Emissions Inventories
Then, Now, and Tomorrow

by Arthur Werner and David Mobley

As late as the 1970s, air pollution was viewed almost exclusively as an urban phenomenon associated with energy production and factories, manifested as smog in Los Angeles, New York, London, and other large cities.[1] For this reason, inventories of air pollutant emissions were originally developed at metropolitan-area scales. These inventories were used to evaluate the effectiveness of control strategies and as inputs for air quality models to evaluate locations for ambient air quality monitors.[2] The focus of initial emissions inventory efforts was primarily on sulfur dioxide (SO_2), nitrogen oxides (NO_x), lead (Pb), particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs). Over the next several decades, emissions inventories evolved to include hazardous air pollutants (HAPs), greenhouse gases, and other pollutants important to human health, ecological effects, and regional haze. Spatial coverage increased to encompass states, regions, countries, continents, and the entire globe. At the same time, the increased sophistication of air quality models increased the demand for finer spatial, temporal, and species resolution of emissions. As our understanding of pollutant effects increases, modeling sophistication grows, and more information is made available to the public in a more timely manner, the demands on inventory developers will increase.

THEN

The first attempt by the U.S. Environmental Protection Agency (EPA) to produce a quality-assured national emissions inventory for use by policy-makers, modelers, human and ecological effects researchers, and industry was the 1985 National Acid Precipitation Assessment Program (NAPAP) Emissions Inventory.[3] Congress established NAPAP in 1980 to focus on problems posed by acid deposition in the United States. A fundamental objective of NAPAP research was to investigate emissions sources that contribute to acid deposition. The 1985 NAPAP Emissions Inventory built on the pioneering work in the 1970s and early 1980s by the California Air Resources Board (CARB), the St. Louis Regional Air Pollution Study (RAPS),[4] the Sulfate Regional Experiment (SURE),[5] the Northeast Corridor Regional Modeling Project (NECRMP),[6] the 1980 NAPAP Emissions Inventory,[7] and others.

In the United States, the process for developing the 1985 NAPAP Emissions Inventory involved compiling point-source emissions data submitted by states, conducting computerized quality assurance checks, sending flagged data back to the states for review, and calculating nonpoint (including mobile) source emissions using EPA models. In parallel, Environment Canada, working with the provinces, provided anthropogenic point and nonpoint source emissions. Biogenic emissions of VOCs, calculated by EPA, were also included in a national inventory for the first time.

To support atmospheric and deposition research, the NAPAP inventory reflected spatial, temporal, and chemical species allocation factors developed for the United States and Canada. County-level emissions from nonpoint sources were allocated spatially into 1/4° longitude by 1/6° latitude (approximately 20 × 20 km) grid cells using 14 surrogate indicators (e.g., population, housing, land-use, arboreal

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Table 1. Goals for future emissions inventories.

Category	Attributes
Pollutants	Criteria and chemically speciated pollutants, size-differentiated PM, NH_3, black and organic carbon, listed HAPs, persistent bioaccumulative and toxic chemicals (PBTs), greenhouse gases, aerosols
Source categories	*Point:* process-level, stack data, control equipment, regulatory driver; *Nonpoint:* county-level activity, controls; *Mobile:* urban- and county-level vehicle miles traveled and fuel use, fleet characteristics, temperature, and nonroad equipment populations; *Biogenic:* county-level species, daily meteorological data *All:* emissions factors, temporal factors, speciation profiles, location
Emissions factors	Up-to-date and comprehensive factors
Speciation profiles	Up-to-date and comprehensive profiles
Measurement methods	Continuous methods for major sources, accurate and affordable methods for all pollutants and sources
Data collection techniques	Timely and affordable survey techniques, satellite data for ground cover and fires
Timeliness	Annual reporting and inventories
Daily forecasting and recording	Continuous emissions monitoring (CEM) data for the largest point sources, load forecast of the largest emitting sources, mobile source indicators of events (e.g., major traffic events, accidents, ball games), nonpoint sources (e.g., major upset events, fires, spills, accidental releases)
Accessibility	Electronic reporting by sources and states, Web-based electronic access to data and exchange of information
Accuracy	Uncertainty indicators for all data elements, evaluation criteria with complementary measurements (e.g., tunnel studies, aircraft studies)
Transparency	All material documented, inventories transportable, calculations reproducible

type). Representative emissions were also estimated for weekday, Saturday, and Sunday for each season. Biogenic emissions were adjusted for hourly temperatures. For chemical speciation, 600 VOCs were organized into a set of 32 reactivity categories. The 1985 NAPAP Emissions Inventory, completed in 1989, became the "gold standard" and the progenitor for future national emissions inventories.

NOW

An outgrowth of the 1985 NAPAP Emissions Inventory process was the identification of key areas needing improvement to quantify all sources of emissions and all pollutants comprehensively, to better assess control strategies, to understand the linkage between emissions and effects, and to provide accurate resolved inputs for atmospheric modelers. Key needs were better emissions models for on-road and off-road mobile sources, better algorithms and emissions data for nonpoint sources, data on biogenic and other natural source emissions, and better chemical speciation. As these areas began to get attention from the inventory community, the uses for inventories, and hence the demands on them, began to increase. A recent NARSTO report[8] identified more than a dozen applications of emissions inventories, including control strategy development, compliance determinations, trends analysis, emissions trends tracking, air quality forecasting, environmental impact modeling, and international treaty reporting.

Over the past 15 years, many of the procedures begun during NAPAP have been modified and improved, although the basic approach to creating national and regional inventories has remained essentially the same. One major advance has been the development of emissions inventories for hazardous air pollutants and fine particles. Emissions factors are still derived primarily from AP-42.[9] EPA is currently exploring approaches for restructuring the emissions factor program to provide better guidance on the use of factors, quantitatively estimating uncertainties and variabilities, collecting data from state agencies for more robust factors, and providing up-to-date factors via the Internet.

New data systems and processing software to expedite emissions estimating and data processing have been developed by EPA and others. Models and tools include

- SPECIATE,[10] which contains more than 1000 speciation profiles for total organic carbon and PM emissions sources;
- FIRE,[11] which contains EPA's recommended emissions factors for criteria and hazardous pollutants;
- The Carnegie Mellon University ammonia model,[12] which provides county-specific activity data and emissions factors for ammonia sources;
- MOBILE6.2,[13] which estimates criteria and hazardous emissions factors for 28 on-road vehicle types;
- NONROAD,[14,15] which predicts criteria pollutant emissions from non-road equipment ranging from lawn mowers to heavy-duty commercial vehicles;
- BEIS[16] and GLOBEIS,[17] which allow users to estimate biogenic emissions of CO, speciated VOCs, and soil NO_x for a range of land uses;
- TANKS,[18] which estimates VOC and HAP emissions from organic liquid storage tanks;
- WATER9,[19] which estimates emissions from wastewater constituents; and
- SMOKE,[20] which processes emissions to provide spatial allocations, temporal allocations, chemical speciation, control technology applications, and biogenic emissions.

In addition, the Emissions Inventory Improvement Program (EIIP), a joint EPA, state, and local initiative, has published a 10-volume set of guidance documents[21] of "preferred and alternative methods" for most inventory-associated tasks. This standardization improves the consistency of collected data, provides better quality control and documentation, and results in increased usefulness of emissions information. Canada and Mexico use these or similar tools, adapted to their local conditions.

The most significant advance in the collection of accurate, real-time emissions data has been the use of Continuous Emissions Monitoring Systems (CEMS) in the United States to support the allowance trading program developed by EPA to comply with the Acid Rain Requirements (Title IV) of the 1990 Clean Air Act Amendments (CAAA). Each quarter, more than 2600 electric-generating units report hourly emissions of SO_2, NO_x, volumetric flow, and either O_2 or CO_2. Although the installation of CEMS and extensive quality assurance of the data was implemented to support the allowance trading program, the hourly data are readily available for use as inputs for atmospheric dispersion and deposition models and are summed to provide annual emissions for national, regional, state, and local inventories.

The United States produces a comprehensive, bottom-up National Emissions Inventory (NEI) approximately every three years, along with a top-down trends emissions inventory for the intervening years. Canada has produced an inventory approximately every five years since 1980, but is now moving toward producing an emissions inventory every year.[22] Mexico is in the final stages of producing its first national emissions inventory, with periodic updates anticipated.[23]

The NEI is designed to meet five specific needs: (1) provide input to national and regional modeling; (2) serve as the basis for air toxics risk analyses; (3) serve as a starting point for rule development; (4) provide trends and Government Performance and Results Act (GPRA) tracking; and (5) provide readily accessible information for the public. The emissions inventory includes data on all criteria pollutants, including ozone and fine PM ($PM_{2.5}$) precursors (i.e., NO_x, SO_2, VOCs, CO, primary PM_{10}, primary $PM_{2.5}$, and ammonia [NH_3]) and all 188 HAPs, including individual HAPs reported for compound groups listed in the CAAA. Biogenic emissions are not included in the NEI; rather, they are generally calculated when an air quality model is applied to reflect the temperature and conditions of the specific time and geographic area of interest.

In addition to national inventories, regional, state, provincial, and local inventories are developed periodically to meet the needs noted above. Five Regional Planning Organizations (RPOs) have been formed in the United States to coordinate air planning and management activities to meet the requirements of the Regional Haze Program. These RPOs have initiated development of inventories for 2002 in conjunction with EPA, state, local, and tribal activities. The emissions inventories are used for regional haze studies and contain its precursors, including ammonia and $PM_{2.5}$, as well as SO_2, NO_x, and VOCs. The 2002 emissions inventories cover all geographic areas at the county or subcounty level for each sector.[7] The emissions inventories will also be used to support air planning activities for the ozone and fine PM National Ambient Air Quality Standards. Most states in the United States, provinces in Canada, and some states and regions in Mexico have developed their own emissions inventories for specific regulatory, tracking, and exposure analyses.

NEI data and documentation are made available through EPA's Web site,[24] as are links to state, local, and tribal emissions inventories in the United States. Guides to the Canadian provincial and Mexican state and local inventories can be found on their respective Web sites.[21,22] A summary of and links to emissions inventories in the three countries can also be found in the draft NARSTO report.[8]

Emissions inventory data management systems have changed dramatically over the past 20 years from older mainframe systems used for 1985 NAPAP Emissions Inventory to simple spreadsheets and desktop databases. Current emissions inventory data management system development efforts revolve around issues of size, data usage, data accessibility, funding, and to a certain extent, the familiarity of the user/developer with certain database management software systems. Most of the large database management systems currently in use or in development are based around relational database management systems that use structured query language (SQL) to retrieve, store, sort, and provide overall data handling and management. These systems typically reside on client/server networks. The primary mechanism for data access and dissemination is by the Internet, which has revolutionized emissions inventory programs. NEI data files are in Microsoft Access-compatible format, and can therefore be used by anyone with access to the Internet and a personal computer.

TOMORROW

As demands on air quality management intensify, emissions inventories will be pushed to be more accurate, more comprehensive, and more timely. In addition, users have consistently identified specific short-term needs to address the following areas that pose significant uncertainty in emissions inventories:

- Size-segregated, speciated emissions of fine particles and their precursors, including black and organic carbon emissions;
- Emissions from on-road motor vehicles;
- Ammonia from agricultural and other area sources;
- Speciated, spatially, and temporally resolved organic emissions from biogenic sources;
- Emissions of total VOCs and organic HAPs at petrochemical industrial facilities;[25]
- Emissions from off-road mobile sources, including aircraft and airport ground equipment, commercial marine facilities, and locomotives;
- Emissions from open biomass burning, including agricultural and forest prescribed burning, wildfires, and residential backyard burning;
- Residential wood combustion, including woodstoves and fireplaces;
- Toxic air pollutants and HAPs; and
- Paved and unpaved road dust.

We envision the priorities for the next decade as set forth in Table 1. These priorities include items to be developed, and others that just need to be readily available. Addressing these uncertainties and attaining the attributes listed in Table 1 will take a concerted effort by regulators, field measurement specialists, information technology practitioners, chemical transport modelers, and policy-makers. Much of the emphasis on emissions characterization is moving from point sources to diffuse, nonpoint sources, which provide greater challenges not only in measuring emissions over time, but also in accurately defining the location of the emissions. While some of these challenges can be met by extending the use of current technologies and approaches, most improvements will come from the creative application of emerging technologies or technologies used in other fields. Examples of exciting new tools for emissions inventory improvement include satellite, aircraft, and surface remote sensing for natural, mobile, and nonpoint sources; application of CEMS to PM, metals, black carbon, and VOCs at electricity-generating units and other major point sources; roadway tunnel studies, portable emissions measurement systems, and onboard sensors for mobile sources; as well as aircraft plume measurements and inverse modeling. In addition, data collection, storage, and distribution will be enhanced by rapid improvements in information technology, use of the Internet, and linkage to geographic information systems.

For information on the current emissions inventories in North America, assessment of their strengths, weaknesses, and uncertainties, along with recommendations to improve the timeliness, quality, and affordability of emissions inventories, readers are encouraged to read the report, *NARSTO Assessment—Improving Emissions Inventories for Effective Air Quality Management Across North America*.[8] This document is currently undergoing peer review and is scheduled to be published in spring 2005.

The future presents a challenging and exciting time for emissions inventory programs across the country, continent, and the world as they strive to meet the needs and expectations of the air quality management community. With dedicated professionals and adequate resources, significant advances in emissions inventory programs should continue.

DISCLAIMER

Although this article has been reviewed and approved for publication, any views expressed by the authors do not necessarily reflect the views of the U.S. Environmental Protection Agency. **em**

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