.75	101.93	2,500
Great Smoky Mountains National Park	Tennessee	35.63	83.92	2,700
Big Bend National Park	Texas	29.30	103.18	3,500
Guadalupe Mountains National Park	Texas	31.85	104.82	5,400
Bryce Canyon National Park	Utah	37.62	112.17	8,000

Table 1–2. IMPROVE and IMPROVE Protocol Sites Collecting Data from 1994 through 1998 *(continued)*

IMPROVE Site	State	Latitude (ºN)	Longitude (ºW)	Elevation (ft)
Canyonlands National Park	Utah	38.45	109.82	5,950
Lye Brook Wilderness	Vermont	43.17	73.00	3,250
Shenandoah National Park	Virginia	38.55	78.40	3,600
Mount Rainier National Park	Washington	46.75	122.12	1,400
Snoqualmie Pass – Alpine Lakes Wilderness	Washington	47.43	121.42	3,600
Dolly Sods Wilderness	West Virginia	39.10	79.43	3,800
Bridger Wilderness	Wyoming	42.95	109.75	8,000
Yellowstone National Park	Wyoming	44.55	110.40	7,700

[1] Although the Grand Canyon (South Rim) monitoring site was replaced in August 1998, its results are included in this report.

[2] Not a mandatory Federal Class I area, but the data from this site are included in the national and regional analyses presented in Chapter 3.

1999, the Mid-Atlantic Regional Air Management Association (MARAMA) was added, and the State of Arizona also acts as an associate member.

The IMPROVE network has been collecting data since 1987 to support the visibility protection regulations for the mandatory Federal Class I areas. The objectives include establishing current visibility levels, identifying existing sources of manmade visibility impairment, and tracking progress toward the long-term goal of removing manmade impairment from mandatory Federal Class I areas. Monitors at IMPROVE sites across the country document scenic conditions through photographs and obtain direct optical measurements, particulate matter samples, temperatures, and relative humidities.

The particulate matter samples are collected on filters on Wednesdays and Saturdays. The filters are sent to laboratories to measure the mass (weight) and chemical composition of the particulate matter. The laboratory tests are then reported as measurements of fine mass ($PM_{2.5}$), total mass (PM_{10}), coarse mass (difference between PM_{10} and $PM_{2.5}$), sulfates (as ammonium sulfate), nitrates (as ammonium nitrate), organic carbon, elemental carbon, and soil. The light extinction coefficients and the deciview indices are calculated from the site relative humidities and the measurements of the key species: sulfates, nitrates, organic carbon, elemental carbon, and crustal material (calculated from soil and coarse mass measurements). Table 1–2 lists the IMPROVE monitor sites that collected data continuously from 1994 through 1998. The following chapters describe the visibility trends in corresponding areas. Since this report serves as a follow-on to a 1993 Congressional report on visibility issues in mandatory Federal Class I areas, 1994 was chosen as the starting year for many of the calculated values.

The Regional Haze Rule requires states to establish goals for each affected Class I area to 1) improve visibility on the haziest days, and 2) ensure no degradation occurs on the clearest days over the period of each implementation plan. The haziest (most-impaired) days in this report have been classified as the 80th to 100th percentile of the measurement days based on the calculated mass concentrations, but not directly on visibility impairment. The numbers reported in the following chapters represent the average characteristics of this percentile group. The clearest (least-impaired) days are represented by the 0 to 20th percentile of the measurements based on the calculated mass concentrations. The mid-range days are characterized by averaging the values within the 40th to 60th percentile range.