Assessment of Carbonaceous $PM_{2.5}$ for New York and the Region

Final Report 08-01
Volume I
March 2008

New York State
Energy Research and
Development Authority

NYSERDA

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Assessment of Carbonaceous $PM_{2.5}$ for New York and the Region

Final Report

Volume I: Executive Summary, Systhesis and recommendations

Prepared for the

New York State Energy Research and Development Authority

Albany, NY

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PREFACE

The New York State Energy Research and Development Authority is pleased to publish this "Assessment of Carbonaceous PM2.5 for New York and the Region, Volumes I and II." The report was prepared by the Northeast States for Coordinated Air Use Management (NESCAUM), principle investigators Philip Johnson and John Graham.

This assessment focuses on a significant fraction of the ambient PM in New York State and synthesizes information in three key areas: (1) atmospheric science and emissions sources, (2) human health effects, and (3) control technologies and strategies. Volume I includes an executive summary and synthesis of major findings. Volume II contains a comprehensive technical assessment report.

This work was funded by the **New York Energy $mart**[SM] Environmental Monitoring, Evaluation, and Protection (EMEP) Program. This study is one of a broader portfolio of research projects characterizing particulate matter (PM), performing source apportionment on PM datasets, and addressing policy-relevant questions for PM control strategies in New York State.

ACKNOWLEDGMENTS

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The authors gratefully acknowledge contributions of NESCAUM staff members Michael Block, Iyad Kheirbek, Paul Miller, Ph.D., Emily Savelli, Matthew Solomon, and Jung-Hun Woo, Ph.D.. Mort Lippman, Ph.D., of New York University and Ken Demerjian, Ph.D., of SUNY Albany provided helpful guidance and comments, as did the project advisory committee. Finally, the authors thank NYSERDA, especially Ms. Janet Joseph and Ellen Burkhard, Ph.D. for supporting this investigation.

EXECUTIVE SUMMARY

This report presents a comprehensive assessment of the carbonaceous fraction of ambient fine particulate matter ($PM_{2.5}$) in New York State. Carbonaceous components comprise a significant fraction of ambient levels of $PM_{2.5}$ in many areas in the Northeast, and they may play a critical role in observed adverse human health effects associated with $PM_{2.5}$ exposure. In order to design future policies based on sound scientific and technical knowledge that will reduce carbonaceous $PM_{2.5}$ levels in New York, this project synthesized available and emerging information in three key areas: (1) atmospheric science and emission sources, (2) human health effects, and (3) control technologies and strategies.

In collaboration with its Project Advisory Committee (PAC), NESCAUM staff developed five central questions listed below to help guide the project's overall research and assessment effort. Central findings for each question follow.

1. **DOES CARBONACEOUS $PM_{2.5}$ CONTRIBUTE SIGNIFICANTLY TO HIGH LEVELS OF AMBIENT $PM_{2.5}$ IN NEW YORK STATE?**
2. **WHAT PROPORTION OF CARBONACEOUS $PM_{2.5}$ PRESENT IN NEW YORK IS DERIVED FROM IN-STATE SOURCES?**
3. **DOES CARBONACEOUS $PM_{2.5}$ PRESENT A PUBLIC HEALTH CONCERN?**
4. **WHAT ARE THE TECHNICAL OPTIONS FOR REDUCING EMISSIONS OF CARBONACEOUS $PM_{2.5}$ FROM SOURCES?**
5. **WHAT ARE THE NEAR-TERM STRATEGIES FOR REDUCING EMISSIONS OF CARBONACEOUS $PM_{2.5}$ FOR NEW YORK AND THE REGION?**

Questions 1 & 2:
AMBIENT $PM_{2.5}$ CARBONACEOUS AEROSOL LEVELS AND IN-STATE CONTRIBUTION

In New York State, ambient measurements of $PM_{2.5}$ indicate that carbonaceous aerosols represent a sizeable fraction of the $PM_{2.5}$ mass, and much of that aerosol comes from in-state sources. Analysis reveals appreciable spatial and temporal variations in measured carbon aerosols. On an annual basis, organic carbon (OC) constitutes between a fourth and a third of the ambient $PM_{2.5}$ mass, with elemental carbon (EC) contributing as much as 8% of total $PM_{2.5}$ at urban sites (Figure ES-1). Seasonally, contributions range a bit wider, while individual 24-hour measurements can be nearly all carbonaceous. OC levels peak in summertime across the State, driven by increased photochemical activity that also results in increased ozone levels. EC levels, however, tend to be flat with some evidence of wintertime increases at urban sites with abundant local motor vehicle sources.

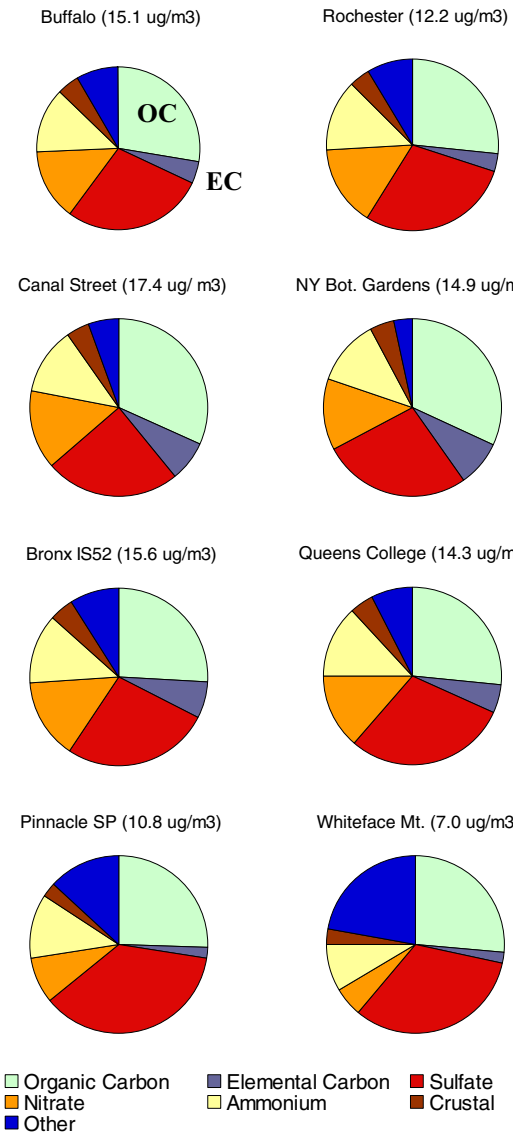


Figure ES-1. Annual Average Fine Particle Species Mass at New York State Speciation Trends Network Sites (data collected 2/00 through 11/05).

On average, urban areas experience higher levels of carbon aerosols than more remote regions. For both OC and EC, significant gradients exist across the metropolitan areas. Comparing OC measurements across New York City, the maximum seasonally averaged OC concentrations can be 50% greater than the minimum measured levels. Seasonally averaged EC concentrations at the site with maximum levels can be nearly twice as high as at the site with the minimum. These intra-urban differences offer a lower bound estimate of highly local impacts of carbon aerosol emissions. Local EC contributions reach as high as 85% of monitored EC in urban areas based on regional background levels. Local urban OC contributions generally do not exceed two-thirds of the ambient urban OC levels. The more regional nature of OC is due, in part, to its being both a primary pollutant (e.g., directly emitted) and a secondary pollutant (one formed in the atmosphere), as well as the large diversity of contributing source categories. Uncertainties associated with the relative importance of primary and secondary contributions to OC complicate the ability to accurately describe the emission sources responsible for ambient OC.

Question 3:

PUBLIC HEALTH CONCERNS ASSOCIATED WITH CARBONACEOUS $PM_{2.5}$

A growing number of health studies focusing on the carbonaceous fraction of $PM_{2.5}$ demonstrate that exposure to carbonaceous $PM_{2.5}$ presents a public health concern. Toxicological, clinical, and epidemiological research has, to varying degrees, investigated the potential role of individual carbonaceous constituents, carbonaceous mixtures and surrogates, emissions sources, and different particle size fractions that are rich in carbonaceous $PM_{2.5}$. While health effect studies suggest the toxicity of carbonaceous $PM_{2.5}$,

they do not point conclusively to which of its many characteristics are most responsible for eliciting adverse effects. Nor do they rule out other, non-carbonaceous components of $PM_{2.5}$. It is likely that different agents may contribute to adverse health outcomes, and fine carbonaceous particulates may be a significant contributor to some or all of these.

The pervasiveness of carbon-rich combustion sources represents an important exposure risk to populations in New York State. For vehicular source emissions, some studies of populations residing near roadways in major cities find increased risks for a variety of adverse health effects, including respiratory and cardiac effects. Moreover, recent studies in urban settings have shown that "hot-spot" exposures can take place at micro-environmental scales. These include studies near highway corridors, airports, and bus, marine and railroad terminals; studies inside subways, buses, cars, ferries, and trains; and studies close to small nonroad internal combustion engines, such as lawn equipment. A growing number of exposure assessment and measurement studies in Europe, North America, and the New York City area indicate that urban populations can be exposed to high levels of mobile source emissions. Few comparable exposure assessments of rural populations, however, have been undertaken. A limited number of studies have begun to evaluate the effect of mobile source emissions on health in New York State populations.

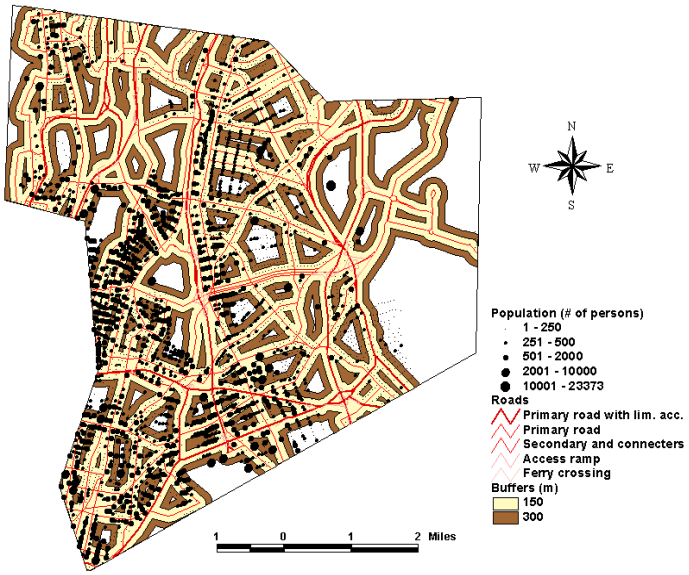


Figure ES-2. Census block-level population living within 150m and 300m of major roads in Bronx County, NY

For this report, a screening-level analysis of residential population proximity to, and traffic volume on, major roads in selected New York State counties was conducted. The analysis demonstrated that a large number of residents in rural, suburban, and urban (Figure ES-2) counties live within a distance of 150 and 300 meters of highly traveled major roads. The correspondence between high traffic volume—as determined by vehicle miles traveled and average annual daily traffic counts—and densely populated neighborhoods indicates that elevated exposure to mobile sources may occur in any size community, including cities such as Albany and Buffalo, as well as along busy roadways in more rural areas.

Residential wood combustion in New York represents another important source category for carbonaceous aerosols based on the emissions inventory, especially in rural locations. Although a large body of health studies indicates that wood smoke inhalation presents a health risk to exposed populations, wood combustion exposure assessment, measurement, and health studies conducted within New York State and in the Northeast region are limited. Studies of other areas that have large wood combustion contributions, however, provide evidence that wood smoke is a potential exposure concern in New York State. Residential wood combustion emissions may pose a seasonal exposure risk to populations, especially during wintertime in areas where terrain and meteorology contribute to poor dispersion of pollutants under conditions that are common in many parts of the Northeast.

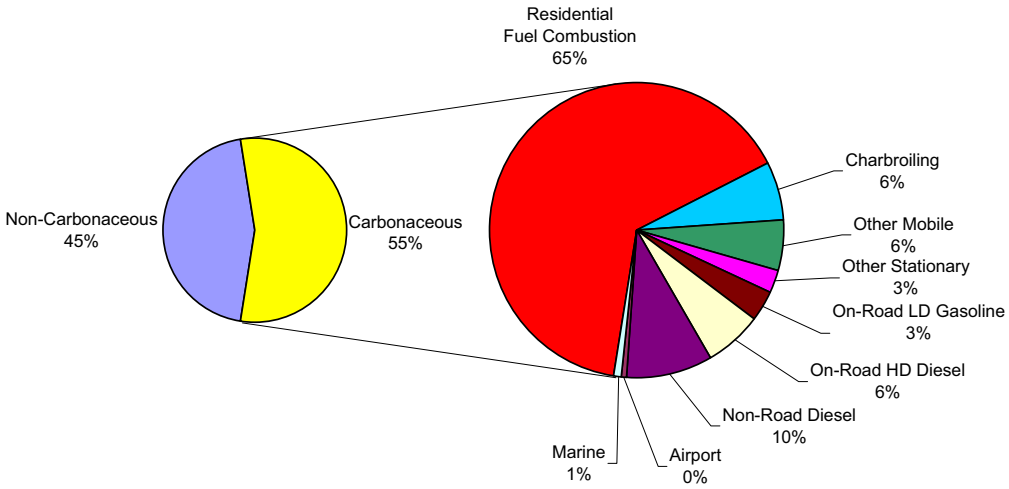
Questions 4 & 5:
TECHNICAL OPTIONS AND NEAR-TERM STRATEGIES FOR REDUCING EMISSIONS OF CARBONACEOUS $PM_{2.5}$ IN NEW YORK STATE AND THE REGION

Many source categories contribute to the overall emissions of primary carbonaceous $PM_{2.5}$ emissions in the State. The relative proportions, however, vary substantially in urban, suburban, and rural areas. This report estimates emissions from seven major source sectors including five mobile source sectors (nonroad equipment, heavy-duty trucks, light-duty vehicles, airports and marine ports) and two stationary source sectors (residential fuel combustion and commercial cooking), and then evaluates specific control measures considered most promising. The sectors were chosen based on their contributions to the inventory of carbonaceous $PM_{2.5}$ emissions.

Figure ES-3 shows that the carbon fraction is 55% of the primary $PM_{2.5}$ emissions in New York State. Residential fuel (almost all wood) combustion, diesel sources, and commercial cooking are major contributors. Relative contributions of source sectors, however, are quite different in the urban New York nonattainment area (NAA) as compared to rural areas. For example, whereas more than half of carbonaceous $PM_{2.5}$ in New York NAA is from onroad and nonroad mobile sources, almost all (>90%) of carbonaceous $PM_{2.5}$ emissions in rural counties are attributed to residential wood combustion. These statewide differences have implications for optimum selection of strategies to reduce emissions.

The technical options and long-term strategies considered in this report cover a range of geographic scales. Local, statewide or regional controls are assessed for organic carbon given its important local and regional-transport components. Elemental carbon emissions in theory represent a more local issue. In practice, however, mobile sources such as construction equipment, heavy-duty trucks, and light-duty vehicles move freely into and out of urban areas. In consideration of the physical movement of sources and the atmospheric transport of source emissions, controls are reviewed for all relevant spatial scales.

Figure ES-3. Total New York State $PM_{2.5}$ and Carbonaceous Detail (2002).



The combined measures evaluated in this report have the potential to reduce carbonaceous $PM_{2.5}$ emissions in the New York NAA by approximately 9,000 tons each year (tpy), equal to approximately one-third of current carbonaceous $PM_{2.5}$ emissions. Given the complexity of atmospheric formation processes of secondary organic aerosols, the emissions of volatile organic compounds (VOCs) from the seven sectors evaluated in this report are not explicitly addressed. Sector selection, however, would not likely differ had detailed information on VOCs been included. Major reductions in the ambient secondary organic fraction of $PM_{2.5}$ could be realized through reductions in motor vehicle and other gasoline engine hydrocarbon emissions. A suite of additional options is outlined in the body of the report.

According to inventory data presented in this report, nonroad engines are the largest source of carbonaceous $PM_{2.5}$ (24%) in the New York NAA. Policy options to achieve reductions from this sector could include the adoption of retrofit requirements similar to those that the California Air Resources Board (CARB) finalized in August of 2007 and would result in a reduction of approximately 1000 tpy of carbonaceous $PM_{2.5}$. To reduce emissions from locomotives, New York State could consider developing a loan fund for installation of anti-idling devices for railroad switchers and locomotives.

Residential fuel combustion represents the next largest $PM_{2.5}$ source in the New York NAA at 19%, with a much greater relative contribution in the rest of the State. A strategy to attain the National Ambient Air Quality Standards (NAAQS) and reduce public exposure to $PM_{2.5}$ should address emissions from this source category. Major options include requiring cleaner-burning wood for fireplaces, establishing controls on outdoor wood-fired boiler emissions, and implementing residential woodstove change-out programs. Together these programs could reduce carbonaceous $PM_{2.5}$ emissions by 2,000 to 3,000 tpy. Extending these programs statewide would produce substantially greater benefit.

Fine particulates derived from charbroiling (largely meat grilling) comprise 18% of the carbonaceous $PM_{2.5}$ emissions in the New York NAA. Approximately 10% of the total comes from chain-driven charbroilers, and 74% from under-fired charbroilers. If restaurants that use chain-driven charbroilers were required to retrofit their equipment with catalytic oxidizers, a reduction of approximately 250 tpy of carbonaceous $PM_{2.5}$ could be realized. The existing rules in the Los Angeles area could be used as a model. The State could also consider a requirement to retrofit under-fired charbroilers with pollution control technologies, which could reduce emissions by an additional 3,000 tpy.

Another important combined category, light- and heavy-duty vehicle emissions, accounts for 20% of New York NAA carbonaceous $PM_{2.5}$ emissions. These emissions exclude road dust, a significant source of PM, and may lead to an underestimation of emissions from this source category. A number of recommendations stand out for heavy-duty vehicles. Approximately 75% of heavy-duty truck $PM_{2.5}$ emissions are from Class-8 trucks and school buses, combined. Retrofitting vehicles with diesel particulate filters would reduce carbonaceous $PM_{2.5}$ by 1,500 tpy—assuming a high compliance rate. Several local laws in New York as well as the New York State Diesel Emission Reduction Act require retrofitting of vehicles owned by or on contract to the State, municipalities, or counties. County and municipality retrofit requirements could be expanded to other municipalities or counties in the State. CARB's truck retrofit regulations and New Jersey, Connecticut, and Rhode Island's school bus retrofit requirement provide models for privately owned vehicles and for school buses. Last, adopting a requirement similar to California's truck-refrigeration-unit regulation in New York State could significantly reduce carbonaceous $PM_{2.5}$ from this source.

For light-duty vehicles, the State could consider encouraging replacement of older (pre-1997) vehicles with newer vehicles. Older vehicles emit half of passenger-car $PM_{2.5}$ emissions. California's Voluntary Accelerated Vehicle Retirement initiative could provide a model for such a program. Improved maintenance is another potential approach to reduce vehicle $PM_{2.5}$. Programs in California and Spokane, Washington could provide models for New York State. Both early retirement and improved maintenance would address emissions of primary carbonaceous $PM_{2.5,}$ as well as hydrocarbons, and their associated secondary $PM_{2.5}$ production potential. Adoption of congestion pricing -currently being considered by New York City and State - could reduce light-duty vehicle exhaust $PM_{2.5}$ emissions by approximately 15% in addition to emissions associated with brake, tire, road wear, and road dust.

Mobile sources operating at airports and marine ports emit approximately 5% of carbonaceous $PM_{2.5}$ in the New York NAA. One approach to reduce emissions would be to require electrification or a Best Available Control Technology (BACT) retrofit of ground service equipment, using the CARB Ground Service Equipment regulation as a model. Two other CARB rules require emissions reductions from harbor craft and cargo handling equipment and could be adopted by New York State. These programs taken together could eliminate approximately 300 tpy of carbonaceous $PM_{2.5}$. The strategies provide a suite of options from which policy makers may choose. They do not target a specific level of $PM_{2.5}$ reduction.

Analysis of measurement and emissions data presented in this report show that substantial sources of carbonaceous $PM_{2.5}$ exist in New York and they contribute to the overall $PM_{2.5}$ concentrations. The strategies described in the report, if implemented, would reduce overall carbonaceous emissions significantly in New York. They would reduce exposure to $PM_{2.5}$ and would assist the State in meeting federal air quality standards. In addition to considering implementation of the above strategies, policy makers might place a high priority on reducing $PM_{2.5}$ exposure from mobile sources that carry passengers.

The emission control strategies recommended here rely on current information on emissions inventories, ambient measurements, and health effect studies. Although a considerable body of knowledge exists, substantial gaps remain. Further research should be conducted to identify the relative toxicity of specific $PM_{2.5}$ components or combinations of components, and other parameters beyond particle mass such as particle size (including ultrafine particles), surface area, or number. Laboratory and *in situ* studies of atmospheric chemistry and gas-particle partitioning behavior should continue. Applications of the emerging real-time analytical instrumentation will provide key information that should be rapidly incorporated into next-generation air-quality models, which will improve their ability to assess $PM_{2.5}$ carbon-based control strategies.

Enhancements to current emissions inventories are required to improve assessments in the future. These inventories serve multiple needs of the air quality and public health communities, both as a direct indicator for source importance and as a resource for modeling studies. Inventories often lack specificity and accuracy, especially with respect to elemental and organic carbon components. They fail to characterize fully an emission source's magnitude, temporal variation, and chemical composition, in part because they were not constructed to provide that data or collection of such data represents a high hurdle. In addition, demonstration projects are needed to assess the real-world reductions that can be achieved with various control strategies.

Expanded spatial and temporal ambient measurements will also greatly improve understanding of the atmospheric behavior of carbonaceous $PM_{2.5}$ and its health implications. Current monitoring networks may not adequately represent total population exposure, and may not therefore be a good predictor of population risk. Daily (24-hour) and annual-averaged ambient air quality data collected at central-site locations for regulatory compliance in rural and urban areas may not reflect real and potentially meaningful population exposures to $PM_{2.5}$ sources rich in carbonaceous material. Unfortunately, the current regulatory system suffers from a lack of data. Indications of health effects exist, but the measurements are too sparse in time and space to characterize them properly; yet funding for measurements will not materialize until the true nature of the health effects is known and can justify the expenditure.

This report synthesizes current understanding of sources of fine particulate carbon pollution, atmospheric processes, analytical methods, and health effects. It describes current emissions inventories, including how they need to be improved. It reviews the control technologies currently available and suggests which of those are cost-effective for reducing carbonaceous $PM_{2.5.}$ The project's findings should benefit policymaking efforts to improve ambient air quality that will bring social benefits in the form of improved health for residents throughout New York State.

SYNTHESIS AND RECOMMENDATIONS

The Assessment of Carbonaceous Fine Particles for New York and the Region exists as two volumes. Volume I includes the Executive Summary and this synthesis of major findings, which is organized around five questions developed by Northeast States for Coordinated Air Use Management (NESCAUM) and the Project Advisory Committee. Volume II contains a three-chapter comprehensive assessment report and its appendices. The chapters are titled (1) Atmospheric Processes and Measurement of Carbonaceous Aerosols, (2) Health, and (3) Control Strategies to Reduce Primary Carbonaceous $PM_{2.5}$ Emissions in New York State. There are seven appendices to this report: Appendix A provides $PM_{2.5}$ inventory information from EPA's 2002 National Emissions Inventory (NEI), Appendix B contains information on diesel engine technologies, Appendix C summarizes cost-effectiveness analyses for emissions controls from vehicles, Appendix D provides information on new vehicle and engine emission standards, Appendix E contains information related to airports and aircraft, Appendix F provides speciation profiles for different emission sources, and Appendix G tabulates data reported in figures from ambient data analyses presented in the first chapter. The central findings for the five policy-relevant questions and their corresponding recommendations are discussed below.

CARBONACEOUS AEROSOLS IN NEW YORK'S AMBIENT $PM_{2.5}$

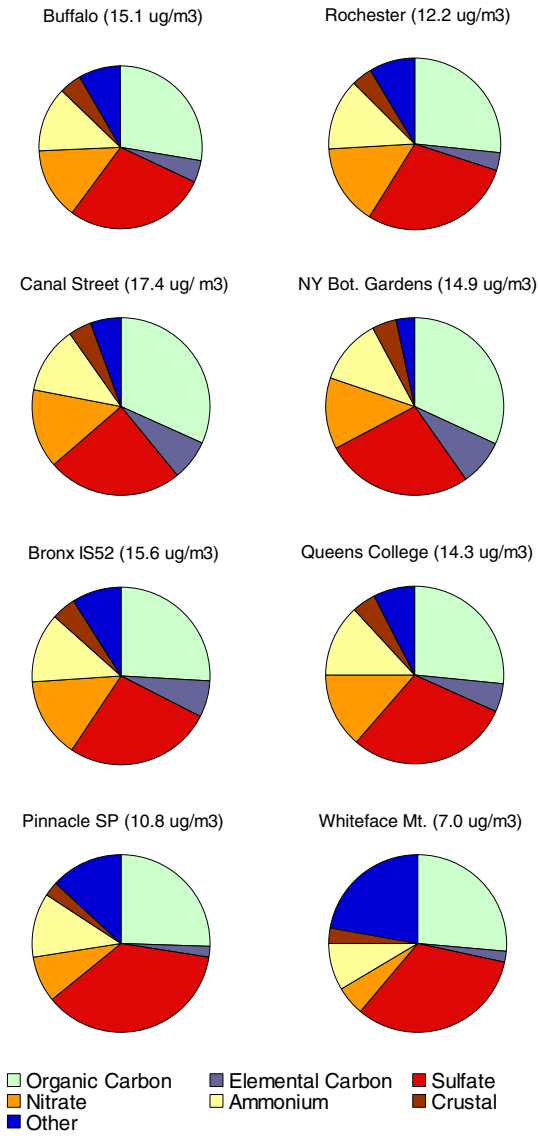
New York State (NYS) faces a difficult challenge in reducing fine particulate pollution to attain the mass-based National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$[1]. With a wide array of emission sources and chemical species contributing to the problem, the State must carefully consider the available data and analytical tools for effective policy development and decision-making. Existing evidence indicates that carbonaceous aerosols represent a sizeable fraction of the fine particle burden in New York, and much of that aerosol comes from in-state sources. National programs have been proposed for reducing transported inorganic aerosol constituents (mostly sulfates, and to a lesser extent, nitrates); these initiatives will greatly benefit the State's ability to reach attainment of the annual $PM_{2.5}$ standard. In the near future, however, the tighter daily standard recently promulgated by the US Environmental Protection Agency (US EPA) could result in implementation of controls that address both local and regional sources of $PM_{2.5}$ pollution.

To understand the relative importance of major chemical constituents (e.g., sulfates, nitrates, ammonium, organic carbon, elemental carbon), eight ambient particle speciation monitors operated by the New York State Department of Conservation (DEC) were put in place across the State, with four in the metropolitan New York City area, one in Buffalo, one in Rochester, and two at rural sites, (one in the central part of the state at Pinnacle State Park and the other in eastern New York at Whiteface Mountain). Sampling at one of the New York City area monitors was discontinued in December 2005 and an additional monitor will likely

[1] The annual standard is 15 $\mu g/m^3$, while the daily standard was recently revised to 35 $\mu g/m^3$ (from 65), effective December 17, 2006.

be installed in Albany. Data collected from these monitors show carbonaceous aerosols contribute substantially to ambient fine particle levels in New York State. The analyses reveal both spatial and temporal variations in monitored levels of carbonaceous aerosols. A clear understanding of this variability will enable the development of more effective control strategies for the major sources of emissions.

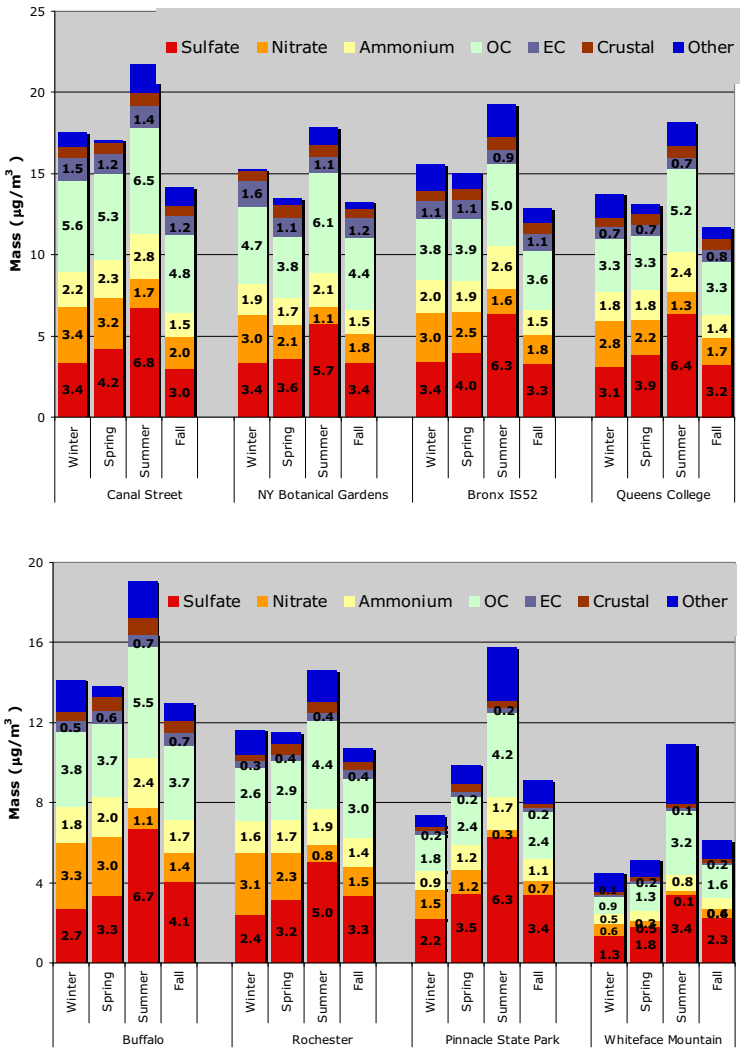
Figure S-2. Annual Average Mass of Speciated Fine Particle Contributions at NYS STN Sites (data collected 2/00 through 11/05).



For all sites, sulfates and organic carbon (OC) play dominant roles, representing 25-37% and 26-32%, respectively of the total $PM_{2.5}$ mass on an annual basis, as shown in Figure S-2. In general, sulfates play a slightly greater role in rural areas and organic carbon slightly less, as compared to urban areas. Elemental carbon (EC) and nitrates contribute relatively more mass in urban areas, with unattributed mass (shown as "other") being a larger fraction in rural areas. Mass balance calculations from the speciation monitors generally fail to account for the entire $PM_{2.5}$ measured mass. Unattributed mass is primarily believed to be particle-bound water; some fraction is probably of organic origin. (Further details can be found in Chapter 1). On an absolute basis, sulfate levels are quite uniform across the state (annual average ~4 $\mu g/m^3$), with the exception of Whiteface Mountain, which is both farthest from the source region and also at a higher elevation. Mass measurements of carbonaceous and nitrate aerosols are higher in urban areas. Inter-urban and intra-urban differences exist for both OC and EC. Within the metropolitan New York City area, city maximum seasonal OC can be 50% greater than measurements at the lowest monitored site, while seasonally averaged EC concentrations at the maximum site (Canal St.) can be twice as high as the minimum (Queens College).

The seasonal distribution of particle concentrations is plotted in Figure S-3. Summertime concentrations (June through August) are consistently greater than for other seasons, as a result of elevated sulfate and organic carbon levels. Summertime sulfate concentrations are twice as great as wintertime lows in urban areas, and three times as great at the two rural sites. Increased photochemical activity in summer that results in higher oxidant levels also drives this behavior. The summer increases in sulfate and OC overwhelm the corresponding opposite nitrate trend, which reaches its lowest levels during the warm summertime period. Elemental carbon shows little seasonal variation, with the exception of slightly higher measured values in the more urban locales in winter. Possible explanations include meteorological conditions that suppress vertical mixing due to frequent wintertime temperature inversions and increased emissions from residential and commercial heating.

Figure S-3. Seasonal $PM_{2.5}$ Concentration (data collected 2/00 through 11/05).

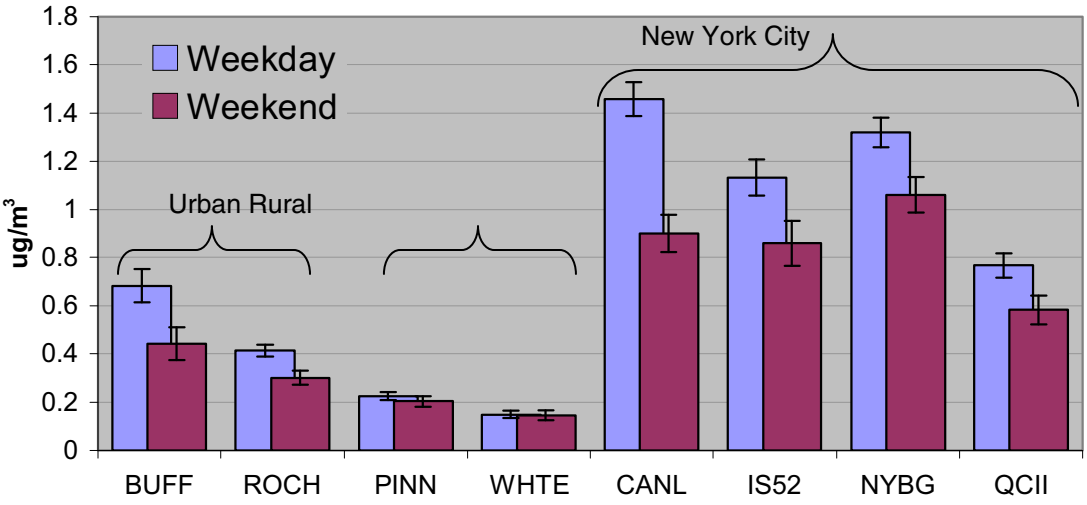


Even shorter-term temporal variability has been noted in urban areas for both EC and OC. To supplement 24-hour filter measurements, several techniques measure sub-daily concentrations of carbonaceous aerosols, including semicontinuous carbon monitors for both OC and EC, aethalometers for EC, and aerosol mass spectrometers (AMS) for OC. Analysis of filter data, plotted in Figure S-4, reveals marked differences in urban EC levels between weekdays and weekend days, with weekdays showing higher EC levels that are likely due to increased diesel mobile source emissions. Mobile source emission contributions have also been implicated in observed diurnal cycles, where morning and afternoon rush-hour

signatures appear. Diurnal OC measurements show more limited hour-to-hour changes, with greater levels often seen in the afternoon, indicative of photochemical formation processes.

Organic aerosol data from an aerosol mass spectrometer at the New York Supersite in Queens suggest that the superposition of two different OC source processes masks an overall diurnal variability. Traffic-related primary OC measurements show patterns similar to EC, with apparent rush-hour peaks, while secondary OC produces mid- to late afternoon peaks. Taken together, the net diurnal patterns tend to flatten out.

Figure S-4. Weekday and Weekend Averages for Elemental Carbon from STN Monitors for data through November 2005.



Key information required for improving the understanding of observed atmospheric processes includes better particle composition resolution in time and space, and by size. Meteorology, with its humidity, temperature and wind parameters, plays a substantial role as well. Diurnal patterns, where they exist, are driven by a combination of meteorological influences and variations in local source emissions. Proximity to sources influences the magnitude of the short-term variations. Day-to-day differences primarily reflect transport and other meteorological drivers that impact a local area, changing the mix of regional sources and the extent of chemical transformations occurring in the air mass.

NEW YORK SOURCES OF CARBONACEOUS $PM_{2.5}$

In light of the previous conclusion that carbonaceous aerosols contribute a substantial fraction to fine particulate matter in New York State, the next logical question is the extent to which these come from emission sources located within the State. The State needs to design policies to address $PM_{2.5}$ nonattainment in metropolitan New York based upon the best understanding of which sources cause the observed particulate levels. These judgments must also account for the relative contributions of other PM constituents and the fraction generated through in-state emissions. A further complication arises due to the need to understand the interactions between fine particle formation and atmospheric oxidants, particularly

ozone, as control of ozone represents another key air quality management issue for the State. Ideal solutions would address both fine particle and ozone pollution simultaneously.

Identifying the relative contribution of sources of air pollution presents a substantial challenge to air quality scientists and policy makers. No single approach by itself achieves satisfactory apportionments. However, the judicious application of many different techniques can provide insights regarding the relative importance of different sources to observed pollution levels. Review of available studies and data analyses conducted for this report indicates that the sources within New York State contribute a substantial fraction of the measured carbonaceous aerosols.

Several different analyses have estimated the local (metropolitan) and regional contributions to $PM_{2.5}$ in NYC, with different apportionments for different particle constituents. The most common technique employs 24-hour filter samples from multiple sites, relying on inter-site differences for estimation of local and regional fractions. Contrasts within urban areas provide a lower limit for local contributions, while remote rural sites may represent regional pollution levels. Differences between urban and remote sites provide some information on potential contributions of local pollution sources in urban areas.

This approach reveals that sulfates and EC represent the extremes in regional and local pollutants, respectively. Intra-urban sulfate differences are generally small, typically on the order of 10%. Urban-rural sulfate differences, on the other hand, are much higher and reach a maximum of 35% during wintertime. Sulfur dioxide emissions associated with the increased residential, commercial and industrial fuel use in wintertime likely explain the seasonal differences. Note, however, that substantially higher transported sulfate estimates (on the order of 50%) were predicted by a different approach that relied on analysis of wind patterns associated with atmospheric transport (Dutkiewicz et al. 2004).

On the other extreme, most of the urban EC measured is of local origin. Urban sites can differ by a factor of two, while as much as 85% of the EC could be local when relying on the rural measurements to represent the regional EC component. This strong local component for EC seems reasonable given the high traffic density and other combustion activities in highly urbanized areas. Local diesel traffic influence can also be estimated directly through weekday-weekend contrasts of EC levels, where the increase in EC on weekdays represents the lower bound in the predicted range of traffic-related impacts.

Nitrates and OC behave somewhere between the two extremes of sulfates and EC. Up to 35% of nitrates could be locally generated as determined by intra-urban differences. Greater estimates arise from differences in urban and remote measurements, especially in summertime, when three-fourths of the nitrates may be of local origin. Again, this seems reasonable given the high nitrogen oxides (NO_X) emission density in urban areas and the strong dependence of nitrate formation on temperature (elevated nitric acid concentrations and ammonia are required for aerosol formation).

The relative local fraction of OC varies seasonally. Intra-urban differences indicate a 30-40% local OC component for summer and winter. The range for urban-remote differences reaches as high as 65% for local urban contribution of OC in winter but results in a wide 10-35% range for local urban contribution in summer. The wintertime estimate may be more accurate than the summertime, in part due to differences in the underlying source strengths of organic aerosol precursors and their spatial differences. This approach may underestimate local urban contributions if a large fraction of the OC measured at the rural site comes from biogenic sources that may not be present in urban locales.

Estimates of secondary OC using the EC-tracer method, which uses measurements of EC as a surrogate for primary OC, show both seasonal and spatial variation in New York. In the cooler months, secondary organic aerosols (SOAs) represent about half of the organic aerosol in the non-New York City sites (and are assumed to be minor in New York City). The average of secondary OC for warmer months is as high as 80% of total OC in the non-New York City areas, with a range of 15-40% predicted for the New York City area. Summer urban peak SOA estimates are even higher. Similar contributions of secondary organics during summer in New York City were estimated by two alternative approaches, relying on AMS data and theoretical calculations based on measured volatile organic compound (VOC) levels. The latter technique predicted high SOAs from primarily anthropogenic hydrocarbons, which may support a higher estimate of locally derived organic aerosols than that determined from the EC-tracer method.

Improved determination of biogenic hydrocarbons versus anthropogenic hydrocarbon contributions will become available in the near future through analysis of existing samples. Better characterization of biogenic hydrocarbon influence and urban-rural contrast is expected to advance the current understanding of local urban source impacts for organic carbon aerosols. Results using one chemical transport model indicate the biogenic hydrocarbon contribution to be over 10%, although the estimate is quite sensitive to the level of anthropogenic hydrocarbon emissions, in addition to being highly uncertain. Results from this model also suggest that strategies that minimize ozone production may also lower the aerosol production capacity of the atmosphere by limiting atmospheric oxidant levels.

Research indicates that a substantial fraction of carbonaceous aerosols measured at New York monitoring sites derives from in-state sources. Local sources dominate urban elemental carbon levels, with the motor vehicle sector representing a major source category. Organic carbon levels can also be tied substantially to local sources. Exact quantification of organic carbon and predominant sources in both rural and urban areas cannot readily be determined due to the complex array of organic species. Apportionment is complicated due to the substantial percentage of organic aerosols in New York produced *in situ* through atmospheric reactions. Secondary aerosol production makes air quality management of ambient carbonaceous aerosols more difficult.

Information Gaps and Research Needs:

Emissions Inventories. Emissions inventories (EI) represent the basis for much air quality management and policy decisions and need to be improved. They can be used directly to assess primary emissions, to provide a crucial input for chemical transport modeling, or to yield insights to help interpret derived profiles based on source apportionment of ambient data. Although current inventories have generally been useful for past air quality management tasks, substantial refinements are needed to continue the significant progress in air quality improvement (NARSTO 2005, Miller et al. 2006). Specific recommendations for the emissions inventory of $PM_{2.5}$, especially OC and OC precursors, include:

- Update speciation profiles for mass of OC and EC with appropriate "definition" of analytical method for various source categories (area, stationary, and mobile).
- Develop accurate primary emission factors for fine PM mass (and its speciated components) for various combustion sources using methods based on "dilution tunnel technology," or other advanced techniques.
- Measure inert tracer organic species required for receptor model analysis in source characterizations.
- Measure VOC precursor emissions relevant for secondary aerosol production and develop methods to allow assessment of their secondary aerosol production potential, similar to the Incremental Aerosol Reactivity concept (Griffin et al. 1999).
- Identify and develop explicit definitions for other relevant properties for inclusion in the inventory database for such things as source emissions variability or quantification of analytical and other uncertainties.
- Conduct source apportionment analysis for the Speciation of Organics for Apportionment of $PM_{2.5}$ (SOAP) project. This will require a complete suite of major source profiles for sources of carbonaceous aerosols in New York State. This work is being conducted in collaboration with US EPA.

Chemical Transport Models. Chemical transport models represent a fundamental tool for evaluating air quality and control strategies effectiveness. These tools currently fail to capture the complexity of organic aerosol processes and so require improvements. Potential avenues for model development follow.

- Expand models to incorporate a broader range of precursor VOC species or at least improve the mapping of species from species-specific emission inventory profiles to model species.
- Update models to address recent research results that indicate the existence of heterogeneous processes and their resultant reaction products.
- Develop new modeling approaches as needed, since complete gas-phase chemistry coupled with partitioning treatment may be unfeasible given its complexity, the computational demands (current

computer technology may be inadequate), and unresolved details of the atmospheric chemistry and thermodynamics of organic aerosols.

Ambient Measurements. In the last decade, new methods have been developed for aerosol detection and quantification. Continued effort should focus on real-time approaches with high time resolution in place of more traditional 24-hour filter-based sampling. The artifacts are likely to be less, and the data generated would be much more useful in understanding the atmospheric behavior of carbonaceous aerosols, with likely improvements in source apportionment techniques. Below are suggestions for improvements:

- Emphasize techniques that rely on direct analysis, such as liquid chromatography-mass spectrometry or single-particle mass spectrometry, over those that require extensive sample preparation.
- In regions with high levels of OC, conduct gas-phase measurements focused on semivolatile precursor species in addition to aerosol measurements to improve the understanding of gas-particle partitioning.
- Pursue refinements in understanding the non-carbon (e.g., oxygen, sulfur, nitrogen) mass associated with measured C ('mass factor'). Semicontinuous and real-time methods should provide greater detail in temporal variation in the associated mass factor. Sub-daily, seasonal, and spatial variations in the factor exist but are not accounted for in the analyses conducted in this report.
- Develop well-documented calibration standards. A current lack of such standards, from bulk carbon analysis down to that of individual species, prevents successful sample quantification. Calibration standards and analytical methodologies should be well-documented to allow the cross-comparison of ambient measurements from different research initiatives.
- Continue application and method refinement of semicontinuous carbonaceous aerosol monitoring. These results become more critical in light of the newly revised and more stringent 24-hour NAAQS for $PM_{2.5}$. Such highly time-resolved data, especially when coupled with other similar data sets (e.g. trace gases, AMS data, and elemental particulate composition through Davis Rotating Drum Unit for Monitoring [DRUM] or semi-continuous elements in aerosol system [SEAS] sampling) will provide a rich data set that will improve the scientific understanding of source variability and impact.
- Conduct expanded sampling to better define both spatial and temporal gradients in carbonaceous aerosols. The current filter-based regulatory sampling networks suggest that substantial intra-urban and regional gradients exist. More measurements are required, especially in remote areas and smaller urban centers. Given limited resources, a combination of a reference site(s) and short-term satellite sites should provide more complete characterization of the temporal and spatial differences across the State.

Chamber Studies. Chamber studies represent a primary tool for improving the scientific understanding of the atmospheric chemistry of organic aerosols. Organic aerosol composition is a complex function of many variables, including atmospheric mix of biogenic and anthropogenic hydrocarbons, humidity, oxidant/reactant levels, and temperature. Studies investigating these dependencies often occur under conditions that do not reflect ambient conditions. Areas for improvement include the following:

- Design studies that are relevant to ambient atmospheric conditions.
- Expand efforts to examine organic carbon precursors, both individually and collectively, to improve the understanding of real-world interactions. Many studies attempt to isolate individual reactants or very specific reaction conditions. In real-world interactions, however, hundreds of different parent VOCs may contribute to observed condensed-phase organic carbon.
- Encourage development of improved real-time analytical tools to minimize uncertainty introduced from sampling artifacts or derivatization procedures. These new instruments could be used to track short-term changes in initial reactant, intermediates, and final product levels.

HUMAN HEALTH EFFECTS

A large number of human health studies have associated exposure to mass-based fine particulate matter with significant cardiopulmonary morbidity and mortality. Atmospheric aerosols have chemical and physical characteristics that may be more important to understanding the toxicity of PM than mass concentrations alone. Chemical components of ambient $PM_{2.5}$ that might contribute to adverse health effects include acids, a variety of trace metals, reactive organic species, and biological agents. Other characteristics of particles—including their size, shape, and inert materials—might also be responsible for deleterious health effects. Carbonaceous material (both EC and OC) comprises a sizeable portion of $PM_{2.5}$ mass and often dominates combustion-related source emissions. Carbonaceous compounds also are efficient vehicles for the pulmonary deposition of toxic substances condensed on their surfaces. A better understanding of carbonaceous $PM_{2.5}$ might help to elucidate mechanisms underlying PM toxicity. It may also explain epidemiological findings of adverse health effects and ultimately lead to more focused $PM_{2.5}$ emissions control strategies.

Current health studies indicate that carbonaceous $PM_{2.5}$ presents a public health concern. Toxicological, clinical, and epidemiological research has to varying degrees investigated the potential role of individual carbonaceous constituents, carbon mixtures and surrogates, emissions sources, and particle size fractions rich in carbonaceous $PM_{2.5}$. While the combined findings of health studies suggest evidence of the toxicity of carbonaceous $PM_{2.5}$, these studies by and large do not provide conclusive evidence pointing to which carbonaceous PM characteristics are most responsible for adverse health effects. Nor do they rule out other $PM_{2.5}$ characteristics and components, whose assessment was not within the purview of this report.

An integrated assessment of research on monitoring, source apportionment, emissions inventory, health effects, and demographic research suggests that various population groups in New York are at potential risk from emissions from combustion sources rich in carbonaceous materials. In-state sources comprise a large fraction of carbonaceous aerosols measured in New York, with local mobile sources dominating urban elemental carbon levels. Current analytical methods, however, cannot precisely apportion carbonaceous material to its sources in rural and urban areas. Emissions inventory analysis of selected counties shows that residential wood combustion dominates total carbonaceous $PM_{2.5}$ emissions in rural areas (92%), and mobile sources (vehicles, especially diesel engines) dominate emissions in urban areas (58%). In light of current findings by researchers associating health problems with exposure to wood smoke and traffic exhaust, more study is needed to characterize residential wood combustion and mobile source concentrations, exposure, and health risk in rural, suburban, and urban New York areas. This is especially important for densely populated locations and where terrain and meteorology can affect pollutant loading. The New York City nonattainment area and, to a lesser extent, other urban centers across the state are densely populated and home to a large portion of the state's total population. Note that even small towns and villages situated in predominately rural areas can exhibit relatively high population densities.

Carbonaceous $PM_{2.5}$ concentrations can vary across short distances and over small time periods, with local sources contributing to "hot spots." These sources include highway, airport, marine, and railroad corridors and terminals; ferry, locomotive, and vehicular environments; lawn mowers and similar portable internal combustion engines; and areas where terrain and meteorological conditions could limit pollution mixing (e.g., valley communities where wood burning occurs). A NESCAUM analysis of residential population proximity to and traffic volume on major roads in selected New York counties found that a large percentage of rural, suburban, and urban populations live close to high-volume traffic corridors. These locations and sources require further research.

The current NAAQS for PM are based upon four attributes: the pollutant indicator, averaging times, numerical levels of the indicator, and the statistical form of the standards. Identifying the relative toxicity of particle components and characteristics might inform future revisions of the NAAQS for particulate matter, enabling the regulation of sources emitting the most toxic material. Additional research might draw attention not only to PM, but also to combinations of other pollutants, thus addressing overall atmospheric mixture toxicity. Multiple pollutant combinations, including co-varying gaseous pollutants, may produce multiple effects by different biological mechanisms compared to individual pollutants or components. These considerations present substantial challenges that caution against any expectation of finding a single source category or particle component whose regulation would eliminate the $PM_{2.5}$ pollution problem.

Information Needs and Research Gaps:

Health Effects Research Needs. Recent review papers, workgroups, and proceedings on the topic of health research relating generally to PM constituents or specifically to carbonaceous $PM_{2.5}$ provide comparable findings (e.g., HEI 2005; Lippmann and Ito 2000; Mauderly et al. 2004; NRC 2004; Schlesinger 2004; Schlesinger et al. 2006; Sheppard 2004). The suggestions for future research on health effects include:

- Future research efforts should draw upon a combination of toxicological and epidemiological approaches. Such multidisciplinary study designs should consider a range of health-related measures to improve understanding of the different effects of a variety of components. These suggestions apply not only to analysis of carbonaceous $PM_{2.5}$, but also to mixtures of air pollutants, including gaseous air pollutants.
- More specific data are needed. Current data resources such as the EPA's $PM_{2.5}$ Chemical Speciation Trends Network (STN), for example, might have sufficient temporal resolution to support time-series epidemiological studies, but they provide insufficient spatial resolution to support cohort epidemiological studies. When using speciated concentration data, health researchers should be aware of the possible uncertainties that characterize various data sources.
- Toxicology studies should endeavor to use comparable research protocols and biological endpoints to help determine which components of different pollutant mixtures are more or less harmful across different study areas.
- Future PM toxicology research needs to be directed to provide better understanding of how environmentally relevant exposure conditions affect health.
- A systematic approach is needed to link and integrate epidemiological investigations across different study methods, metrics, and approaches to ensure better comparison and compilation of findings for the many pollutant constituents, mixtures, and exposure scenarios studied.
- Future epidemiological research should address how measurement errors might affect exposure-response findings. It should investigate whether there is significant spatiotemporal variation by species relative to total mass within and across monitored areas. It should identify whether current exposure assessment and statistical methods are of suitable design and estimation rigor, and how to determine the number and location of samplers necessary to investigate exposure effects.
- Methods to estimate health effects by using pollutant source study techniques hold promise but are still analytically in formative stages and should be improved.
- More assessment is needed to characterize population exposures to a variety of sources rich in carbonaceous material in rural, suburban, and urban areas. Greater understanding of the effects of complex terrain, meteorological conditions, and atmospheric processes on physicochemical PM composition and concentrations is needed. Research should include the specific investigation of temporal and spatial variability across populations, especially in specific locations where source dominance and population attributes could influence health.

- Concentration differences in carbonaceous $PM_{2.5}$ between monitoring sites in populated areas require more accurate resolution to guide future exposure assessments and health effects investigations. Investigators should continue epidemiological research using proximity measures and intra-urban exposure contrasts.

New York State Research Needs. A review of health and exposure findings leads to the following recommendations on specific research needs for New York State:

- Because carbonaceous $PM_{2.5}$ concentrations can vary across short distances and over small time periods, methods to assess exposure variability need to move beyond the use of central-monitor NAAQS compliance data alone. Daily (24-hour) and annual averaged ambient air quality data collected at central sites for current regulatory compliance in rural and urban areas may not reflect real and potentially meaningful population exposures to $PM_{2.5}$ sources rich in carbonaceous material.
- A greater understanding of population activity and behavior patterns is needed to determine how day-to-day actions of general and susceptible populations contribute to the magnitude, duration, and intensity of exposures to carbonaceous $PM_{2.5}$ sources, especially in densely populated areas (both nonurban and urban) in proximity to large local sources. Exposure should be assessed for:
    1. populations in proximity to residential wood combustion emissions (including outdoor wood boilers), especially in densely populated villages, towns, and small cities, and areas where meteorology and terrain are conducive to high pollutant concentrations;
    2. populations in proximity to commercial meat-cooking establishments; and
    3. populations in proximity to mobile sources, including vehicles and airports, ferry, harbors, and locomotive corridors and terminals, as well as in or onboard aircraft, ferries, locomotives, and vehicles.
- The potential relevance of the above research to public health and preventative measures could be considered in the future determination of appropriate $PM_{2.5}$ standards and pollution control measures.

Future NAAQS Reviews and Public Health in New York. With respect to future NAAQS reviews for PM and possible effects of carbonaceous $PM_{2.5}$ on public health in New York, a review of health and exposure findings leads to the following general findings:

- Policy makers need to reach agreement on a common research agenda. Calls for funding large-scale research on the health effects of specific PM components, on the one hand, and multiple pollutant combinations on the other, should be reconciled toward more efficient standards setting. The National Research Council's Committee on Research Priorities for Airborne Particulate Matter Research Topic 5 calls for an assessment of hazardous PM components, envisioning a matrix of PM components and health responses. The committee's Research Topic 7 calls for

research into the combined effects of PM and gaseous pollutants, envisioning a shift in focus from PM to a multipollutant research program. Researchers are therefore challenged to develop a systematic program to assess toxicity of PM mixture components while also considering PM's health effects within the broader context of other pollutants present in ambient air.

- Until a more definitive understanding of particle and multiple-pollutant toxicity is reached, an interim public health management approach should attempt to integrate current knowledge of toxicity and health effects with additional study of exposure distributions and magnitudes to inform emission control options. One possible management approach would proceed in three chronological steps:
    1. determine pollutants with known toxicity,
    2. assess exposure distribution and magnitude in relation to sources of these pollutants, and
    3. use this information to determine the most efficient implementation of local and regional controls to maximize public health benefits.

  The framework could be informed by exposure assessment methodology and policy uses for exposure estimates as outlined, for example, by Smith (1995) and Brauer et al. (2002). Such an approach would recognize that $PM_{2.5}$ reductions have led in the past to measurable health gains, and therefore efforts should be made to reduce emissions based on available evidence of health effects and exposure. For example, a decrease in mass-based $PM_{2.5}$ concentrations regionally across the central and eastern U.S. was associated with a reduction in adult mortality rates (Laden et al. 2006). A decrease in traffic volumes in Buffalo, NY, was associated with a decrease in health care utilization for respiratory diseases (Lwebuga-Mukasa et al. 2003).

TECHNOLOGICAL OPTIONS FOR REDUCING EMISSIONS OF CARBONACEOUS AEROSOLS

Technical approaches for reducing primary carbonaceous $PM_{2.5}$ emissions from seven source categories in New York State were evaluated in this study. These include five mobile source sectors (nonroad equipment, heavy-duty trucks, light-duty vehicles, airports, and marine ports) and two stationary source sectors (residential fuel combustion and commercial cooking). The major focus was on the New York City nonattainment area (NAA), however, the study also addresses other major urban areas in New York as well as selected counties representative of a rural environment[2].

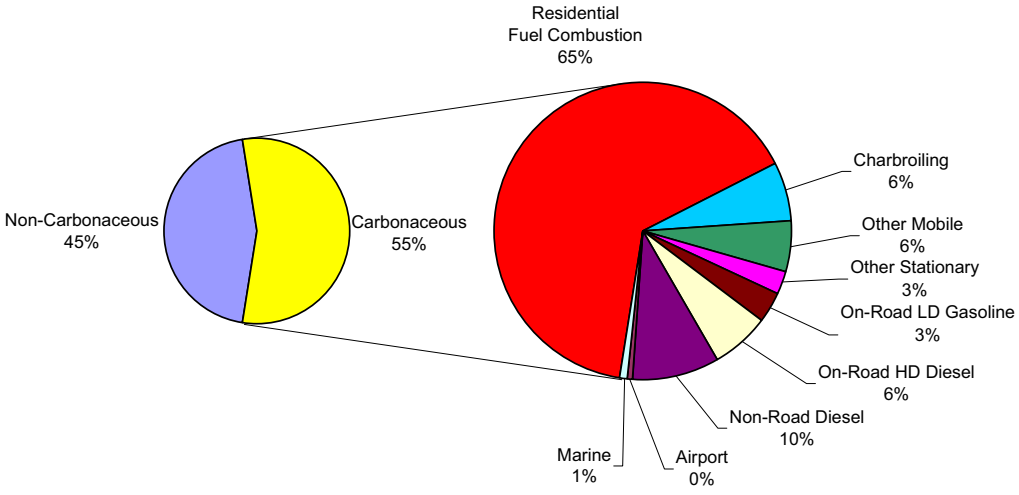
In order to select the sources to be evaluated in this chapter, primary $PM_{2.5}$ emissions in New York State for different sources were speciated into carbonaceous and non-carbonaceous emissions using EPA speciation factors. According to this analysis, the seven source categories evaluated in this chapter account for approximately 90% of primary carbonaceous $PM_{2.5}$ emissions in New York State, for which speciation

[2] The New York (tri-state) metropolitan nonattainment area refers to a 22-county area that includes the five New York City boroughs and 17 other counties in the states of New York, New Jersey, and Connecticut.

factors for primary $PM_{2.5}$ emissions for elemental and organic carbon are available. Detailed $PM_{2.5}$ inventory data for New York can be found in Appendix A. The study did not attempt to evaluate control strategies for a multitude of small source categories that collectively emit about 30% of total primary $PM_{2.5}$ in New York. For these hundreds of different types of stationary sources, reliable speciation data are not available. Where available, the study used the EPA's sector- or category-specific speciation profiles for primary $PM_{2.5}$ emissions to estimate the carbonaceous fraction of $PM_{2.5}$ emissions from that sector or category. For outdoor wood boilers, the study relied on inventory data developed by Mid-Atlantic Regional Air Management Association (MARAMA)[3] since EPA data are not available for this sector. [4]

Reducing levels of fine particulates requires a better understanding of which source sectors generate these pollutants, and how much can be attributed to each source sector. Figure S-5 shows the split between primary carbonaceous and noncarbonaceous $PM_{2.5}$ emissions in New York State.[5] Of the total primary $PM_{2.5}$ mass emissions, 55% are carbonaceous in nature (sum of primary elemental carbon and primary organic carbon). The carbonaceous fraction is then apportioned among the seven sectors addressed in this report plus "other mobile" and "other stationary" sectors. Again, approximately 30% of $PM_{2.5}$ that could not be speciated into carbonaceous and non-carbonaceous emissions is missing from the pie charts in Figure S-4.

Figure S-5. Total New York State $PM_{2.5}$ and Carbonaceous Detail (2002).



The relative contribution to primary carbonaceous $PM_{2.5}$ from the various sectors is quite different in the NYNAA (Figure S-6) as compared to rural areas (Figure S-7). In this metropolitan area, onroad and

[3] There are no EPA $PM_{2.5}$ emission factors for outdoor wood boilers. The National Emissions Inventory (NEI) does not include outdoor wood boilers.
[4] Appendix A of this report shows the New York State $PM_{2.5}$ inventory as it appears in EPA's National Emissions Inventory. This inventory was used by NESCAUM to determine which source sectors to evaluate for this report.
[5] An analysis of primary carbonaceous $PM_{2.5}$ in the NAA was also conducted but is not presented. The analysis showed the seven source categories also accounted for 90% of primary carbonaceous $PM_{2.5}$ in the NAA in 2002.

nonroad mobile source emission sectors, primarily emissions from gasoline- and diesel-powered engines, make up half of the carbonaceous $PM_{2.5}$ inventory. In contrast, the residential fuel combustion sector dominates carbonaceous $PM_{2.5}$ emissions in nonurbanized areas, accounting for more than 90% of the total, with the vast majority of the contribution coming from residential wood combustion. Residential wood combustion is relatively uncommon in the NAA except in the Long Island counties of Suffolk and Nassau.

Figure S-6. Total Carbonaceous $PM_{2.5}$—NAA.

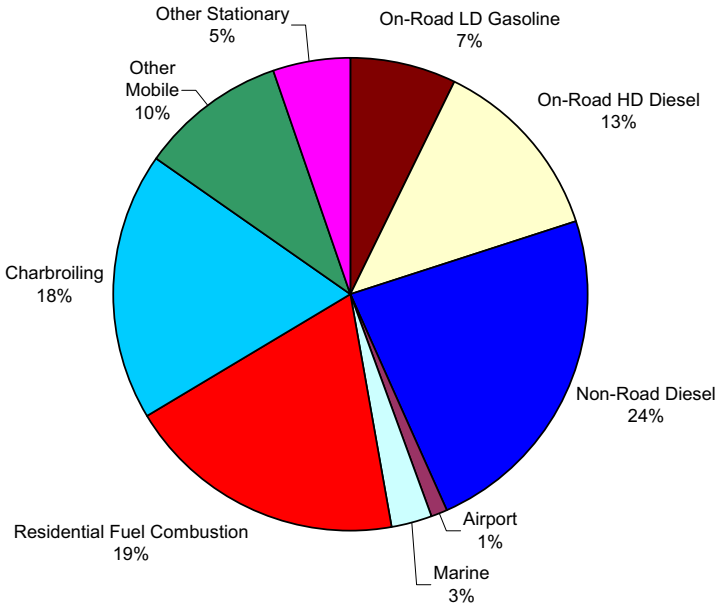
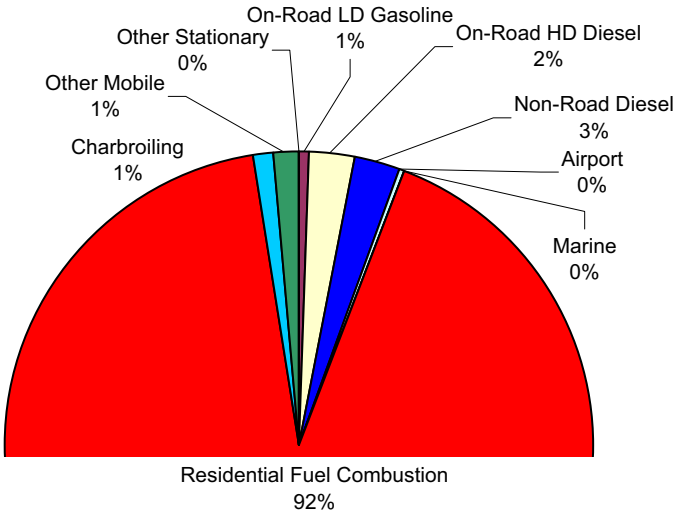


Figure S-7. Total Carbonaceous $PM_{2.5}$—Three Rural Counties (Combined).



Also noteworthy is the commercial charbroiling category, concentrated in population-dense urbanized areas and representing a significant fraction (almost 1/5 of the total) of overall carbonaceous emissions in the metropolitan area. While carbonaceous emissions from diesel engines (onroad and nonroad) outside the metropolitan area account for only about 5% of the upstate total from all source sectors, they account for almost 40% of total emissions in the metropolitan area.

Nonroad Equipment

The largest single contributor to $PM_{2.5}$ in the NAA is pollution from nonroad diesel equipment (24%). Given the great variety of nonroad equipment, retrofitting these machines is more difficult than retrofitting heavy-duty trucks. Targeting retrofit efforts toward the machines that produce the largest fraction of the PM inventory and/or machines that are the easiest to retrofit could simplify the task. For example, modeling with the EPA's National Mobile Inventory Model (NMIM) (2005) indicates that front-end loaders, backhoes, and skid-steer loaders will produce the majority of construction equipment-related $PM_{2.5}$ emissions between 2006 and 2020 in New York State, indicating that these categories would be good candidates for cost-effective retrofits. Recent experience with retrofitting in the field indicates that rear-engine machines can more easily be retrofitted with diesel particulate filters than front-engine machines. For some nonroad engines, retrofitting with one of the EPA's or CARB verified technologies for nonroad engines can greatly reduce emissions, as is the case for diesel trucks. Fewer technologies for nonroad engines have been verified, however, and the great variety of equipment makes these engines more difficult to retrofit, possibly pointing to the need to retrofit as many trucks as possible as the first option.

- New York could consider adoption of a regulation similar to the CARB construction equipment retrofit regulation that was finalized by the CARB this year (2007). Two other CARB rules could be adopted by New York -- the Cargo Handling Equipment and Harbor Craft rules. These rules, when finalized, could produce reductions of up to 85% in nonroad engine PM emissions.
- To reduce exposure to construction equipment emissions, New York DEC could work with agencies to establish a retrofit requirement for equipment operating near "sensitive receptors" as has been done by Massachusetts.
- The State could pursue electrification for centralized nonroad equipment. For some nonroad applications—notably cranes at marine ports and ground service equipment at airports—equipment electrification provides a cost-effective approach to reduce $PM_{2.5}$ emissions.

Emissions from Charbroiling

Charbroiling generates over 80% of the $PM_{2.5}$ emissions from the commercial cooking sector in the State, and an even larger fraction for the urban areas like New York City. Commercial cooking facilities in the State use two major types of charbroilers: underfired and chain-driven. Most emissions

(74%) come from the underfired charbroilers, although regulatory efforts (mostly in California) have focused on control of $PM_{2.5}$ emissions from chain-driven charbroilers (about 10%).

- New York could consider adopting the California approach for chain-driven charbroilers. Catalytic oxidizers are capable of reducing $PM_{2.5}$ emissions by over 80% and should be highly cost-effective ($1,680 to $2,800 per ton of PM and VOCs reduced).
- Additionally, the State could investigate the feasibility of controlling $PM_{2.5}$ emissions from underfired charbroilers, even though it may be more expensive than controlling chain-driven charbroilers. South Coast AQMD has estimated the cost of controlling underfired broiler emissions to be $1,100 to $7,300 per ton of PM_{10} reduced.

Emissions from Residential Fuel Combustion

The residential source category produces 85% of organic $PM_{2.5}$ emissions in rural areas of New York State from the consumption of fuels such as natural gas, fuel oil, wood, and coal. The most important sources of elemental and organic carbon emissions are wood combustion (woodstoves, fireplaces, and fireplace inserts) and the emerging source category of outdoor wood-fired boilers.

- Replace older woodstoves with an EPA-certified model; this can significantly reduce $PM_{2.5}$ emissions. This strategy will become more important as the costs of heating oil and natural gas rise and households in New York State (especially in rural areas) become more reliant on woodstoves for heating.
- New York State could consider the regulation of $PM_{2.5}$ emissions from outdoor wood boilers through the adoption of performance-based emission standards.

Heavy-duty Truck and Bus Emissions

Within the truck category the largest contributors include Class-8 trucks (tractor trailers), urban buses, school buses, and to a lesser extent, delivery vehicles (Classes 5 and 6). Approximately 74% of $PM_{2.5}$ from diesel trucks is primary elemental carbon, 23% is organic carbon, and 3% is sulfate.

- Reduce idling emissions through the use of cabin heaters, hybridization, auxiliary power units, and idling restrictions. This will reduce PM emissions. In addition, by lowering fuel consumption some approaches result in a cost savings to operators after a year or two. Also, consider adoption of CARB's truck refrigeration unit (TRU) rule, which will reduce TRU emissions by 85%.
- Retrofit heavy-duty trucks with diesel particulate filters; this can eliminate 90% of elemental carbon from diesel engine emissions and—if catalyzed—can virtually eliminate organic carbon emissions as well. Approximately 50 fuel and retrofit technologies have been verified by the EPA and by the CARB to reduce truck emissions. Also, consider installation of diesel oxidation catalysts in heavy-duty diesel engines. This will remove only the organic carbon fraction, which in older engines represents as much as 40% of $PM_{2.5}$ emissions.

- Consider prioritizing retrofits of vehicles that carry passengers—such as school buses, tour buses, and urban buses (outside of NYC since these have been retrofitted within the city)—to reduce exposure to $PM_{2.5}$.
- Conduct a study to improve the understanding of vehicle miles traveled and emissions for heavy-duty vehicles in the NYNAA. Many out-of-state trucks travel in New York City and information on the emissions impact from out-of-state trucks is necessary in order to design optimum control strategies.

Light-Duty Vehicles

According to EPA data, half of light-duty PM emissions come from vehicle exhaust and half from brake and tire wear. A large fraction of exhaust PM emissions comes from older vehicles.

- Efforts to reduce emissions from older cars—including funded maintenance programs and programs to replace aging vehicles—could reduce light-duty vehicle PM emissions.
- The State could conduct a pilot demonstration to evaluate the $PM_{2.5}$ reduction potential of vacuum and air-assist street sweepers. Studies have shown that new-technology street sweepers reduce 90% of road dust (PM_{10}) emissions, Approximately 15% to 25% of PM_{10} from road dust is $PM_{2.5}$.[6] New York could promote the introduction of greater numbers of advanced technology vehicles to reduce PM emissions. Recent research has shown that advanced technology vehicles such as "super ultra low emission vehicles" (SULEVs) and "ultra low emission vehicles" (ULEVs) have extremely low levels of pollutants and very low emissions deterioration rates.

NEAR-TERM STRATEGIES FOR SOURCE REDUCTIONS

Strategies for the New York Nonattainment Area

There are a number of near-term strategies that the State of New York could consider to obtain necessary emission reductions of EC and OC fraction of fine PM, These near-term options are listed below.

- New York State could reduce emissions from heavy-duty trucks either by using its authority under Section 177 of the Clean Air Act Amendments to adopt CARB rules or developing regulations based on CARB's rules. Adoption would require the development of regulations by New York's DEC. The two regulations are for trash truck and transportation refrigeration units. Requirements for diesel truck emissions reductions could also be considered at the regional level, given the large fraction of interstate truck miles traveled in the Northeast.
- New York State could require or provide incentives for the retrofit of nonroad construction equipment not covered by the New York State Diesel Emission Reduction Act of 2006 or

[6] According to AP-42, road dust emissions equal half of combined light- and heavy-duty vehicle related $PM_{2.5}$, however, mobile source experts have questioned this finding. A recent study concluded that 15% of road dust is $PM_{2.5}$ (Midwest Research Institute 2006).

municipal laws such as Local Law 77 in New York City. The CARB recently finalized a nonroad diesel retrofit requirement that could be used as a model in New York State.

- The State could consider adopting California's regulations for cargo handling equipment operating at marine ports.
- To facilitate use of retrofit devices in harbor craft, the City of New York could consider amending the law that sets the allowable level of sulfur in marine fuel (NYC AC 24-164). The sulfur level should be limited to 500 ppm. The State could consider adoption of the California harbor craft emissions standards once they are finalized by California.
- New York could consider regulating $PM_{2.5}$ emissions from new and existing chain-driven charbroilers. The State could adopt a regulation similar to the South Coast AQMD's Rule 1138. This requires operators of both the new and existing chain-driven charbroilers to install control devices.
- The State could also investigate the applicability of cost-effective technologies to reduce PM emissions from underfired charbroilers.
- New York could consider establishing a subsidized program to reduce older light-duty vehicle $PM_{2.5}$ emissions by providing incentives for the replacement of older vehicles or funding to repair vehicles that fail inspection for poor New York residents.

Reducing Exposure to $PM_{2.5}$ outside of the New York City Nonattainment Area

The focus of this report is on attaining the NAAQS for $PM_{2.5}$ and reducing emissions for that purpose. In some cases, emissions from mobile sources are not a very large contributor to overall $PM_{2.5}$ levels, but they are emitted in close proximity to people and thus pose a potential public health threat. Technical approaches to reduce exposure to $PM_{2.5}$ from some smaller sources of emissions are described below.

- Priority funding could be considered for retrofit of passenger vehicles to reduce exposure to $PM_{2.5}$. Examples of these vehicles include tour buses, school buses, urban buses, ferries, and locomotives.
- New York State could consider development of a regulation to restrict locomotive idling. Diesel locomotives idle up to 75% of the time. Installing idling reduction technologies is one of the most cost-effective means to reduce $PM_{2.5}$ emissions from nonroad diesel engines. Two-year payback times are typical.
- New York could establish a retrofit requirement or voluntary agreement with locomotive operators in the State to control diesel commuter rail locomotive $PM_{2.5}$ pollution through the use of retrofit devices. This could significantly reduce commuter exposure at rail stations and onboard trains. Reducing freight locomotive emissions will reduce $PM_{2.5}$ exposure in and around rail yards.
- New York could consider adopting the CARB harbor craft rule, which would result in substantial emissions reductions. There were over 1,000 ferry trips in New York Harbor in

2002. Typically, ferry engines are not fitted with PM-controlling devices, resulting in high levels of PM emissions near passengers.

- The State of New York could create voluntary incentives or regulatory requirements to require replacement of noncertified woodstoves. Examples of requirements are: (1) a real estate transfer requirement requiring all stoves that are not EPA-certified be removed prior to the sale of a property; or (2) a requirement that replacement of noncertified stoves takes place by a date specified in regulation. Voluntary and mandatory programs are being implemented in other parts of the U.S. (for example, Montana and Pennsylvania). Another option is to establish limits on use or "no-burn" days as has been done on the West Coast.
- The State could regulate emissions from residential outdoor wood-fired boilers, a rapidly increasing source of PM emissions in rural areas. These boilers are a large source of the organic and elemental carbon fraction of $PM_{2.5}$ emissions in the State and are a major concern from the human exposure perspective. In 2005, an estimated 14,000 of these units were in use in the State, providing an alternative source of energy in the face of rising fossil fuel prices. A growing number of complaints to local health agencies provides evidence of the adverse impact of these outdoor boilers on local air quality.

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