Improving Emission Inventories for Effective Air Quality Management Across North America

A NARSTO Assessment

Prepared by:

NARSTO EI Assessment Team

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Review Draft

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PREFACE

This is a draft document prepared by the NARSTO Emission Inventory Steering Committee for peer review by the NARSTO membership and other interested parties. Please send your comments to Diane Fleshman at diane@owt.com by October 29, 2004. In particular, we request comments on the question of whether the document needs an Executive Summary, or do the Introduction (Chapter 1) and the Recommendations and Conclusions (Chapter 7) meet that need.

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The Co-Chairs of the NARSTO Emission Inventory Assessment were: Marc Deslauriers (Environment Canada), Howard Feldman (American Petroleum Institute), Christopher Frey (North Carolina State University), David Mobley (USEPA), Leonora Rojas-Bracho (National Institute of Ecology of Mexico), and Susan Wierman (MARAMA).

The NARSTO leadership who also contributed significantly to the planning and preparation of the document included: Steven Cadle, Co-Chair, NARSTO Emissions Team (General Motors); Jeremy Hales, NARSTO Management Coordinator (Envair); George Hidy, Co-Chair, NARSTO Assessment Team (Envair); David Mobley, Co-Chair, NARSTO Emissions Team (USEPA); Jeffrey West, NARSTO Associate Management Coordinator (NOAA); and Susan Wierman, Co-Chair, NARSTO Assessment Team (MARAMA).

NARSTO would also like to thank the lead and contributing authors of the seven chapters of this Assessment:

Chapter 1 – *Introduction*: Jeremy Hales (Envair);
Chapter 2 – *Vision for Future North American Inventory Programs*: Lead Author: Charles Kolb (Aerodyne). Contributing Authors: Jeremy Hales (Envair), David Mobley (USEPA), David Parrish (NOAA), and Art Werner (MACTEC);
Chapter 3 – *North American Emission Inventories*: Lead Authors: Bernd Haneke (MACTEC) and Arthur Werner (MACTEC). Contributing Authors: Leonora Rojas Bracho (Mexico INE), Veronica Garibay Bravo (Mexico INE), Marc Deslauriers (Environment Canada), Paula Fields (ERG), David Streets (Argonne National Laboratories), and Jim Wilson (Pechan);
Chapter 4 – *Tools for Developing Emission Inventories*: Lead Author: Bernd Haneke (MACTEC), and Arthur Werner (MACTEC). Contributing Authors: Bill Barnard (MACTEC), Leonora Rojas Bracho (Mexico INE), Veronica Garibay Bravo (Mexico INE), Andrew Bollman (Pechan), Marc Deslauriers (Environment Canada), Paula Fields (ERG), and Jim Wilson (Pechan);
Chapter 5 – *Strengths and Weaknesses of Current Inventories and Models: Sensitivities, Uncertainties and Evaluation Procedures*: Lead Author: Christopher Frey (NCSU). Contributing Authors: David Parrish (NOAA) and Junyu (Allen) Zheng (NCSU);
Chapter 6 – *Future Perspectives: Evolving Measurement Technology, Interpretive Methods, and Scientific Issues*: Lead Author: Jeremy Hales (Envair), and George Hidy (Envair). Contributing Authors: Stefan Falke (Washington University), Charles Kolb (Aerodyne), David Parrish (NOAA), Jim Szykman (USEPA/NERL), and Art Werner (MACTEC);
Chapter 7 – *Recommendations and Conclusions*: Lead Author: Andy Miller (USEPA). Contributing Authors: the NARSTO Steering Committee.
Appendix B – David Streets (Argonne National Laboratories).

The Steering Committee has been instrumental in the development of this Assessment. Members included:

Michael Benjamin	California Air Resources Board
Kevin Black	DOT, Federal Highway Administration
John Bosch	USEPA/OAQPS
Garry Brooks	Eastern Research Group
Steve Cadle	General Motors
Bart Croes	California Air Resources Board
Marc Deslauriers	Environment Canada
Cyril Durrenberger	University of Texas
Stefan Falke	Washington University
Howard Feldman	American Petroleum Institute
Adrián Fernández	Mexico INE
Paula Fields	Eastern Research Group
Chris Frey	North Carolina State University
Veronica Garibay Bravo	Mexico INE
Jake Hales	Envair/NARSTO
Bernd Haneke	MACTEC Federal Programs, Inc.
George Hidy	Envair
Leslie Hook	Oak Ride National Laboratory
Bill Kuykendal	USEPA/OAQPS
Chuck Kolb	Aerodyne
Phil Lorang	USEPA/OAQPS
Doreen Neil	NASA
Dave Niemi	Environment Canada
Betsy Owczarski	NARSTO
Tim Parkin	USDA/ARS
David Parrish	NOAA
Bill Pennel	PNNL
Tom Pierce	USEPA/NERL
ST Rao	USEPA/NERL
Leonora Rojas Bracho	Mexico INE
Randy Strait	EH Pechan and Associates, Inc.
David Streets	Argonne National Lab
Jim Szykman	USEPA/NERL
Gene Tierney	USEPA/OTAQ
Jeffrey West	NARSTO
Peter Westlin	USEPA/OAQPS
Arthur Werner	MACTEC Federal Programs, Inc.
Roger Westman	Allegheny County, Pennsylvania
Susan Wierman	MARAMA
Jim Wilson	EH Pechan and Associates, Inc.
Allen Zheng	North Carolina State University

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DISCLAIMER

The views expressed in this Assessment are those of the authors and do not necessarily reflect the views or policies of any organization within or outside the NARSTO community. Further, any policy implications derived from the material herein cannot be considered to be endorsed by NARSTO.

CONTENTS

CHAPTER 2. VISION FOR FUTURE NORTH AMERICAN EMISSION-INVENTORY PROGRAMS

CHAPTER 3. NORTH AMERICAN EMISSION INVENTORIES

CHAPTER 4. TOOLS FOR DEVELOPING EMISSION INVENTORIES

CHAPTER 5. STRENGTHS AND WEAKNESSES OF CURRENT INVENTORIES AND MODELS: SENSITIVITIES, UNCERTAINTIES AND EVALUATION PROCEDURES

CHAPTER 6. FUTURE PERSPECTIVES: EVOLVING MEASUREMENT TECHNOLOGY, INTERPRETIVE METHODS, AND SCIENTIFIC ISSUES

CHAPTER 7. RECOMMENDATIONS AND CONCLUSIONS

LIST OF ACRONYMS

Acronym	**Definition**
AA	Atomic Absorption
AASHTO	American Association of State Highway and Transportation Officials
ACE-Asia	Aerosol Characterization Project-Asia
AF	Analytical Ferrography
AFSEF	AIRS/Facility Subsystem Emission Factors
AGEBs	Areas Geoestadísticas Básicas
AIRS	Aerometric Information Retrieval System
ALAPCO	Association of Local Air Pollution Control Officials
ANAFAPYT	Asociacíon Nacional de Fabricantes de Pinturas y Tintas (National Association of Paint and Dye Manufacturers)
ANOVA	Analysis of Variance
AP-42	USEPA’s Compilation of Air Pollutant Emission Factors
APINA	Air Pollution Information Network
ARP	Acid Rain Program
ASCII	American Standard Code for Information Interchange
ASME	American Society of Mechanical Engineers
ASPEN	Assessment System for Population Exposure Nationwide
ASTM	American Standards for Testing and Materials
ATBDs	Algorithm Theoretical Basis Documents
AVHRR	Advanced Very High Resolution Radiometer
BART	Best Available Retrofit Technology
BC	Black carbon
BEIS	USEPA’s Biogenic Emission Inventory System
BELD	Biogenic Emission Landcover Database
BLS	U.S. Department of Labor’s Bureau of Labor Statistics
BRAVO	Big Bend Regional Aerosol and Visibility Observational Study
CAA	Clean Air Act
CAAA	1990 Clean Air Act Amendments
CAC	Criteria Air Contaminants
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMD	USEPA’s Clean Air Markets Division
CANALAVA	Cámara Nacional de la Industria de Lavanderías (National Chamber of the Dry Cleaning Industry)
CARB	California Air Resources Board
CART	Categorical and Regression Trees
CB-IV	Carbon Bond Mechanism Version IV
CEC	Commission for Environmental Cooperation
CEMS	Continuous Emissions Monitoring System
CENRAP	Central States Regional Air Partnership

Acronym	**Definition**
CEPS1.0	Centralized Emissions Processing System
CFC	Chloroflourocarbons
CFR	Code of Federal Regulations
CGEIC	Canadian Global Emissions Interpretation Centre
CGER	Center for Global Environmental Research
CH2=CH-CH=CH2	1,3-Butadiene
CI	Chemiluminesence
CICA	Centro Información de sobre Contaminación de Aire (Information Center on Air Pollution)
CMB	chemical mass balance
CMU	Carnegie Mellon University
CNG	Compressed Natural Gas
COAs	Cédulas de Operación Anual (Annual Operating Reports)
CRC	Coordinating Research Council
CTM	Conditional Test Methods
CVAA	Cold Vapor Atomic Absorption
CVAFS	Cold Vapor Atomic Fluorescence Spectrophotometry
DARS	Data Attribute Rating System
DATGEN	Datos Generales (Emissions inventories for areas with air quality plans)
DGICURG	INE’s Dirección General de Investigación sobre la Contaminación Urbana, Regional y Global (General Directorate of Urban, Regional, and Global Air Pollution Research)
DIAL	Differential absorption lidar
DOAS	Differential optical absorption spectroscopy
DoD	Department of Defense
DOE	Department of Energy
DSA	Differential sensitivity analysis
EC	Elemental carbon
EDGAR	Emission Database for Global Atmospheric Research
EDMS	Emissions Data Management System
EFDB	database on greenhouse-gas emission factors
EFIG	Emissions Factor and Inventory Group
EGAS	Economic Growth Analysis System
EGUs	Electric Generating Units
EI	emission inventory
EIA	Energy Information Administration
EIIP	Emission Inventory Improvement Program
EMCH	USEPA's Emissions Modeling Clearing House
EMEP	Co-operative programme for monitoring and evaluation of long range transmission of air pollutants in Europe
EMFAC	EMission FACtors Model
EMS	Emissions Modeling System
EPRI	Electric Power Research Institute

Acronym	**Definition**
EPS	Emissions Processing System
EPWG	Emissions and Projections Working Group
ESA	European Space Agency
ESP	Electrostatic Precipitator
ESRI	Earth Sciences Research Institute
ETS	Emissions Trading System
EU	European Union
FAA	Federal Aviation Administration
FAST	Fourier Amplitude Sensitivity Test
FHWA	Federal Highway Administration
FID	Flame ionization detector
FIRE	Factor Information and Retrieval
FPD	Flame Photometric Detector
FTIR	Fourier Transform Infrared Spectroscopy
FTP	File transfer protocol
GC	Gas chromatograph
GCVTC	Grand Canyon Visibility Transport Commission
GEIA	Global Emissions Inventory Activity
GEMAP	Geocoded Emission Modeling and Projections
GEOS CHEM	Goddard Earth Observing System Chemical Model
Geo-SCIAMACHY	Geostationary Orbit-SCIAMACHY Model
GeoTRACE	GEostationary Observatory for TRopospheric Air ChEmistry
GFC	Gas filter correlation
GHGs	Greenhouse gases
GIGO	Garbage in, garbage out
GIS	Geographic information system
GloBEIS3	Global Biosphere Emission and Interactions System, Version 3.1
GOES	Geostationary Satellite
GOME	Global Ozone Monitoring Experiment
GPG	Good Practice Guidance
GPRA	Government Performance and Results Act
HAPs	Hazardous air pollutants
HC	Hydrocarbon
HCFC-22	Chlorodifluoromethane
HDD	Heavy-duty diesel
HFCs	Halocarbons
HPMS	Highway Performance Monitoring System
HTBR	Hierarchical Tree-Based Regression
I/M	inspection/maintenance programs
IC	Internal combustion
IECM	Integrated Environmental Control Model
IGES	Institute for Global Environmental Strategies
IMIP	Instituto Mexicano de Investigación y Planeación

Acronym	**Definition**
IMPROVE	Interagency Monitoring of Protected Visual Environments
INE	Instituto Nacional de Ecología (National Institute of Ecology)
INEGI	Instituto Nacional de Estadística, Geografía e Informática (National Institute of Statistics, Geography, and Computing)
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Planning Model
IR	Infrared
ISCST3	Industrial Source Complex Short Term Model
ITS	Intelligent Transportation System
L&E	Locating and Estimating Document
LGEEPA	Ley General del Equilibrio Ecológico y la Protección al Ambiente (General Law of Ecological Balance and Environmental Protection)
Lidar	Light detection and ranging
LPG	Liquiefied Propane Gas
LRTAP	Long Range Transboundary Air Pollution
LTOs	Landing and take-off cycles
LULUC	Land use change category
MACT	Maximum Achievable Control Technology
MANE-VU	Mid-Atlantic/Northeast Visibility Union
MCMA	Multiple-Criteria Model Analysis
MISR	Multi-angle Imaging SpectroRadiometer
MLE	Maximum Likelihood Estimation
MMS	Mineral Management Service
MOBTOX	Mobile Source Air Toxics Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurement of Pollution in the Troposphere
MOVES	Motor Vehicle Emission Simulator
MOZART	NCAR Model for OZone And Related chemical Tracers
MRPO	Midwest RPO
MS	Mass spectrometry
MSA	Metropolitan Statistical Area
NAAQS	National Ambient Air Quality Standards
NAFTA	North America Free Trade Agreement
NAICC	National Alliance of Independent Crop Consultants
NAICS	North American Industrial Classification System
NAPAP	National Acid Precipitation Assessment Program
NARSTO	North American Research Strategy for Tropospheric Ozone
NASA	National Aeronautics and Space Administration
TRACE-P	Transport and Chemical Evolution over the Pacific
NCDC	U.S. National Climatic Data Center
NDIR	Non-Dispersive Infrared

Acronym	**Definition**
NEDS	National Emissions Data System
NEI	National Emissions Inventory
NEON	NEI Emissions on the NET
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NFRAQS	Northern Front Range Air Quality Study
NGGIP	National Greenhouse Gas Inventories Programme
NIF	NEI Input Format
NMVOC	Non-methane volatile organic compounds
NOAA	National Oceanic and Atmospheric Administration
NOM	Normas Oficiales Mexicanas
NPRI	National Pollutant Release Inventory
NRC	National Research Council
NRSA	Nominal range sensitivity analysis
NSF	National Science Foundation
NSPS	New Source Performance Standards
NTI	1996 National Toxics Inventory
NWS	U.S. National Weather Service
OAQPS	Office of Air Quality Planning and Standards
OBD	onboard engine diagnostic
OC	organic carbon
OMB	Office of Management and Budget
OMI	Ozone Monitoring Instrument
ORD	Office of Research and Development
OTAG	ozone transport assessment group
OTAQ	USEPA's Office of Transportation and Air Quality
PAHs	polycyclic aromatic hydrocarbons
PAN	peroxyacetyl nitrate
PAR	photosynthetically active radiation
PART5	Particulate emission factor model
PBL	planetary boundary layer
PBTs	Persistent bioaccumulative toxins
PCBs	polychlorinated biphenyls
PCDD	polychlorinated dibenzo-p-dioxin
PCDF	polychlorinated dibenzo furan
PEMEX	Petróleos Mexicanos (Mexican National Petroleum Company)
PEMS	portable emission measurement systems
PEMS	Predictive Emissions Models
PFCs	perfluorocarbons
PM	particulate matter
PM10	particulate matter smaller than 10 microns in diameter
PM2.5	particulate matter smaller than 2.5 microns in diameter
POP	persistent organic pollutants
PROAIRE	Programas para Mejorar la Calidad del Aire (Programs for the Improvement of Air Quality)

Acronym	**Definition**
PTC	Performance Test Code
QA	quality assurance
QC	quality control
QCEW	Quarterly Census of Employment and Wages
RADM	Regional Acid Deposition Model
RAPIDC	Regional Air Pollution in Developing Countries
RH	relative humidity
RIVM	National Institute of Public Health and the Environment
RKIS	rotary kiln incinerator simulator
RM	Reference Method
ROM	Regional Oxidant Model
ROVER	Real-Time On-Road Vehicle Exhaust Gas Modular Flowmeter and Emissions Reporting System
RPO	Regional Planning Organization
RSD	Remote Sensing Division
RVP	reid vapor pressure
SAGARPA	Secretaría de Agricultura, Gandería, Desarrollo Rural, Pesca y Alimentación (Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food
SAPRC99	State Air Pollution Research Center module
SBUV-2	Solar Backscatter Ultraviolet Ozone Experiment 2
SCAQMD	South Coast Air Quality Management District
SCC	source classification code
SCF	speed correction factor
SCIAMACHY	SCanning Imaging Absorption Spectrometer for Atmospheric ChartograpHY
SCOS-NARSTO	Southern California Ozone Study-North American Research Strategy for Tropospheric Ozone
SEDIS 2.0	Spatial Emissions Distribution Information System
SEDS	State Energy Data System
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales (Secretariat of the Environmental and Natural Resources)
SENER	Secretaría de Energía (Secretariat of Energy)
SIC	Standard Industrial Classification
SIDA	Swedish International Development Co-operation Agency
SIPs	State Implementation Plans
SMN	Servicio Meterológico Nacional (Mexican National Weather Service)
SMOKE	Sparse Matrix Operator Kernel Emissions Modeling System
SNAP	Selected Nomenclature for Air Pollution
Sodar	Sound detection and ranging
SURE	Sulfate Regional Experiment
SOS	Southern Oxidant Study
SPOT	Simple Portable Onboard Test

Acronym	**Definition**
SQL	structured query language
SS	Secretaria de Salud (Health Secretariat)
STAPPA	State and Territorial Air Pollution Program Administrators
STPS	Secretaría del Trabajo y Previsión Social (Secretariat of Labor)
TAC	Technical Advisory Committee
TCEQ	Texas Commission on Environmental Quality
TDF	tire-derived fuel
TDLS	Tunable diode laser spectroscopy
TDMs	travel demand models
TES	Total Emission Spectrometer
TexAQS	Texas Air Quality Study
TFEIP	Task Force on Emission Inventories and Projections
TFI	Task Force on National Greenhouse Gas Inventories
THC	total hydrocarbons
TILDAS	tunable infrared laser differential absorption spectroscopy
TNO	Netherlands Organization for Applied Scientific Research
TOC	Total Organic Compounds
TOG	total organic gas
TPM	total particulate matter
TRI	Toxic Release Inventory
TRS	total reduced sulfur
TSP	total suspended particulate matter
UAM	urban airshed model
UN	United Nations
UNAM	Universidad Nacional Autónoma de México (National Autonomous University of Mexico)
UNDP	United Nations Development Pogramme
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USEPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
UV	ultraviolet
VISTAS	Visibility Improvement State and Tribal Association of the Southeast
VKT	vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	volatile organic compounds
WGA	Western Governors Association
WRAP	Western Regional Air Partnership
XATEF	Crosswalk/Air Toxics Emissions Factor
XML	eXtensible Markup Language

1

GLOSSARY

Acid rain – Precipitation more acidic than normal because it contains dissolved sulfuric and/or nitric acid produced from the dissolution of sulfur or nitrogen oxides into water vapor.

Activity factor – A measure of the driving force that causes a source to emit pollutants. Emissions are generally determined by multiplying an emission factor by the activity factors. Examples of activity factors are pounds of coal burned per year by a power plant, vehicle miles traveled per day by an auto fleet, barrels of oil produced monthly by a refinery.

Aerosol – A gas containing suspended solids or liquid that stays suspended in air due to its small size.

Air pollutant – A substance in ambient air that has the potential to cause harm to humans or the environment.

Ambient air – Outside air; the air in which people, animals, and plants live.

Anthropogenic emissions – Emissions resulting from human activities.

Biogenic emissions – Emissions produced by natural sources.

Concentration – The amount of a substance in a given volume of air.

Continuous Emissions Monitoring System (CEMS) – The equipment, instruments, and measuring components necessary for continuous measurements of pollutants emitted to the atmosphere from exhaust gases from combustion or industrial processes.

Criteria pollutants (U.S.) – Pollutants identified by the 1970 Clean Air Act leading to adverse health effects. These are sulfur dioxide (SO_2), oxides of nitrogen (NO_x), lead (Pb), particulate matter (PM), and volatile organic compounds (VOCs).

Emission – Discharge of a pollutant from an anthropogenic or natural source into the atmosphere.

Emission factor – A representative value that relates the amount of pollutant emitted to the atmosphere to an activity associated with that source.

Emissions inventory – A comprehensive data base of air pollutant emissions from individual sources and categories of sources over a geographic area for a specified time period.

Emission model – An algorithm or computer program that calculates emissions for a source or group of sources from the various factors that produce those emissions. For example, onroad mobile source emissions depend on several variables including vehicle type and make, ambient temperature, travel speed, operating mode, fuel volatility, and mileage accrual rate.

Emissions processor – A tool used to prepare and manipulate emissions and related data (e.g., temporal profiles, chemical speciation profiles, and control strategies) for input to air quality simulation models.

Greenhouse gas – A gas in the atmosphere that produces a net increase in the amount of energy absorbed by the Earth. The primary greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

Hazardous Air Pollutants – Toxic air pollutants including heavy metals and persistent organic pollutants defined for regulatory purposes by the US Clean Air Act.

Mobile source –A source or group of sources not located at fixed geographical coordinates.

Nonpoint or area source -- A stationary or mobile source that is too small to be counted individually.

Ozone or smog – A gas with the formula O_3 formed by the reaction in the atmosphere of hydrocarbons, nitrogen oxides in the presence of sunlight. The term smog was coined in Los Angeles to characterize a combination of smoke and fog.

Particulate matter. .A small solid or liquid droplet that remains suspended in air.

Point source – A stationary source that emits a sufficient quantity of pollutants to be inventoried individually.

Regional haze – Visibility impairment caused by cumulative air emissions from numerous sources over a wide geographical area.

Speciation/speciate – The identification of component chemical species making up the particle/compound mass.

State Implementation Plan – In the United States, a federally enforceable plan at the State level that describes in detail how a State will comply with the requirements of the US Clean Air Act.

Stationary source – A generator of air pollutants located at fixed geographical coordinates.

Valley of Mexico – The region immediately surrounding Mexico City.

Volatile Organic Compounds – Organic (carbon-based) chemical that easily form vapors at normal pressures and temperatures. Examples include solvents, paint thinner, spray can propellants, gasoline, kerosene, and dry cleaning products. VOC’s are also emitted by plants and trees.

CHAPTER 1. INTRODUCTION

Emission inventories are collections of data describing pollutants emitted from specified sources over a specified geographic area for a specified time period. As such, emission inventories form a crucial foundation for air-quality management at local, regional, national, and continental scales. This introduction to ***Improving Emission Inventories for Effective Air Quality Management Across North America: A NARSTO Assessment*** identifies the background and objectives for the Assessment, its intended audience and scope, and the report structure.

1.1 BACKGROUND AND OBJECTIVES

This Assessment of North American air-pollution emission inventories addresses current inventory status as well as projected future progress of emission-inventory applications and research. Its primary goal is to guide the development of future inventories, as well as to facilitate inventory application for atmospheric-process evaluation and pollution management.

The development and application of emission inventories is a particularly timely subject for several reasons. The previous NARSTO Assessments of ozone and airborne particulate matter (NARSTO 2000, NARSTO 2004) identify a number of desired improvements in North American emission inventories, which are essential for development of future, more efficient and reliable particulate-matter and ozone management strategies.[1] Moreover, the recent National Research Council reports *Air Quality Management in the United States* (NRC 2004a) and *Research Priorities for Airborne Particulate Matter* (NRC 2004b) spotlight several areas where substantial emission-inventory enhancements are needed, including new emission-monitoring techniques, regularly updated and field-evaluated inventories, organic PM-precursor speciation and the characterization of physiologically important PM components. Further, with the exception of continuous emission monitoring at some large stationary sources, air-quality management systems of Canada, the United States, and Mexico lack a comprehensive and quantitative program to assess emission reductions resulting from management actions. These reported recommendations reflect relatively recent findings regarding health impacts of PM and other pollutants, as well as the traditionally appreciated fact that emission inventories constitute an essential component of our ability to model and manage atmospheric pollution.

Four additional features further emphasize the need for an emission inventory assessment. The first of these is the evolving recognition that traditional emission inventories contain substantial (and largely unspecified) levels of uncertainty, which severely limit the reliability of associated pollution-management strategies.[2] Systematic identification and quantification of these

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[1] The emission-inventory chapters of these two Assessments tabulate annually averaged national North American inventory data for primary PM emissions as well as for emissions of gaseous PM and ozone precursors. As a partial response to actions recommended in these Assessments, NARSTO hosted a technical conference in October 2003, entitled *Innovative Methods for Emission Inventory Development and Evaluation* (Mobley and Cadle, 2004). Presentations from this workshop form an important technical basis for the current Assessment, and can be viewed on the NARSTO Web site, www.cgenv.com/Narsto.

[2] Although several relatively recent developments can be cited, the Texas 2000 field study's discovery of major VOC underestimates in Houston's emission inventory provides a key example to illustrate this point (see Section 5.2.3).

uncertainties are essential to further progress in the field. Second, past successes in reducing emissions from many traditional sources have led to a current situation wherein substantial emission fractions originate from malfunctioning and/or previously uncharacterized sources. To characterize many of these emission categories, new methodologies are required.

A third feature reflects scientific advances made during recent years, which suggest that several innovative techniques are potentially applicable for future emission-inventory development and verification. It is probable that application of these methods, in conjunction with the more established approaches, will be highly beneficial to the overall inventory development and verification process. There is no doubt that current emission-inventory activities provide information that has been, and will continue to be, invaluable for modeling and management efforts. It is probable, however, that simply increasing these traditional activities will not reduce associated uncertainties in an efficient or cost-effective manner. Thus a systematic and serious consideration of new and innovative methods to augment traditional methodologies is in order.

Fourth, inventory-related needs among Canada, the United States, and Mexico are diverse. Stemming from geographical and industrial differences as well as from varying states of inventory development, this diversity suggests that Canada, the United States, and Mexico should emphasize different priorities for immediate development efforts. In recognition of these considerations, this Assessment takes a decidedly forward-looking perspective, which is reflected by the following sub-objectives to its primary goal:

1. **Promote Efficient and Effective Use of Current Emission Inventories and Identify Critical Uncertainty Areas in these Inventories.**
    - Provide a comprehensive resource for locating and acquiring all current North American inventories.
    - Provide a comprehensive location resource for emission-inventory application tools, including emission models and emission processors.
    - Provide guidelines for efficient and appropriate application of existing inventories.
    - Assess the strengths and weaknesses associated with emission inventories in general as well as with selected specific inventories.

2. **Guide the Development of Future Emission Inventories.**
    - Itemize advanced and potential future techniques for emission-inventory development, including their potential applications, their prospects for enhancing inventory development, and their implementation requirements and time-lines.
    - Discuss possible future archival methodologies for emission-inventory data, which will ensure greater accessibility and more reliable application.
    - Encourage thoughtful consideration, development, and application of these methods as a consequence of this itemization.
    - Encourage the further development of instrumentation, interpretive methodologies, and archival/retrieval systems as a consequence of this itemization;
    - Encourage the development of user friendly interfaces to provide improved methods of data retrieval and interpretation.
    - Encourage harmonization of emission inventories prepared for different and adjoining areas, especially among Canada, the United States, and Mexico.

3. Establish a Roadmap for the Future.

- Chart a recommended plan for development and deployment of the advanced methodologies discussed in this document.
- Recommend actions to enhance the timeliness, quality, and cost effectiveness of current emission inventory approaches.

1.2 AUDIENCE AND SCOPE

To fulfill the above objectives this Assessment is directed to a diverse audience. In particular, it focuses on a variety of decision analysts, scientists, and practitioners, including

- Decision makers, who are responsible for selecting among multiple technologies and pathways for emission-inventory research, development, and application

- Users of emission inventories
  - Policy analysts, policy planners, and policy implementers
  - Chemical-transport modelers
  - Field-campaign designers and practitioners
  - Community interest groups
  - Planners, regulators, and implementers of international agreements

- Developers of emission inventories
  - State-, provincial-, and local-agency developers in Canada, the United States, and Mexico
  - Makers of tools to derive emissions from process information
  - Makers of tools to measure emissions.

In addressing its audience this Assessment confines its scope mainly to North American emissions and to criteria pollutants and their precursors, although some discussion of non-criteria pollutants such as greenhouse gases and air toxins is naturally included owing to commonality of measurement, characterization, and data-archiving technologies. This Assessment does not duplicate currently available documents in the emission-inventory field. It is not a methods manual and, although it provides a valuable user's guide to locating current emission-inventory data, it is not a compendium of these data. Rather, this Assessment provides an examination of uncertainties in current emission inventories, identifies critically important aspects of these uncertainties, and indicates future pathways for improvement. The application of evolving and anticipated future technology, as well as measurement and database quality, are particularly important aspects of this improvement process.

1.3 REPORT STRUCTURE

The chapters of this Assessment follow a progression that closely reflects the objectives and scope noted above. Chapter 2 provides a summary vision statement which, from the authors' viewpoint, sets forth a desired yet technologically feasible state of future North American emission inventories and emission-inventory research. Chapters 3 and 4 present an overview of current North American emission inventories, emission processors, and emission models. These chapters are intended to set a basis for subsequent discussion, and to serve as a valuable location resource for persons seeking current inventory information. As noted above, this Assessment is not intended to be a data compendium but rather to serve as a convenient "signpost" for information location.

Chapter 5 deals directly with the estimation and quantification of uncertainty in emission inventories – a particularly challenging problem owing to the multitude of potential uncertainty sources, the lack of quantitative treatment in most past efforts, and the technical difficulty of grounding the multifaceted uncertainty issue on a sound mathematical basis. This chapter addresses the issue of setting a consistent framework for interpreting inventory uncertainties, and is decidedly forward-looking in its objective of setting the stage for quantitative treatment of this issue in future inventory studies.

Chapter 6 provides an overview of future and evolving emission-measurement technology, interpretive techniques, and data-management practices. Individual methods described here are accompanied by discussions of potential feasibility and projected future application.

Chapter 7 synthesizes the previous six chapters, using information from Chapters 2 through 6 to construct a blueprint for moving from the present state of emission-inventory science to the advanced state anticipated in Chapter 2. Chapter 7 is intended to be not only a statement of conclusions and recommendations, but also a concrete, cohesive pathway for the effective implementation of these recommendations to achieve a desired future state.

With its stated objectives, its audience, and its presentation, this Assessment is intended to stimulate creative thinking and future activity by instrument and methodology developers, decision makers, policy analysts, and inventory developers and users. As is noted in Chapters 2 and 7, significant advancement in emission-inventory science is anticipated during the coming years as a consequence of combined efforts of members of these communities. This Assessment is intended to serve as a first step in that direction.

References for Chapter 1

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CHAPTER 2. VISION FOR FUTURE NORTH AMERICAN EMISSION-INVENTORY PROGRAMS

Emission inventories were originally based on annual equivalent emission estimates and were developed to serve the relatively narrow purpose of identifying key sources for emission management. They were subsequently adapted to estimate rates of primary- and secondary-pollutant precursor emission fluxes for input into air-quality models. Initially, emission inventories were developed on the scale of individual cities or metropolitan areas, primarily to devise and evaluate emission-control based implementation plans designed to reduce criteria pollutant levels. However, as air-pollution issues of regional to semi-continental scale (acid rain, regional haze) and, eventually, global scale (stratospheric ozone depletion, climate change) were recognized, emission inventories covering increasingly larger spatial scales were created. A list of current uses for emission inventories is shown in Table 2.1.

Table 2.1. Emission Inventory Applications

Number	Emission Inventory Application
1	Implementation Plan or Control Strategy Development
2	Compliance Determination
3	Emission Offsets/Emission Banking Confirmation
4	Early Reduction Program Design
5	Emission Trends Analysis
6	Permit Limit Determination
7	Toxic Release Inventory Reporting
8	Information for Public
9	Excess Emission Reporting
10	Emission Statement/Fee Collection
11	Environmental Impact Modeling and Assessment
12	International Treaty Reporting
13	Ambient Pollutant and Emission Measurement Design

The atmospheric chemistry community now recognizes that pollution issues on all scales strongly influence each other, and that efforts to systematically understand and manage airborne pollution and its effects will require knowledge of emission fluxes over a wide range of spatial scales. In particular, the understanding that photochemical oxidant and fine particulate pollution can be significantly influenced by emission and transport on continental (or greater) scales motivates the vision for a high quality North American Emission Inventory with sufficient resolution to input into models that deal with pollution issues from neighborhood to hemispheric scales.

In addition to issues of spatial scale, future emission inventories will need to be both more current and better able to address problems requiring higher temporal resolution. Current emission inventories are often based on information that may be several years old. The increasing pace of technical change in the transportation, energy, manufacturing and other important emission sectors, as well as, the rapid population growth in some urban areas and the changing distribution of manufacturing activities in North America all combine to require frequently updated or dynamic emission inventories. Finally, new types of air-quality models and new uses for their output will, as discussed below, motivate emission inventories with both high spatial and temporal resolution.

While accurate emission inventories are necessary to understand and assess current air-quality and global-change issues, more importantly, they are critical to the design and evaluation of cost-effective control strategies to address these problems. A vision for future North American emission inventory activities must recognize and promote the tight coupling between accurate, comprehensive, and timely emission inventory data and effective pollution management strategies. The technical and societal motivations for improved North American emission inventories and a discussion of anticipated emission inventory requirements are presented in more detail in Section 2.2.

2.1 CURRENT EMISSION-INVENTORY STATUS AND PRACTICE: A BRIEF OVERVIEW

At the outset to this discussion of a desired future vision it is appropriate provide an initial setting by briefly summarizing conventional practice in emission-inventory preparation. Simply stated, an emission inventory is a collection of emission data from specified sources over a specified geographic area for a specified time period. Figure 2.1 is a flow chart showing an overview of the general process employed for compiling emission inventories in Canada, the United States, and Mexico. The boxes on the left of the chart list the information inputs for constructing emission inventories, while the center boxes indicate the procedural steps required for inventory construction, review, quality assurance, and completion. The right-hand side of the figure indicates some of the more important inventory applications. Ongoing tests, evaluations, and reviews of existing inventories are crucial for uncertainty identification and reduction.

In standard practice, emission rates associated with individual sources are derived using the following calculation:

$$\text{emission quantity} = \text{emission factor} \times \text{activity factor} \times \text{control factor} \qquad (2.1)$$

An *emission factor* is a representative value that relates the amount of pollutant emitted to the atmosphere to an activity associated with that source (e.g., pounds of NO_x emitted per ton of coal burned). An *activity factor* is a measure of the driving force for the operation that produces emissions (e.g., pounds of coal burned per month). The *control factor* is the fraction reduction in that source achieved by an add-on control device (e.g., from selective catalytic reduction) or process modification (e.g., installation of low-NO_x burners). In many cases, control factors are included within the emission factor.

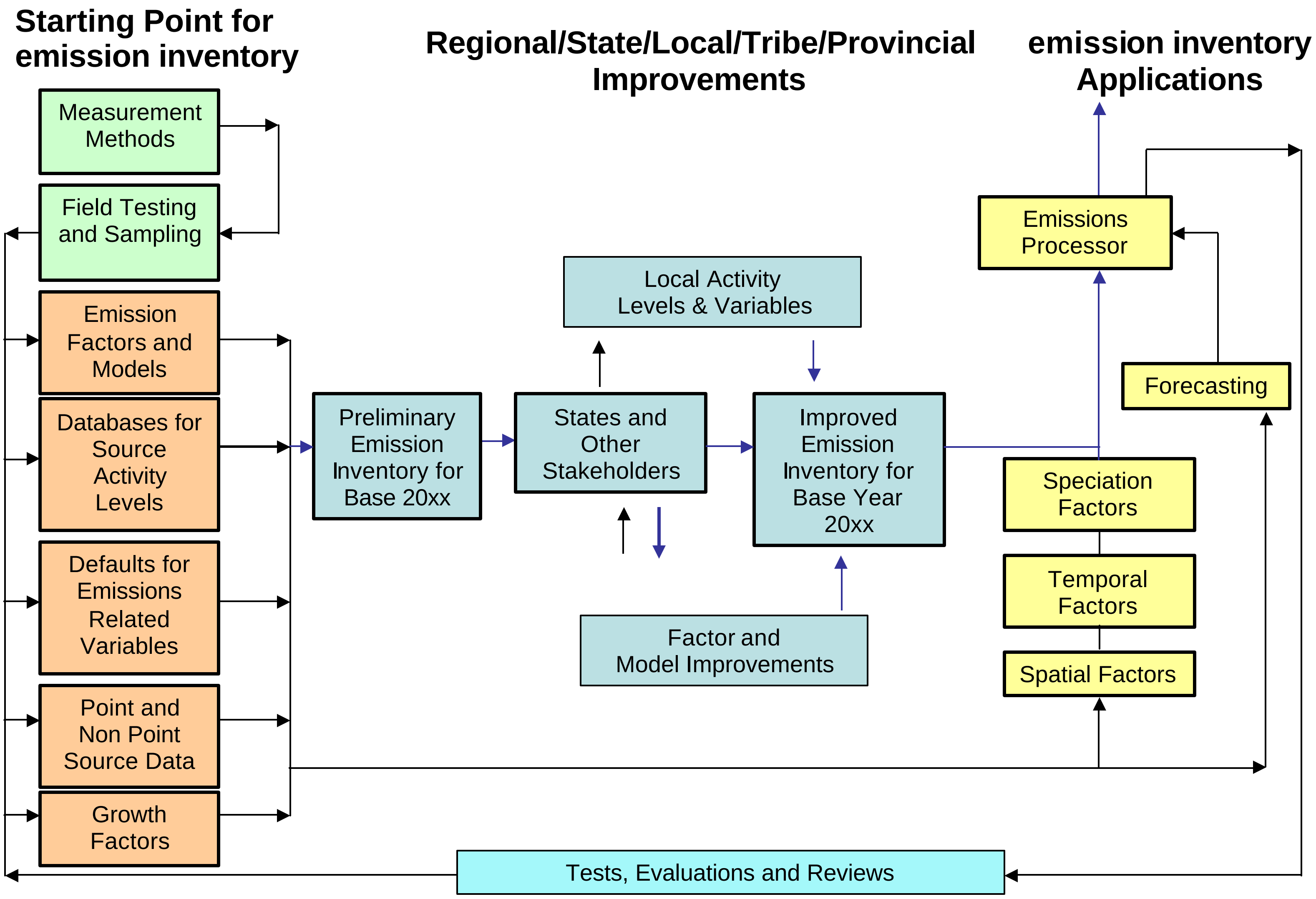

Figure 2.1 Emission-Inventory Development

Emission models are tools that apply equation (2.1) to area-source emitters such as onroad and offroad mobile sources to estimate emissions by geographic area. Models also are available to allocate emissions by time, location, and chemical or physical species. Current-year inventories for some source categories are estimated by applying growth factors to previous inventories to reflect up-to-date activity levels.

Emissions calculated or reported at the national level from the information sources on the left-hand side of Figure 2.1 are typically sent to state, provincial, tribal, or local agencies for review, updating, and insertion of locally generated data. After local improvements and updates are applied to the draft national inventory, a revised national inventory with the best information available is produced. After additional QA by the national agency, the inventory is released to the public. The new national inventory can be applied by policy makers, atmospheric and economic modelers, regulators, planners, for their respective needs. The applications on the right-hand side of Figure 2.1 illustrate how atmospheric modelers may apply temporal, spatial, and speciation allocation factors to the national inventory or a geographic subset to create appropriate inputs for detailed studies.

As discussed in Chapters 3 and 4, emission inventories and models are currently available for a variety of criteria and non-criteria pollutants, with various levels of temporal and spatial resolution. Acknowledged deficiencies in these inventories as well as emerging societal needs, however, provide a strong impetus for future improvement. Section 2.2 summarizes important motivations in this respect.

2.2 SOCIETAL DRIVERS FOR FUTURE NORTH AMERICAN EMISSION INVENTORIES

Both human activities and natural processes emit pollutants. Most pollutants emitted by human activities such as electric utilities, industrial plants, and automobiles can be controlled. Natural sources such as wildfires, and dust storms are not manageable. Human-made sources are generally characterized as point, nonpoint or area, and mobile. Point sources (power plants, chemical plants, incinerators, and industrial boilers) are emitters located at fixed geographical coordinates that are large enough to be enumerated individually. A large facility may have many individual point sources. Nonpoint or area sources, such as such as dry cleaners, wood stoves, and home furnaces, are groups of sources whose individual emissions taken singly are too small to be considered as lone emission points. Agricultural tilling, controlled burning, construction activities, and dust from mining also fall into this category. Some facilities such as refineries contain both point sources and nonpoint sources. The mobile-source category includes both on-road vehicle emissions and off-road sources such as construction equipment, farm tractors, airplanes, railroads, and ships. Natural emissions include forest fires, volcanic eruptions, lightning-caused emissions, emission of volatile compounds by trees, sea salt, and wind-blown dust.

All three North American countries have instituted major efforts to improve their air quality, particularly in urban and industrialized areas where criteria air pollutant standards are routinely exceeded. In the United States, the 1990 Clean Air Act Amendments (CAAA) prescribe that national ambient air quality standards (NAAQS) are to be set at levels to protect the public health with an adequate margin of safety. Accurate and timely emission inventories for criteria pollutants and their precursors are widely recognized as crucial to develop state implementation plans (SIPs) to achieve NAAQS compliance. In addition, in the U.S. the 1986 Emergency Planning and Community Right-to-Know Act (EPCRA) increased the demand for both criteria pollutant and hazardous air pollutant (HAP) emission data.

In Mexico, federal law establishes the framework for the development of specific NOMs, which specify maximum allowable limits for stack emissions due to combustion; point source emissions from specific industries (e.g., VOCs from automobile manufacturing, TSP and fugitive emissions from cement plants); and mobile source emissions (e.g., opacity of diesel exhaust, emissions from natural gas and other alternative fuel vehicles). These apply to all sources under federal jurisdiction and represent minimum criteria, although states may implement more stringent standards. All states including the Federal District have established local environmental protection and management agencies for air-pollution prevention and control. State environmental laws are also based on the Federal Law of 1996. Furthermore, some municipalities, mainly those having large industrial parks or extensive industrial development within their boundaries, have established additional regulations to control air pollution. Ambient air quality standards are established by the Secretariat of Health (SS). However, air-quality information is retrieved, stored and maintained by SEMARNAT, which receives information from the country's air-quality-monitoring networks. Local environmental authorities are responsible for setting up plans and programs, based on emission inventories and ambient pollutant concentrations from monitoring stations, to prevent population exposure to high pollutant concentrations.

As the range and scale of air quality and global environmental change issues evolve, the need for improved emission data escalates. Current problems forcing this trend are summarized below.

Photochemical Oxidants

As noted above, the range of problems attributed to airborne pollutants has grown steadily over the last fifty years. After the pioneering work of Haagen-Smit and co-workers identified photochemical production of oxidants, especially ozone, as the cause of air quality degradation and vegetation damage in the Los Angeles basin in the 1950s, our understanding of both the spatial scale and the undesirable effects of photochemical smog have expanded significantly. Motivated primarily by evidence of the detrimental impacts of airborne oxidants on human health, the Clean Air Act of 1970 initiated efforts to reduce ozone and related oxidants in major cities across the US. Similar efforts soon followed in Canada and Mexico (NARSTO, 2000). By the early 1990s the National Research Council (NRC, 1991) was able to demonstrate both that simple control of precursor anthropogenic volatile organic compounds (VOCs) would not be sufficient to control photochemical oxidant production in many areas and that long-range transport of photochemical oxidants and their precursors endowed the problem with a regional to semi-continental length scale (NRC, 1991). NARSTO's recent assessment of tropospheric ozone pollution in North America confirmed the regional nature of photochemical oxidant pollution episodes and raised the issue of a rising background level of ozone on the continental scale, motivating a continental perspective for the problem (NARSTO, 2000). Furthermore, increasing evidence of the detrimental human and ecosystem health impacts of ground-level ozone and related oxidants have resulted in a more stringent national ambient air quality standard (NAAQS) for ozone in the United States, a review of the Canadian air-quality standard for ozone, and an enhanced effort to enforce Mexico's ozone standard, particularly in the key Mexico City and Guadalajara metropolitan areas (Molina and Molina, 2004; NARSTO,2000, INE, 2003).

Airborne Particulate Matter

The detrimental health effects of urban airborne particles largely due to primary particle and secondary particle precursor emissions from home, commercial, industrial, and transportation combustion sources were recognized early in the twentieth century and were dramatically demonstrated by London's 1952 "killer fog" episode that resulted in over 4000 deaths. This concern has prompted the establishment of air quality standards for airborne particulate matter (PM) in all three North American countries. Mexico enacted standards for particles with aerodynamic diameters = 10 µm (PM_{10}) in 1993, and the proposal for a new standard to regulate $PM_{2.5}$ has been published for public comment in the Diario Oficial (a publication similar to the U.S. Federal Register) on October 2002, but has not yet been enacted. Canada regulates particulates with aerodynamic diameters = 2.5 µm ($PM_{2.5}$); while the United States originally established standards for total suspended particulates (TSP) and subsequently set both PM_{10} and $PM_{2.5}$ NAAQS values, recently tightening the $PM_{2.5}$ standard in response to epidemiological evidence that higher ambient airborne PM levels correlate strongly with premature deaths from both lung and cardiovascular diseases (NARSTO, 2004). The close tie between photochemical oxidant production and secondary fine particle formation through NO_x and VOC emissions has been recognized and discussed in previous NARSTO assessments (NARSTO, 2000; NARSTO, 2004). Secondary PM, which often dominates $PM_{2.5}$ loadings, is also dependent on SO_2 emissions.

Air Toxics

In addition to criteria air pollutants, the atmosphere in urban and industrial areas is often burdened with a range of hazardous substances that can be detrimental to both human health and ecosystem viability. Under the U.S. Clean Air Act, the EPA has established a program to characterize emission sources and ambient concentrations of a wide range of hazardous air pollutants (HAPs), currently recognizing 188 chemical species or species classes believed to be threats to human health (EPA, 2003). Particular attention is being paid to several compounds emitted by motor vehicles that are known or suspected human carcinogens, including benzene, formaldehyde, acetaldehyde, acrolein, and 1,3 butadiene. Emission reporting requirements are also being implemented in Mexico and will likely include selected air toxics. Future emission inventories will need to track emissions of the many organic HAPs out of direct concern for their health impacts, as well as for their role as precursor species for criteria air pollutants like O_3 and PM..

Regional Haze and Visibility

Both primary and secondary PM can contribute to the formation of persistent haze conditions that degrade visibility in both urban and rural locations. Degraded visibility is often thought of as an aesthetic problem that degrades the local quality of life by obscuring vistas and casting a pall on outdoor activities. However, it is also a safety issue since poor visibility can lead to airborne and ground transportation accidents. The National Research Council has reviewed the challenge of reducing haze levels that degrade the quality of U.S. national parks (NRC, 1993).

Regional Ecosystem Effects

Acid deposition (acid rain) was the first widely recognized regional scale ecosystem impact produced by urban and industrial emissions. The process is driven by atmospheric oxidation of NO_x and SO_2, emitted in combustion exhaust, to ambient HNO_3 and H_2SO_4. Problems arise when these acid gases and the secondary sulfate/nitrate PM they form are deposited downwind on poorly buffered surface waters or soils. A range of detrimental impacts on sensitive lakes, streams, forests and farmlands has been well documented (NAPAP, 1990).

A closely related problem involves fertilization effects caused by the deposition of airborne fixed nitrogen species (PM ammonium and nitrate and their gas-phase precursors) to buffered soils and fresh or marine surface waters that are not susceptible to acidification. Combined with fixed nitrogen and phosphorus from fertilizer, animal waste and human sewage sources, atmospheric deposition of fixed nitrogen can contribute to over fertilization of soils, lakes, streams, and estuaries leading to changes in primary productivity and, potentially, to eutrophication. Atmospheric nitrogen deposition can even have impacts on the open ocean, including the stimulation of phytoplankton blooms (Molina and Molina, 2004). More recently it has been documented that high levels of fixed nitrogen deposition can have significant effects on ecosystem diversity, even when deposition receptor areas are not heavily acidified (Stevens et al., 2004).

In addition, high regional emissions of fine primary PM and PM precursors may lead to high levels of ambient fine PM with absorption and scattering properties that significantly influence both the direct and diffuse components of photosynthetically active radiation (PAR) (Bergin et al., 2001; Cohan et al., 2002). It has been suggested that attenuation of PAR by both atmospheric PM and PM deposited on plant leaves may significantly impact solar radiation available for photosynthesis in important agricultural regions in China (Chameides et al., 1999). The impact of high PM on the viability of crops and natural ecosystems downwind of large North American cities may require future characterization.

Finally, as noted above, it has been recognized that as urbanization spreads photochemical oxidant production increasingly becomes a regional problem (NARSTO, 2000; NRC, 1991). Photochemically produced oxidants and their precursors flowing out of major cities frequently produce high levels of ozone and other oxidants all the way to the next major city, subjecting the intervening towns, forests, and agricultural areas to high oxidant exposures. Exposure to O_3 and related photochemical oxidants is known to damage both native and agricultural vegetation (NRC, 1991).

Regional Climate Change

The role of primary forcing greenhouse gases (CO_2, CH_4, N_2O, and long-lived halogenated gases like perfluorocarbons, chlorofluorocarbons, and SF_6) in driving climate change on a global scale is widely recognized and global scale emission inventories for these species are being actively pursued (IPCC, 2001). Less widely appreciated are the important roles of several largely secondary pollutants on climate change at a regional scale. These include tropospheric ozone, a very potent greenhouse gas over and downwind of large sources of precursor emissions. They also include fine particles, usually with diameters = 1 µm, which can often be transported over regional to hemispheric scales (Menon et al., 2002).

A review of the impacts of regional to continental impacts of PM pollution from megacities has documented several recent studies that demonstrate depression of sunshine duration and maximum daily surface temperatures in and downwind of major urbanized areas in China and India (Molina and Molina, 2004). Unfortunately, the uncertainties in both the regional atmospheric PM burdens, which depend on both meteorology and precursor emission levels, and the magnitude of both direct and indirect radiative effects for PM, which depend on their composition, combine to make quantitative evaluation of their climate forcing highly uncertain (IPCC 2001). Further, recent satellite and cloud modeling studies indicate that high atmospheric PM burdens can suppress downwind precipitation (Molina and Molina, 2004).

Characterizing the impacts of tropospheric ozone and PM on regional climate change in North America will likely require emission inventories for their precursor species defined over different spatial scales than those needed to assess ground-level health effects from these same species.

Air Quality Forecasts

The need to characterize and manage each of the air-quality-related issues described above will force disparate and challenging requirements on future emission-inventory activities. However, another emerging activity, the development of predictive air-quality forecasts for North American cities, may place even more demanding requirements on future emission inventories. Air-quality forecasting is currently the subject of significant research activity, including exploratory work under the auspices of the U.S. Weather Research Program (Dabberdt et al., 2004). Current or planned operational activities include the U.S. EPA's AIRNow program (www.epa.gov/airnow) that provides short-term, city-specific air quality forecasts and the U.S. National Weather Service (NWS) that is preparing to issue four day ozone and PM forecasts for selected cities in the near future. Air quality forecast capabilities are also being developed in Mexico. Such forecasts are generally motivated by public health concerns and are designed to provide warnings of unhealthful pollutant levels to sensitive sub-populations, as well as the general population, including those who spend much time outdoors for work or recreational activities and may need to be warned about potential exposures. However, there is also a substantial and growing demand for air-quality forecasts to inform institutional decision makers who must plan for air-quality-influenced demand changes or who might be asked to curtail emission-producing activities in an effort to manage air quality. Industrial and public sector organizations, including power generators, transportation companies, health care organizations, emergency responders, recreation facilities, and waste management companies all might be heavily impacted by poor air-quality episodes (Dabberdt et al., 2004). Reliable air-quality forecasts may provide a significant economic benefit to each of these sectors.

As air-quality forecast methods move from statistical evaluations to fully coupled, operational meteorological/atmospheric chemistry models, the demand for essentially real-time, highly spatially resolved emission inventories will grow. Just as the physical weather cannot be reliably predicted without current data on wind, water vapor, radiation and heat fluxes, the chemical weather will be hard to predict accurately without current, highly spatially and temporally resolved emission fluxes of key primary pollutants and secondary pollutant precursors. Since severe air-quality episodes are usually multi-day events with extreme pollution levels occurring after two to three days, their forecast will require both timely local and upwind regional emission data plus accurate long-range meteorological prediction capabilities.

2.3 SCALE REQUIREMENTS FOR FUTURE EMISSION INVENTORIES

Urban District Scales

As discussed above, each of the motivating air-quality-driven issues has intrinsic distance and time scales that drive associated emission inventory requirements. Characterization and management of human exposure to photochemical oxidants, PM, or air toxics may need to be refined to the urban neighborhood or district level. Air quality forecasts will be most useful when they can be prepared at the neighborhood/district level as well. It is widely recognized that even on a urban scale, differences in meteorology and emission patterns can cause very significant gradients of pollutant concentrations, just as meteorological and heat flux differences can produce dramatic temperature gradients within a given metropolitan area. The typical urban air-quality model computes chemistry within grid cells that are 4 to 5 km on a side; models with 1-km resolution are currently in use; and even finer scale models are under development. Emission data on a spatial scale larger than the grid scales used in the receiving model are inadequately resolved by definition. Urban-district-scale data is also necessary to estimate the impact of outdoor air pollutant concentrations on indoor air quality at the household and workplace scales. Indoor pollutant levels are influenced both by the intrusion of outdoor pollutants and indoor emissions. While indoor emissions are not considered in this Assessment, they can have a major impact on individual exposure to harmful air pollutants and are an active research topic that may require systematic evaluation and control in the future.

Metropolitan Area Scales

Rapid urbanization has forced the focus of urban air pollution to shift from individual municipalities to metropolitan areas. These areas can encompass high populations and very large areas. For instance, the Mexico City metropolitan area, with a population of 3 million in 1950 reached 18.7 million by 2003 and its urbanized area expanded from 118 to about 1500 km^2 from 1940 to 1995 (Molina and Molina, 2004). Large metropolitan areas like Mexico City, New York City, and Los Angeles typically expand over dozens of municipalities and may extend into several states.

Regional to Continental Scales

It is increasingly clear that the effects of degraded air quality are no longer restricted to areas in or near major cities. Photochemical oxidants and secondary fine PM produced in the plumes from major cities and industrial areas not only cross state/provincial borders but also routinely penetrate national boundaries. Extensive photochemical episodes as well as the pollution events caused by widespread wildfires are observed to impact large fractions of the North American continent. The motivation for addressing air quality issues on at least the continental scale is firm (NARSTO, 2000; NARSTO, 2004). This requires that North American emission inventories be rationalized and coordinated on the continental scale as well. A focus on coordinated emission inventories for the three North America countries is appropriate for most assessments of air quality and the effects of air pollution within the continent. However, a broader view of emissions is necessary as we consider transport phenomena in the northern hemisphere, where the lines between local, regional, continental, and global regimes are becoming increasingly blurred.

Intercontinental/Hemispheric Scales

Evidence for a systematic increase in background pollutants due to intercontinental transport is growing. Asian dust came to the fore shortly after the major event of April 1998 (Husar et al., 2001; Wilkening et al., 2000), which showed that dust from storms originating in the Gobi desert was transported over the Pacific Ocean and the North American coast, reaching as far inland as Minnesota. Average excess aerosol concentrations of 20-50 $\mu g\ m^{-3}$ were observed on the west coast of the U.S., with local excursions >100 $\mu g\ m^{-3}$. A similar dust event occurred in April 2001 and DeBell et al. (DeBell et al., 2004) observed elevated concentrations of dust from this event as far east as New England. Such events have the potential to cause violations of ambient air quality standards for particulate matter. Furthermore, Prospero and Lamb (Prospero and Lamb, 2003) have shown that African dust can be transported across the Atlantic Ocean on the trade winds to the Caribbean, Mexico, and the southern United States.

Several integrated observational and modeling studies (Jaffe et al., 1999; Berntsten et al., 1999; Yienger et al., 2000; Newell and Evans, 2000) have demonstrated the ability of Asian emissions of both aerosol particles and gaseous pollutants to cross the Pacific Ocean to North America. Similar analyses have shown transport across the Atlantic Ocean, demonstrating that North American emission inventories may be necessary to characterize European air quality, and from Europe to Asia (Lelieveld et al., 2002; Pochanart et al., 2004; Duncan and Bey, 2004). It is becoming clear that fine particles and long-lived gases are effectively involved in transport and chemical reactions entirely around the northern hemisphere (similar scale pollutant transport has also been observed in the southern hemisphere).

There is an increase of background ozone on a continental scale (NARSTO, 2000; Lin et al., 2000) with evidence that some of this increase may be due not just to North American emissions, but to Asian emissions transported across the Pacific ocean (Berntsen et al., 1999; Jacob et al., 1999). Jacob et al. (1999) showed that the effect of rising emissions in Asia could influence monthly mean ozone concentrations in the western United States by 2 to 6 ppbv for the April-June time period by 2010. This was asserted by the authors to "more than offset the benefits of 25% domestic reductions in anthropogenic emissions of NO_x and hydrocarbons in the western United States." It is broadly appreciated nowadays that increases in Asian emissions of NO_x and hydrocarbons can affect tropospheric ozone concentrations over a very wide area (Wild and Akimoto, 2001; Wild et al., 2004) and that increases in aerosol emissions can not only increase particulate concentrations in far-removed locations but also affect local radiative forcing and influence ozone chemistry (Martin et al., 2003).

Trace elements and persistent organic species also have the potential to travel for long distances. With an atmospheric lifetime of about one year, elemental mercury can certainly contribute to a hemispheric background that influences concentrations in North America. Seigneur et al. (2004) estimate that 20 to 30% of the mercury deposited in the United States is of Asian origin. This definitely will influence the benefits of a domestic mercury emission control program.

All of this evidence points in the same direction: North America is not an isolated "airshed." Rather, it is a collection of emitting sources situated in a background pool of air pollution, originating particularly in Asia, but more generally encircling the entire globe (Akimoto, 2003). When studies are undertaken of ambient air quality in North America, it may be important to take into account the contributions of sources outside North America, especially fine particles and long-lived gases, which may have significant episodic or seasonal contributions. To ignore such contributions may cause over-optimism regarding the provision of clean air to the people or the effectiveness of local emission control measures. Fiore et al. (2002) suggested that not only may future domestic attempts to reduce ozone concentrations in the US be thwarted by a rise in global background ozone, but also that control of global methane may be an effective way to reduce ozone concentrations in North America. Holloway et al. (2003) even suggested that we may be approaching a time when we need to consider regulating emissions and concentrations on a hemispheric scale, along the lines of the LRTAP Convention. At minimum, continental-scale models used in regulatory studies in North America should be embedded in global models to effectively account for these interactions, which in turn require the input of validated Asian, and eventually hemispheric or global, emission inventories.

Time Scales

As the requirements for emission data at finer spatial resolution grow they create the need for higher temporal resolution data to input urban and regional air quality exposure prediction, assessment, and/or forecast models. Air quality measurements in urban areas consistently show time-of-day profiles that are intimately linked to daily human activity patterns that can be difficult to characterize. For instance, mobile vehicle emissions have very significant temporal dynamics that tend to differ substantially for various parts of a metropolitan area. Neighborhoods containing major arterial roads will typically experience much higher rush hour emissions; with the morning emissions usually concentrated into a shorter time frame than the evening's. Some emissions will be worse, in both flux rate and duration, when accidents or weather stall traffic. Differences in weekday and weekend traffic patterns and vehicle mix may also lead to observable "weekend effects" in air quality (Marr et al., 2002). Further, holiday emissions, and the resulting ambient pollutant concentrations, often vary significantly from regular workdays. It is increasingly clear that a better understanding of the temporal distributions, as well as the spatial distributions, of emissions will be required both to assess the impact of proposed air quality management strategies and to provide reliable air quality forecasts. The goal should be the maintenance of a dynamic emission inventory whose value changes in response to actual activity factors and emissions.

At the other end of the temporal scale is the need to understand emission trends over decadal time scales. This information is required to understand the efficacy of control technologies and the evolution of air quality issues over the years, to evaluate our ability to model air quality over the years, and to understand North America's contribution to global emissions.

2.4 EMISSION INVENTORY CONTENT REQUIREMENTS

Expanded Gaseous Species Requirements

The fact that more chemically complete emission inventories are required to address the photochemical production of oxidants, including speciated VOC and NO_y measurements, has long been recognized (NRC, 1991). The growing recognition that secondary fine aerosol production drives $PM_{2.5}$ levels in many environments also places a priority on increased knowledge of gaseous VOC emissions, especially aromatic and biogenic compounds whose oxidation products are known to form semi-volatile species (NARSTO, 2004; NRC, 2004). In the U.S. this could be accomplished by improving the EPA's SPECIATE database and by increasing the number of related speciated VOC emission measurements. Better emission inventories for NH_3, SO_2, and NO_x will also be required to characterize secondary fine PM formation (NARSTO ,2004; NRC, 2004). The growing attention paid to air toxic ambient levels and related health effects will likely require better stationary and mobile source emission inventories for a variety of aromatic (e.g. benzene, toluene), carbonyl (formaldehyde, acetaldehyde, acrolein, etc.), olefinic (1,3 butadiene), and other priority air toxic compounds.

Expanded PM Requirements

The unsatisfactory state of current PM emission inventories has recently been highlighted by a National Research Council committee advising the U.S. EPA on PM health effects (NRC, 2004). Continued progress is required to better represent the full size distribution of primary PM emissions, including ultra fine (nanoparticle) emissions from mobile sources. An improved knowledge of primary particle composition as a function of particle size is also required. In particular, both the black and organic content of primary PM require characterization at the molecular level. The black carbon content of PM has become an important issue in determining the impact of PM on regional climate factors, including solar radiation absorbtion, cloud stability, and rainfall (Molina and Molina, 2004; Menon et al., 2002). Organic PM is known to dominate the secondary aerosol loadings in many urban areas and thus plays a key role in scattering solar radiation (IPCC, 2001).

Better Quantification of Emission Inventory Uncertainty Levels

Numerical values without well-defined error limits are basically unacceptable for any scientific purpose. Future emission inventories must be assembled with careful attention to measurement and activity factor uncertainties. Measured emissions should be evaluated to determine both statistical (measurement variability) and systematic (measurement error) uncertainties. A recent NRC report addressing PM research priorities calls for characterization of emission inventory uncertainties for both primary PM and secondary PM precursors (NRC, 2004).

Consistent and Harmonized Data

The multiple scales of current air-quality issues discussed in Section 2.3 show that emission inventories must be combined to characterize and manage problems that easily span state/provincial and national borders, and in some cases oceans. The combination of emission inventory data from different states and countries will not be possible unless their data collection and reporting practices are reasonably consistent. A harmonization of emission inventory data acquisition and reporting practice across North America and beyond will be necessary to deal effectively with many air-quality issues.

2.5 ISSUES AND RESPONSE STRATEGIES FOR DEVELOPING AND MAINTAINING ENHANCED NORTH AMERICAN EMISSION INVENTORIES

Recognizing Scientific and Professional Motivation Problems

Improving the completeness, accuracy and timeliness of North American emission inventories will require dedicated and talented technical professionals equipped with innovative measurement and modeling tools. Gathering emission and activity factor data and constructing emission inventories for air quality assessment and management have not traditionally been regarded as glamorous pursuits. Scientists, who mount successful field measurement campaigns, conduct clever laboratory experiments to characterize atmospheric pollution, or construct elaborate atmospheric models to explain current observations and predict future pollution levels and impacts are far more likely to have their efforts widely recognized. They win scientific awards, are elected fellows of learned societies, testify before Congressional committees, and are quoted in newspapers and magazines. No one has ever been elected to the U.S. National Academies of Science or Engineering primarily for their work on emission inventories.

However, there is a growing recognition that insufficient knowledge of emission quantities, chemical speciation, spatial distributions and temporal variations are seriously hampering progress in understanding and managing a wide range of air quality issues. As air quality models and measurements become more sophisticated and comprehensive inconsistencies due to inadequate knowledge of emissions become more frequent. Diagnostic and predictive air quality models cannot be expected to be accurate if they suffer GIGO (garbage in, garbage out) problems, and emission data are among the most critical inputs required for air quality models. For example, recent measurements in Mexico City (Arriga-Colina et al., 2004) show that the VOC/NO_x and CO/NO_x ratios calculated from the official 1998 emission inventory for that critical metropolitan area are low by a factor of 2.5 to 3; frustrating attempts of models based on the official emission inventory to reproduce observed photochemical oxidant levels. Recommendations for significantly improving Mexico City's emission inventory (Molina and Molina, 2002) are obviously well-founded and an effort to significantly improve them is now underway. Such problems are not limited to the newly developed Mexican inventories. Section 5.2 discusses similar inconsistencies in the U.S. NEI.

The prestige of performing emission measurements, gathering emission-related data, and developing emission inventories has risen recently, as the atmospheric scientists engaged in addressing global issues like stratospheric ozone depletion and greenhouse-gas-driven climate change recognized that a sustained, international effort was required to develop greatly improved emission inventories for the forcing species (IPCC, 2001; WMO, 2002). Further, the administration of international treaties addressing these issues (the Montreal Protocol, the Kyoto Protocol) is dependent on accurate emission inventories for ozone depleting and radiative forcing substances. Consequently, the creators of those high profile emission inventories are better supported and their contributions are recognized by publication in leading journals and inclusion in international assessments (IPCC, 2001; WMO, 2002).

In order for the vision of improved North American emission inventories for air quality presented in this volume to be realized high quality scientists and engineers must be recruited and supported to develop and utilize innovative and effective methods to improve and expand emission inventories. This will require enhanced and sustained support for emission inventory development and maintenance activities and increased respect for those performing emission inventory research and development.

Utilizing New Tools and Techniques

Part of the challenge of increasing the accuracy, coverage, resolution, and timeliness of North American emission inventories can be met by enlisting new technologies and using them to develop new strategies. Emission inventories are information, and the general advance in information technology is both rapid and profound. Revolutionary methods for acquiring data (real-time sensors, sensor networks, remote sensing), transmitting data (internet, cell phones, wireless networks), accessing data (massive electronic storage systems, search engines, relational data bases), and assessing data (expert systems, sensor fusion algorithms, pattern recognition, image analysis) are rapidly changing they way North Americans acquire and use information in their professional and personal lives. The convenience and power of evolving information technologies, broadly defined, must be harnessed to produce comprehensive and dynamic emission inventories to replace the more limited and static versions currently available. Chapter 4 of this report presents descriptions and discussions of a number of innovative measurement systems and strategies currently used in emission research activities that might be more widely utilized to produce enhanced emission inventories.

In addition, data-gathering systems currently being deployed for other purposes might be co-opted to produce higher spatial resolution and/or dynamic emission inventories. For instance, since vehicle emissions are a major source of both primary pollutants and secondary pollutant precursors, any high temporal and spatial resolution information on vehicle activity factors or vehicle emissions would be invaluable input for air-quality exposure or forecast models. In many North American metropolitan areas, a surprisingly large amount of traffic data is already being gathered each day. Nearly every major urban areas has a system of airborne (eye-in-the-sky) and/or roadside video cameras used to relay traffic reports to the commuting public and/or city transportation officials. Video systems are sometimes supplemented by pneumatic or magnetic vehicle counters deployed on key roads. The activity factors recorded by these systems could be routinely captured, their images/data analyzed and interpreted automatically to inform a dynamic emission inventory.

Similarly, Mexico City officials have recently deployed video cameras imaging over a hundred key traffic points in the Federal District. The main purpose of these surveillance cameras is to discourage police from inappropriately stopping vehicles to solicit bribes. However, a recent Mexico City air quality field measurement program is using data from these cameras to assess time resolved traffic intensity and vehicle mix needed to help interpret real-time ambient pollutant measurements near major roadways. There is no insurmountable technical barrier to capturing and processing this data in real-time on a daily basis.

There may even be opportunities to capture actual vehicle emission measurements. For instance, several US states are experimenting with the routine deployment of cross-road remote sensing systems to "clean screen" on-road vehicles in non-attainment regions. If the NO, CO, and VOC emissions of individual vehicles are shown to be acceptable in a specified number of sensor encounters, the license plate image is used to identify the vehicle's owner who is notified that they are excused for traditional exhaust inspection and maintenance (I&M) procedures for that year. Since each "clean screen" sensor is evaluating and recording the real-time exhaust emissions for thousands of vehicles per day, the data are available for emission inventory improvement. For instance, this data could be used to quickly recognize changes in on-road vehicle emissions due to a change in local fuel formulation or a variation in average vehicle speed caused by a change in road conditions or traffic patterns.

The increasing use and reliability of continuous emission monitors on major point sources also presents an opportunity to make emission inventories dynamic. The information on real-time stack emissions could be routinely transmitted to a dynamic emission inventory model that showed the variation in emissions as units are ramped or taken on- or offline in response to demand.

To develop more comprehensive, robust and dynamic emission inventories for North America alliances with other activities will be necessary. The wide interest and potential large investments in "smart" transportation systems creates an opportunity to ally with transportation professionals. Smart transportation systems rely on collecting a large amount of real-time data and adjusting system parameters in response to those data. In principle, emissions from the transportation system are one category of data that should be measured continuously and the minimization of those emissions should be one operational goal that drives system adjustments. Obviously realization of this goal would not only result in lower emissions, it would also provide continuous transportation systems emission data to inform a dynamic emission inventory.

The examples of strategies to obtain more robust and dynamic activity factor and/or emission data for future emission inventories noted above are suggestive, not comprehensive. They were selected to make the point that information technology will become ubiquitous as the 21st century progresses, and that efforts to construct and maintain better emission inventories will need to take maximum advantage of society's general thrust to gather more and timelier data in many spheres of activity.

Improved and Consistent Emission Models

Emission models for point, area, and mobile sources are becoming more sophisticated. Efforts to capture wider ranges of sources and better apportion emissions in time and space are bearing fruit. However, significant weaknesses in representing offroad and some onroad mobile sources, area sources, including landfills, sewage treatment complexes, airports and intensive agricultural operations, and many smaller commercial solvent and cooking fume sources need improvement. Also, source classes whose emissions are dominated by a small fraction of high emitters can be especially difficult to characterize.

In addition to traditional "bottom up" emission models, observation based models, including inverse and receptor models, deserve continued development and utilization (NARSTO, 2000). The use of models that can process ambient concentration measurements to evaluate the temporal and spatial distributions of emissions may be the only way that truly dynamic emission inventories can be developed. At the very least such models are a valuable constraint on and adjunct to traditional "bottom up" emission models.

Enhanced Data Integration and Access

Emission inventory data need to be easier to access in forms relevant for a variety of applications. For instance, there is a clear need to integrate emission data from multiple inventories in order to support public outreach, emission trends reporting, control strategy application studies, benefit analyses, and estimation of air quality in large regional areas. The overarching challenge in developing an integrated emission inventory is to integrate data that are distributed among many sources without requiring strict data format standards or introducing a new data repository to centrally store and maintain the data. The objective is to create a network of data and associated tools that is:

- Distributed. Data are shared but remain distributed and maintained by their original inventory organizations. The data are dynamically accessed from multiple sources through the internet rather than collecting all emission data in a single repository.
- Non-intrusive. The technologies needed to bring inventory nodes together in a distributed network need not be intrusive in the sense of requiring substantial modifications by the emission inventory organizations in order to participate.
- Transparent. From the emission inventory user's perspective, the distributed data should appear to originate from a single database to the end user. One point of access and one interface to multiple data sets are desired without required special software or download on the user's computer.
- Flexible/Extendable. An emission network should be designed with the ability to easily incorporate new data and tools from new nodes joining the network so that they can be integrated with existing data and tools.

The guiding principles of an integrated emission inventory follow those of distributed databases and distributed computing. New innovative information technologies and increasing collaboration among emission inventory organizations are leading to the creation of a network that shares data for easier access and integration while maintaining each individual inventory's existing system of data management. Spatial data should be available geographical information system (GIS) format that can display emissions from point, area, and mobile sources on a range of scales from neighborhood to hemispheric. Ideally, temporal data will be formatted so that spatially resolved movies of trends in temporal emissions can be visualized for appropriate time scales.

International Cooperation

The discussion presented in Section 2.2 confirms NARSTO's general operating premise that the scale of critical air-quality issues and their effects easily extends to continental dimensions. The development of comparable and coordinated emission inventories for the three nations of North America is clearly compelled by both scientific and public policy considerations. Further, as Section 2.2 clearly indicates, it is becoming apparent that oceans are ineffective barriers to air pollution, and that increasing emissions in Asia (and Africa) may contribute to the decline of air quality in North America. This suggests that there will be future requirements for each continent to construct and maintain comprehensive robust and dynamic emission inventories for exchange as well as internal use. Ideally, the international cooperation that has been necessary to develop accepted global emission inventories for substances that deplete stratospheric ozone (WMO, 2002) or drive global warming (IPCC, 2001) will be replicated to achieve this goal.

In North America, the environmental impacts of manufacturing and transportation activities will respond to changes stimulated by the North America Free Trade Agreement (NAFTA). Cooperative programs aimed at environmental improvement are supported by the Commission for Environmental Cooperation (CEC), which maintains an active air-quality program that includes efforts to encourage better emission reporting from all three North American countries. NARSTO reviews and assesses the status of photochemical oxidant and PM research in North America (NARSTO, 2000; NARSTO, 2004); and also coordinates important air-quality research projects. The establishment of an enhanced and integrated air quality emission inventory for North America could serve as model for the world.

Strategies for the Development of Emission Inventories

The achievement of the more comprehensive, timely, integrated, and effective emission inventories discussed above will require significant changes in the way emission inventory activities are motivated, organized, staffed, funded, and utilized. Some strategies that should help guide future emission inventory activities are outlined below.

Strategy 1 - Learn from other disciplines about how to revolutionize our approach to the creation of emission inventories.

Molecular biology is one of the most successful and fastest growing disciplines in modern science. Several factors have contributed to its phenomenal growth. Advances in instrumentation for sequencing nucleotides, new analytical techniques, the creation of publicly accessible data bases, software analysis tools, open access to data and international participation by multidisciplinary research teams. The new science of Genomics, the technology behind the Human Genome Project, has emerged from the systemization of how information is stored and how it is accessed. Several quite important lessons to be drawn from this landmark project (The Genome International Sequencing Consortium, 2001)include:

1. **Organizational structure:** A key success factor in the project was a clear mission statement, assignment of responsibilities, open and frequent communications, and engagement of the community as a whole.
2. **A multidisciplinary approach is needed:** Eric Lander, one of the key leaders of the Genome Project, is a mathematician. The research team involved engineers, computer scientists, biologists, biochemists, systems analysts, and web designers. Multiple perspectives can enliven both the science and suggest different ways of doing things.
3. **New instrumentation, computational algorithms and databases:** Continued investment and refinement of measurement instruments, analytical techniques, new computational algorithms and databases designed to cope with the explosive growth of information considerably accelerated the decoding of the human genome.
4. **Open access to information:** The project supported an unwritten contract that the data had to be readily accessible to both commercial and academic sectors around the world. Whole new scientific disciplines have emerged because of the standardization of access protocols to the sequence data.

5. **An integrated approach to measurement uncertainty:** Continuous monitoring of raw data quality and assignment of measurement uncertainties helped provide a formal framework for resource allocation.

6. **International collaboration:** The human genome is humanity's common heritage. The same is true for emissions. Trans-boundary pollution transport affects us all and should involve the international community. While NARSTO is focused in North America, the problem of creating emission inventories is of global importance

7. **Sufficient funding:** The early recognition of the scope and importance of the project resulted in significant increases of funding to execute the project. Underfunding, or no funding, is a guarantee of failure.

The parallels with what has to be done to improve urban, regional and global emission inventories are quite clear. The Human Genome project provides a good example of how to organize, execute and deliver relevant results in a timely manner. While it might be argued that some of the components are already in place to create better inventories what is patently obvious is lack of integration of the component parts. NARSTO could provide the organizational framework but it is extremely important to recognize that the execution of the project will require resources. What is needed is an imaginative proposal from the community of the same scale as the Genome Project, a proposal that articulates a clear vision of what needs to be done to create better emission inventories, a realistic assessment of the resource requirements and, most importantly, the benefits to all three North American nations.

Strategy 2 - Integrate emission inventories with the other databases needed to design cost-effective control strategies.

The imperative for better integrated and more cost effective pollution control strategies has long been recognized (Cass and McRae, 1981). Most current emission databases are not seamlessly integrated with other the information sources needed to design emission control strategies. For example, the task of detrending air quality data to isolate the effect of meteorological fluctuations and year-to-year growth in emission is made extremely cumbersome by the data architectures currently used by regulatory agencies. The problem is further compounded by the fact that the emission databases are also not typically integrated with geographically encoded land use and urban planning information systems. There has been an explosion in the use of Geographical Information Systems (GIS) by urban planning agencies but these advances have not as yet migrated into the systems used by air pollution agencies. Many different systems are used by local, state and national air pollution agencies – there are clearly many opportunities to both improve and standardize the approaches.

When designing the data architectures and reporting systems, developers must recognize that inventories serve multiple purposes. One of the reasons why there are no real incentives to improve the quality of the existing data is that the local agencies charged with the permitting process do not derive any real benefits from the current systems that are used to aggregate emissions for air quality modeling studies. Once the local data are aggregated to the state and regional levels, there is no feedback to the permitting officers. Open access to local emission information would provide incentives for both the public and industry to ensure that the information is correct.

It is also important to recognize that emission inventories should not only be adequate to allow the design of successful air-quality management strategies, but they must also provide timely and sustained information to evaluate how effective specific control strategies actually achieve desired emission reductions.

NARSTO should conduct a survey of the systems and databases currently in use by agencies across the country and then develop a plan for a more uniform nationwide systems architecture. The new architecture should make use of standard GIS encoding systems and relational databases that can be accessed by Structured Query Language (SQL) protocols. Open and uniform access to the data would a platform for the development of new tools and protocols for creating emission inventories. Again, the Genome project provides a useful starting point where the data volume and quality is expanding exponentially but many eyes are looking at the information. The open software movement responsible for the Linux operating system is another case in point.

Strategy 3 - Incorporation of cost of control information.

Currently state and local regulatory agencies are charged with the development of emission control programs to bring their regions into compliance with the pertinent ambient air-quality standards. At present, most emission inventory management systems have few if any links to cost of control information. Some exceptions exist (see for example AQMD [2003]), but even those do cannot be easily used for minimizing the cost of control needed to achieve a specified air quality levels. There is a critical need to couple source category information with data bases about Best Available Control Technology (BACT), emerging technologies, and current practices. In addition there is also a critical need to archive actual versus projected costs of control.

When new regulations are imposed, common complaints from those that are affected is that the controls are too expensive, the technology is untried, and the industries will become economically uncompetitive. The high estimates become critical issues in the political debate about which sources should be controlled and by how much. For example, when refinery heater controls were originally proposed in California, the industry response was that they would be far too expensive to implement. When oil embargoes were imposed, the refining industry focused on improving energy efficiency that in turn resulted in much lower NO_x emissions. NESCAUM has carried out a series of studies of the predicted and actual cost of air pollution control measures (NESCAUM, 1998; NESCAUM, 2000). NESCAUM documented that in some cases the control cost estimates made by both industry and the U.S. EPA were overestimated by a factor of 10:1 (NESCAUM, 2000).

In the northeastern United States, the Ozone Transport Commission (OTC) recommended that 12 states control emissions to reduce the NO_x emissions during the 5-month period from May 1st to September 30th that is often called the ozone season. The U.S. EPA extended the area and implemented regulations across 22 states. Since much of the cost of control is represented by the annualized investment in abatement technologies, the cost effectiveness of controlling emissions year-round would only represent a 5 to 10% increment. Year-round implementation of the controls would effectively double the emission reductions. Such a strategy would impact not only ozone but particulates as well. Without sustained efforts at documentation, it is hard to identify these win-win solutions.

Over time, such data would provide important counter points to the debate about which controls to implement in practice. In many regions the cost of controls needed to bring a region into compliance can be enormous. Without linkages to control cost and benefits data bases, it will be extremely difficult to design cost-effective abatement programs and help society make choices between the many competing demands for resources – health care, education, and security.

Strategy 4 - Research and technology development opportunities.

At present the construction of accurate emission inventories is viewed by the atmospheric science community as important but is often not recognized as a scientific priority. A sustained effort is needed to change this viewpoint. As noted above, new tools and techniques must be developed, deployed, evaluated, and refined before the challenge of more comprehensive and dynamic emission inventories can be realized. Many interesting and exciting research and technology development opportunities have been identified. Here are just a few:

- **Emission monitoring:** In a typical urban area there are literally hundreds of thousands of sources. In the past one of the ways to manage the complexity has been the development of emission factors by broad source categories. Development of very low cost emission sensors, wireless networks, and data assimilation techniques could dramatically change the ways in which emissions could be monitored and merged in inventories. The work underway at Cal(IT)^2 gives an inkling of what is possible (Cal-(IT)^2 2004).

- **Chemical Process Modeling:** There is a critical need for more research and modeling to improve the underlying methodologies used in the U.S. EPA's AP-42 series (AP-42, 2004). This work requires fundamental studies of the chemical conversion processes, combustion and pollutant removal technologies. There are many opportunities for technological innovation.

- **Transportation Modeling:** The emergence of instrumented highways and onboard sensors that can measure speed, location and emissions offer the potential to dramatically change the way in which mobile source emissions are generated. For example, work underway at the MIT Center for Transport and Logistics is using advanced surveillance systems to identify the early stages of a traffic bottleneck and then direct traffic to other routes to mitigate the congestion. This type of surveillance and guidance response can occur in real time and such capabilities could be extended to help develop mobile source inventories and verify the models of vehicle usage patterns.

- **Computational Algorithms:** There are numerous opportunities for the development of new mathematical algorithms for inverse modeling. In these approaches the key idea is to use air quality measurements and models of the underlying physical and chemical processes to estimate the emission fields. This information can be used to help improve both the air quality models and the emission inventories. As air-quality sensor networks become more prevalent, such approaches, that are all ready in use in oil field management, offer a way to verify current emission patterns. New algorithms for uncertainty analysis can also be used to identify which of the many sources are contributing to air quality

- **New Instrumentation Strategies:** Many stack-monitoring and vehicle-emission measurements are currently performed using old technologies that are plagued by interferences and that have limited chemical resolution. The emergence of laser based spectroscopic techniques and new tools for continuously monitoring the size and chemical composition of aerosols offer the potential to dramatically improve the accuracy of emission inventories. There are many opportunities for the development of new measurement methods.

The list is not meant to be exhaustive but to simply indicate that there are many opportunities. NARSTO should begin the process of identifying breakthrough technologies, evaluating their development costs, and demonstrating their value in the design of cost-effective control programs.

Strategy 5 - Human resource development.

A crucial ingredient in creating the next generation of emission inventories is people. An obvious question is where will they come from? Excellent researchers will be required to perform the fundamental research required for progress. Many students are passionately interested in the environment but the need fellowship support to contribute to improving environmental science, including emission inventory research and development. There is clear need to examine the human resource pipeline. NARSTO can and should play a critical role in publicizing this problem and making the recommendations to reverse current directions.

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2.6 EMISSION INVENTORY SPECIFICATIONS

With this view of the vast potential for improving data collection and improving the specificity, resolution, accuracy, and precision of emission inventories, we can posit goals for future inventories. While these goals are dependent on a significant increase in funding and all may not be attainable in the near future, they nevertheless provide targets for prioritizing and directing inventory improvement activities. Stated simply, this vision is to provide all emissions from all sources for all time periods in all areas and to make them accessible to all in a timely manner. From this vision comes the objective to make inventories complete, accurate, timely, transparent, and affordable. Table 2-2, which lists the categories and subcategories of inventory constituents and the desired content, reflects priorities and constraints for the next decade. These goals are meant to be illustrative, not prescriptive, and point to the direction in which emission inventories should aspire. Each country will have to address these elements and tailor them to its specific needs.

Table 2.2 Goals for Future Emission Inventories

Category	Subcategory	Goal
Pollutants	Criteria and speciated pollutants, and their precursors	SO_2, NO_x, size-differentiated PM, Pb, total VOCs, VOC reactive species, NH_3, elemental and organic carbon
	Toxics	188 listed HAPs plus persistent bioaccumulative and toxic chemicals (PBTs)
	Greenhouse gases and aerosols	CO_2, CH_4, N_2O, CO, black carbon, HFCs, PFCs, SF_6,
Source categories	Point sources	Focus on sources which contribute 80% of emissions of stationary source pollutants Process level detail (e.g. source classification code, fuel burned, fuel characteristics, boiler capacity, activity indicator, age, operating schedule) Name and location Stack data (latitude, longitude, height, diameter, flow) Control equipment (type, efficiency, age, and regulatory driver -- MACT, BART, NSPS state)
	Nonpoint sources	Source classification codes County level activity, Emission factors, controls, temporal factors Census tracts for localized assessments
	Mobile sources	Urban and county level VMT and fuel use, fleet characteristics, temperature, and non-road equipment populations
	Biogenic sources	County level species, daily meteorological data, emission factors, species profiles
Emission 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	Each year	Point sources reported by April 15 Base information for area and mobile sources and biogenic available by April 15 Area and mobile sources by July 1 Integrated emission inventory by September 30 Modeling processing by December 30

Table 2.2 Concluded

Category	Subcategory	Goal
Daily forecasting and recording		CEM data for the largest point sources Load forecast of the largest emitting sources. Mobile source indicators of events (major traffic events--accidents, ball games, etc) Area sources (Major upset events --i.e. fires, spills, accidental releases)
Future year predictions and forecasting		Reliable annual forecasts for 10 years Reliable five-year forecasts thereafter
Analysis of trends		Annual trends for criteria pollutant emissions Annual trends for greenhouse gases and aerosols Three-year trends for HAPs
Accessibility		Electronic reporting by sources and States. Web-based electronic access to data and exchange of information
Accuracy		Avoid missing sources and double entry of sources Avoid sources in wrong location Avoid sources with supersonic flows or inadequate flow for emission measurements Avoid missing data on key parameters Avoid data entry errors Uncertainty indicators for all data elements and composites Evaluation criteria with complementary measurements (e.g., tunnel studies, aircraft studies source region studies)
Affordability		Software for effective data entry, data computation, data exchange, quality control, and quality assurance Optimize intensive manpower and time consuming steps Affordable emission factor characterization – keep step with technology changes
Transparency		Documentation Transportable Reproducibility
National and International Exchange		US, States, Tribes, localities and RPOs Canada, Provinces, and localities Mexico, States, and localities Europe Asia

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CHAPTER 3. NORTH AMERICAN EMISSION INVENTORIES

This chapter provides a guide to North American emission inventories at the continental, national, state, provincial, and local levels. Where available, links are provided to the individual inventories. For more specific questions regarding inventories, the reader is urged to go directly to the inventory's homepage (if available). Strengths and limitations of individual inventories are not discussed in this chapter. Chapter 5 describes accuracy, precision, and uncertainties of inventories and their components and Chapter 6 presents new technologies for improving inventories.

Emission inventories were originally developed in the 1960s at metropolitan-area scales as inputs for air-quality models and for siting ambient monitors. Over the next several decades, inventories evolved to include hazardous air pollutants and other non-criteria pollutants. Spatial coverage has increased to encompass states, regions, countries, continents, and the entire globe. At the same time, the increased sophistication of air-quality models has increased the demand for finer spatial, temporal, and species resolution of emissions.

The first attempt by the U.S. EPA to produce highly quality assured national inventory for use by policy makers, modelers, human and ecological effects researchers, and industry was the 1985 NAPAP Emission Inventory (Saeger et al., 1989). This inventory built on the pioneering work by the California Air Resources Board (CARB) in Los Angeles and California in the 1970s and the Sulfate Regional Experiment (SURE) funded by the Electric Power Research Institute (EPRI) in the late 1970s (http://src.com/~epriasdc/uapsp/uapsp.htm) The process for compiling this inventory involved receiving National Emission Data System (NEDS) submittals for point sources from states, conducting computerized quality assurance (QA) checks of the data, sending flagged data back to the states for review, and calculating nonpoint source emissions using EPA models. Biogenic emissions of VOCs were also included in a national inventory for the first time. To provide emission inventories to support atmospheric and deposition modeling using the Regional Acid Deposition Model (RADM) and the Regional Oxidant Model (ROM), NAPAP developed spatial, temporal, and chemical species allocations factors for the United States and Canada. County level emissions from non-point sources were allocated spatially into 1/4^o longitude by 1/6^o latitude (approximately 20 x 20 km) grid cells using 14 surrogate indicators (e.g., population, housing, land-use, arboreal 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 VOC s were organized into a set of 32 categories. The 1985 NAPAP inventory, completed in 1989 became the U.S. "gold standard" and the progenitor for future emission inventories.

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 the same. This chapter lists the most current national and regional inventories constructed for the United States, Mexico, and Canada and representative metropolitan, local, and specialized inventories, along with the purpose, pollutants included, and directions for locating the inventory. The larger inventories and some regional, state, provincial, local, and specialized inventories are described in more detail in the text. In the last several years the importance of carbonaceous aerosols to global radiative forcing has been stressed in a number of important papers and commentaries. In response, a detailed discussion on carbonaceous aerosols is presented in Appendix B.

3.1 NATIONAL EMISSION INVENTORIES

National emission inventories are designed to provide information on a country's emissions. The United States, Canada, and Mexico all prepare national emission inventories. These emission inventories are extensive and require the compilation of so much information that they are generally not performed annually. The inventories tend to lag two or more years behind present. This section provides information on the U.S., Canadian, and Mexican national emission inventories.

3.1.1 U.S. National Emission Inventory (NEI)

The NEI is U.S. EPA's national inventory. It can be accessed at: http://www.epa.gov/ttn/chief/net/2002nei_plan_121903draft.pdf. The NEI includes annual emissions for all 50 states and their counties, the District of Columbia, Puerto Rico, the Virgin Islands, and tribal lands (there is as yet no mechanism for including nonpoint and mobile data from tribal lands into NEI). The NEI is prepared by the Emission Factor and Inventory Group (EFIG) of EPA's Office of Air Quality Planning and Standards (OAQPS). The inventory 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.

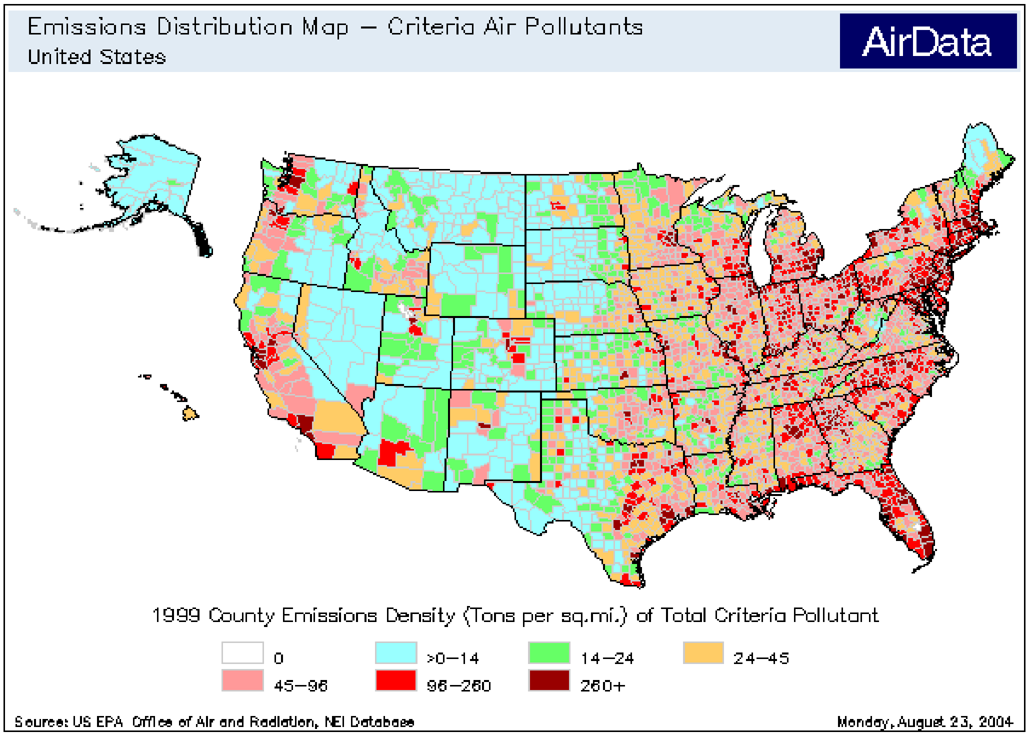
The inventory includes data on all criteria pollutants, including ozone and $PM_{2.5}$ precursors (NO_x, SO_2, VOCs, CO, primary PM_{10}, filterable PM_{10}, primary $PM_{2.5}$, filterable $PM_{2.5}$, and NH_3) and all 188 HAPS including individual HAPS reported for compound groups listed in the Clean Air Act (CAA). The NEI is organized into four main groupings of source categories: point sources [divided into Electric Generating Units (EGUs) and non-EGUs]; nonpoint (area) sources; onroad mobile sources; and nonroad mobile sources. Biogenic emissions are not included in the NEI. The sources for the data in NEI are summarized in Table 3.1. A map showing emission density based on NEI data is presented in Figure 3.1.

Because the NEI is so large, there is no mechanism for downloading the entire inventory. Data for individual states can be downloaded at http://www.epa.gov/ttn/chief/net/index.html#dwnld in Microsoft Access, version 97. Data summaries can be found at http://www.epa.gov/air/data/index.html. The sites currently have the 1999 NEI data posted. The 2002 NEI is scheduled to be completed and posted in December 2005. Additional information can be obtained from the 2002 NEI Coordinator, EFIG/OAQPS/EPA, in Research Triangle Park, NC.

Table 3.1. Sources for U.S. NEI Data

Source Type	Pollutants	Data Source
EGU	NO_x, SO_2	EPA/CAMD/ETS CEMS data
EGU	Hg	EPA/OAQPS model
EGU	Other criteria and HAPs	DOE/EIA 767 data and AP-42
Non-EGU Point Sources	Criteria	State, local, and tribal submittals supplemented by EPA/OAQPS
Non-EGU Point Sources	HAPs	State, local, and tribal submittals, EPA/OAQPS, industry, EPA/TRI database
Non-EGU Point Sources	NH_3	EPA/TRI database
Nonpoint Stationary Sources	Criteria and HAPs	State, local, and tribal submittals supplemented by EPA/OAQPS
Onroad Mobile Sources	Criteria and HAPs	State, local, and tribal submittals, OTAG, FHWA, Mobile6 model
Nonroad Mobile Sources	Criteria and HAPs	State, local, and tribal submittals ; OTAG, Nonroad model

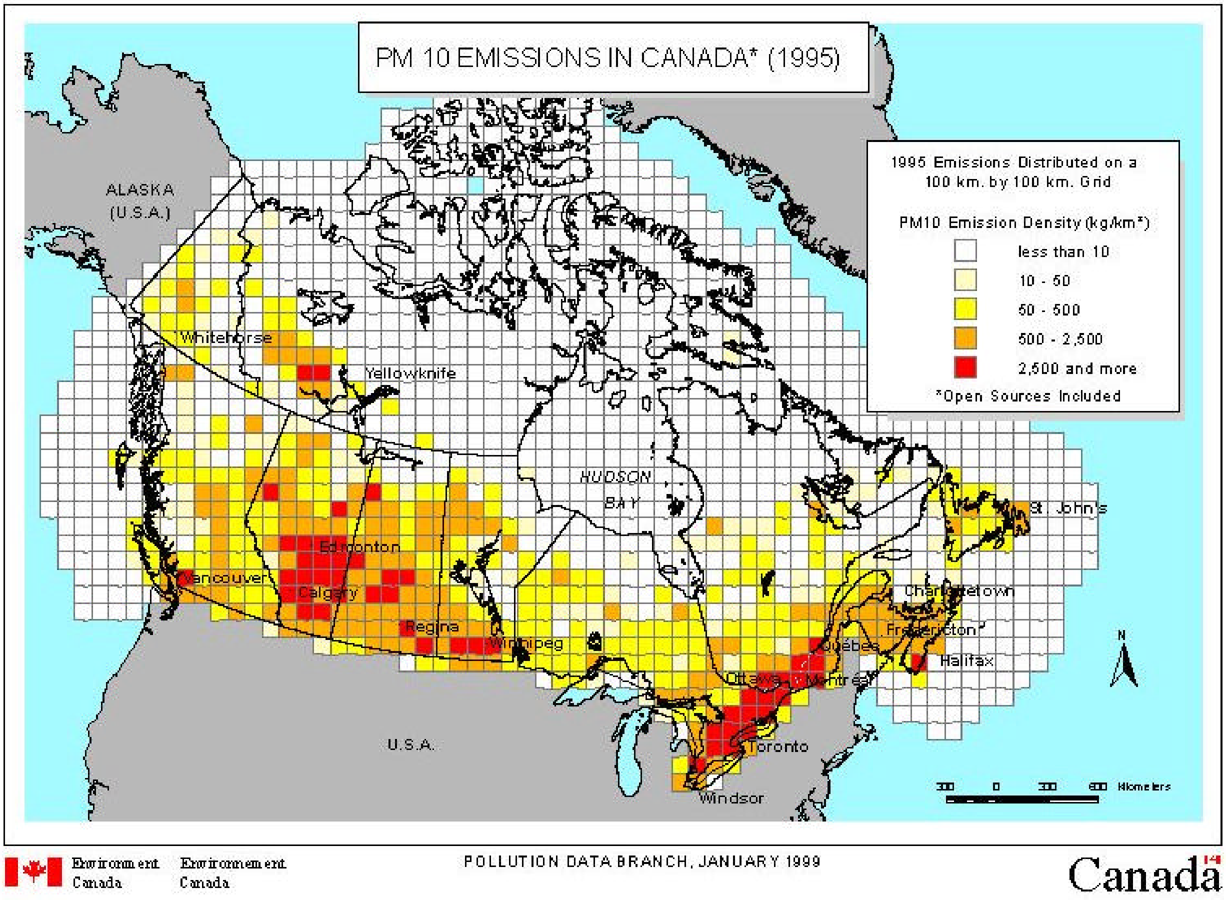
Figure 3.1. Criteria Pollutant Emission Density MAP from NEI Database



3.1.2 Canadian National Emission Inventories for Criteria Air Contaminants

Environment Canada compiles national emission inventories for Criteria Air Contaminants (CAC) on an annual basis. The emission inventories are compiled by the Pollution Data Branch and provide a breakdown of the emissions for all 10 provinces and the 3 territories (http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm). More detailed emission summaries are also available on-line for major urban centers and communities using an on-line mapping application and queries on the Environment Canada web site http://gis.ec.gc.ca/npri/root/main/map.asp#skipNav). The emission inventories include NO_x, SO_2, VOC, CO, TPM, PM_{10}, $PM_{2.5}$, and NH_3. These comprehensive emission inventories include multiple emission sources categorized as industrial sources, non-industrial fuel combustion (which includes electric power generation), transportation, incineration, miscellaneous, and open sources. Biogenic emissions are also captured in these emission inventories but are reported separately. Figure 3.2 provides an emission density map that is based on Canada's CAC inventory.

Figure 3.2. 1995 PM10 Emission Density Map for Canada



The CAC emissions from industrial and commercial facilities are collected annually through Environment Canada's pollutant release and transfer register called the National Pollutant Release Inventory (NPRI). The NPRI is legislated under the Canadian Environmental Protection Act to collect information on releases into the air, water, and land for more than 323 substances. Canadian facilities that meet the reporting requirements of the NPRI are required to report their releases to Environment Canada by June 1st of the following year. The information collected through the NPRI is supplemented with information compiled for smaller industrial and commercial facilities to ensure that all releases from these sources are captured in the national emission inventories. The compilation of the annual emission inventories and additional activities to improve the estimates are lead by Environment Canada and performed in collaboration with the environmental agencies located in the provinces, territories, and specific regions of Canada. These activities are coordinated through the Emissions and Projections Working Group (EPWG), which include emission inventory practitioners representing the federal/provincial/regional ministries of the environment and energy.

The National Emission Inventories are compiled to track the progress of current emission reduction programs and initiatives, and evaluate the needs for adjustments. They are also compiled to support the scientific assessment of the air pollution problems and fulfill the reporting requirements of various domestic and international protocols and agreements such as: the Canada-Wide Standards for PM and Ozone, the Canada-Wide Acid Rain Strategy, the United-Nations Economic Commission for Europe Long-Range Transboundary Air Pollution protocols, and the Canada-U.S. Air Quality Agreement.

The Canadian National Emission Inventories are compiled with estimation techniques that are similar and comparable to the ones compiled in the United States for the NEI. This comparability of the inventories between the two countries is essential due to the joint analyses, the joint air quality modeling, and the joint reporting that are required as part of the Canada-U.S. Air Quality Agreement.

Currently the most comprehensive emission inventory available for air-quality modeling and data analysis is for the calendar year 2000. A comprehensive emission inventory for the calendar year 2002 is currently being compiled. A draft version of this emission inventory will be available near the end of 2004, and the data files should be available for air quality modeling and data analysis during the summer of 2005.

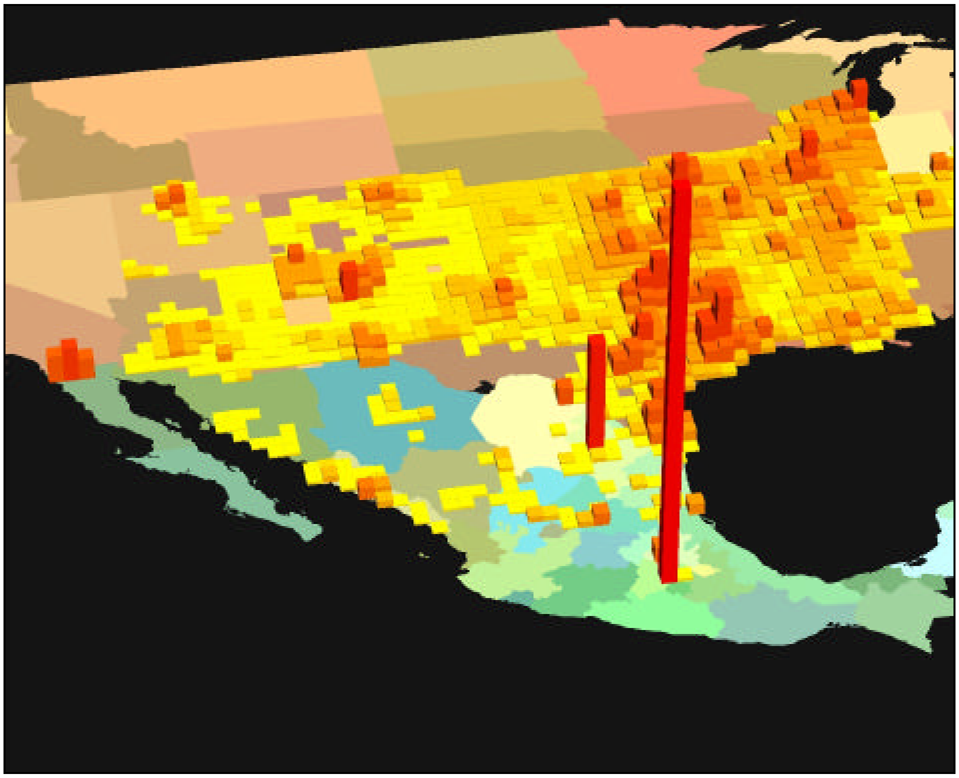
Additional information on the Canadian emission inventories for Criteria Air Contaminants can be obtained from the Criteria Air Contaminants Division of the Pollution Data Branch, located in Gatineau, Quebec, Canada (cac@ec.gc.ca).

3.1.3 Mexican National Emission Inventory (NEI)

Subsequent to the early efforts by the Grand Canyon Visibility Transport Commission (GCVTC) and the Western Governors Association (WGA) to build emission inventory capacity in Mexico, a project to develop the first comprehensive national emission inventory for Mexico began in 2000. The Mexico NEI has financial and technical support of the WGA, EPA, the North

American Commission for Environmental Cooperation (CEC), and Mexico's *Secretaría de Medio Ambiente y Recursos Naturales* (SEMARNAT, Secretariat of the Environmental and Natural Resources) and *Instituto Nacional de Ecología* (INE, National Institute of Ecology). Representatives from these partners, along with other stakeholders from government, academia, and private sector entities on both sides of the U.S.-Mexican border, participate in the Technical Advisory Committee (TAC) and provide technical guidance for the Mexico NEI. Mexico's organizational structure for air pollution analysis and inventory compilation is described in Box 3.1. Figure 3.3 provides map of emissions for Mexico based on the BRAVO inventory (which is discussed later in this chapter).

Figure 3.3. Gridded PM_{10} emissions for the BRAVO EI base year 1999. Each grid cell is 0.5 degrees by 0.5 degrees (Kuhns et al., 2001). *Reproduced with permission from DRI.*



Title VI of the *Ley General del Equilibrio Ecológico y la Protección al Ambiente* (General Law of Ecological Balance and Environmental Protection) establishes the regulatory framework for Mexico's air quality program. INE, as the research entity within SEMARNAT, is the lead agency for the development of the Mexico NEI. Maintaining and updating the Mexico NEI is the responsibility of SEMARNATs *Subsecretaría de Gestión para la Protección Ambiental* (Under-Secretariat of Environmental Management).

The objectives of the Mexico NEI include: (1) development of the first National Emission Inventory for Mexico to help institutional efforts in the areas of air quality and health impacts, (2) compliance with the Mexican Federal Environment Law mandate to integrate and update a National Emission Inventory for Mexico, and (3) promotion of institutional capacity-building to compile, maintain, and update emission inventories. Mexico's NEI will also serve to support CEC efforts in the development of a regional emission inventory and will be a valuable input to regional haze compliance in border U.S. states.

The geographic domain of the Mexico NEI is the entire country of Mexico. Emissions are estimated at the municipality level. The base year is 1999, and the pollutants include the air pollutants and pollutant precursors for which Mexico has air-quality standards: NO_2, SO_2, VOC, CO, PM_{10}, $PM_{2.5}$, and NH_3. The source types include all sources of air pollution: point, nonpoint, onroad mobile, nonroad mobile, and natural sources.

SEMARNAT has offices (*Delegaciones*) located in each of the 31 states plus the Federal District. These offices have responsibility for implementing the emission inventory program on a state level with assistance from the Under-Secretariat of Environmental Management and the individual state and municipal environmental agencies. For example, SEMARNAT *delegaciones* receive, compile, and transfer Annual Operating Reports (Cédula de Operación Annual – COA) from federal jurisdiction facilities to SEMARNAT's Under-Secretariat of Environmental Management for inclusion in the national point source emissions database. Data on mobile sources for emission estimation is collected from local authorities, responsible for enforcing federal Normas Oficiales Mexicanas (NOMs) on mobile source emissions at the local level (i.e. they are responsible for establishing inspection/maintenance programs to check compliance of mobile sources registered within their jurisdiction). Area sources pose a special challenge for compiling emissions data, since there is no uniform method for defining "point" and "area" sources of air pollution in Mexico and the Federal Environmental Law does not provide the level of specificity needed for identifying sources under state and municipal jurisdictions, nor does it differentiate between "large" and "small" polluters. Hence, data for these sources are gathered from other authorities (i.e. the Energy Secretariat, PEMEX, the Transport Secretariat) or from individual trade associations. Table 3.2 summarizes the sources for the data used to develop the Mexico NEI.

Table 3.2. Sources for Mexico NEI Data

Source Type	Pollutant(s)[a]	Data Source(s)
EGU	Criteria plus $PM_{2.5}$	SENER
Refineries and Bulk Terminals	Criteria plus $PM_{2.5}$	PEMEX
Non-EGU/Refineries/Bulk Terminal Point Sources	Criteria plus $PM_{2.5}$	Federal and state COAs, DATGEN
Paved and Unpaved Roads	PM_{10}, $PM_{2.5}$	Satellite imagery, orthographic photography
Area Source Fuel Combustion	Criteria	National Fuels Balance
Area Sources (Excluding Paved/Unpaved Roads, Fuel Combustion)	Criteria plus $PM_{2.5}$ and NH_3	Various government agencies, trade associations, academic institutions (e.g., SAGARPA, INEGI, ANAFAPYT, UNAM)

Table 3.2 Concluded

Source Type	Pollutant(s)[a]	Data Source(s)
On-road Motor Vehicles	Criteria plus $PM_{2.5}$ and NH_3	Per capita VKT estimates; MOBILE6-Mexico model
Nonroad Mobile Sources	Criteria plus $PM_{2.5}$	SAGARPA, INEGI, PEMEX; OTAQ's NONROAD2002 model (modified)
Natural Sources	NO_x, VOC	SMN, NCDC, UNAM, SAGARPA; GloBEIS3 model

Notes:
ANAFAPYT: *Asociacíon Nacional de Fabricantes de Pinturas y Tintas* (National Association of Paint and Dye Manufacturers)
COAs: *Cédulas de Operación I* (Annual Operating Reports)
DATGEN: *Datos Generales* (Emissions inventories for areas with air quality plans)
GloBEIS: Global Biosphere Emission and Interactions System, Version 3.1
INEGI: *Instituto Nacional de Estadística, Geografía e Informática* (National Institute of Statistics, Geography, and Computing)
NCDC: U.S. National Climatic Data Center
PEMEX: *Petróleos Mexicanos* (Mexican National Petroleum Company)
SAGARPA: *Secretaría de Agricultura, Gandería, Desarrollo Rural, Pesca y Alimentación* (Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food)
SENER: *Secretaría de Energía* (Secretariat of Energy)
SMN: *Servicio Meterológico Nacional* (Mexican National Weather Service)
UNAM: *Universidad Nacional Autónoma de México* (National Autonomous University of Mexico)

The Mexico NEI has been completed for the six northern states. The national inventory is scheduled for completion in late 2004, and will include municipality-level emissions for 1999 for the entire country (i.e., 32 states and 2,443 municipalities). Currently, the inventory report is available on a password-protected website (http://www.erg.com/mnei); however, in the future, the inventory will be available on INE's website (http://www.ine.gob/mx/), and the US EPA's website (http://www.epa.gov/ttn/chief/net/mexico.html).

The emissions data (i.e., emission factors and activity data) for point, nonpoint, and nonroad mobile sources were assigned confidence ratings according to the approach shown in Table 3.3. The confidence ratings will be used to identify the priorities for future improvements to the inventory.

Table 3.3 Confidence Rating Approach for Mexico NEI

Rating		**Activity Data**	**Emission Factor**
A	High	Based on comprehensive Mexico-specific data	Based on comprehensive Mexico-specific data
B	Medium	Based on limited/extrapolated Mexico-specific data	Based on limited Mexico-specific data

Table 3.3 Concluded

Rating		Activity Data	Emission Factor
C	Low	Based on expert judgment	Based on expert judgment
D	Preliminary Estimate	Based on extrapolated U.S. data	Based on U.S. factors
E	Not Quantifiable	Insufficient data	No emission factors exist

3.2 GREENHOUSE GAS AND CARBONACEOUS AEROSOL EMISSION INVENTORIES

Studies of global climate change are dependent on accurate emissions inventories of human-produced species. For many years inventories focused solely on gaseous species. Over the last several years the importance of carbonaceous aerosols to global radiative forcing has been recognized. Because of the importance of greenhouse gases (GHGs) and carbonaceous aerosols, to climate change research and policy analyses, this section describes current inventories for both GHGs and aerosols in North America. Global and regional emissions inventories have been prepared under United Nations guidance by various international bodies and individual countries to support research on global climate and transboundary air pollution issues. Box 4.1 describes several of these inventories.

3.2.1 Greenhouse Gases

The United States, Canada, and Mexico each have prepared greenhouse gas (GHG) emission inventories. These emission inventories are central to any study of climate change and attempt to quantify each country's primary anthropogenic sources and sinks of greenhouse gases. What follows is a brief discussion of each country's GHG emission inventory.

3.2.1.1 U.S. Greenhouse Gas Inventory

The United States prepared GHG inventories for the years 1990-2000. These inventories adhered to a common and consistent mechanism that enables signatory countries to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission source and greenhouse gases to climate change. The greenhouse gases accounted for in the U.S. inventory include: CO_2, CH_4, N_2O , HFCs, PFCs, and SF_6. The GHG emission inventory contains information on the emissions of GHGs and on GHG sinks. Emissions are generally reported in terragrams of CO_2 equivalent for all pollutants. Figure 3.4 provides a representation of U.S. GHG emissions by gas.

In 2002, stationary and mobile fossil fuel combustion accounted for 97% of CO_2 emissions. Landfills, enteric fermentation, natural gas systems, and coal mining accounted for over 80% of CH_4 emissions. Over 80% of N_2O emissions were produced by agriculture and mobile sources. Substitution of ozone-depleting substances, HCFC-22 production, and electrical transmission and distribution accounted for more than 90% of the emissions of HFCs, PFCs and SF_6.

Information on the U.S. GHG inventories can be obtained at: http://www.epa.gov/globalwarming/.

Box 3.2 GLOBAL AND REGIONAL EMISSION INVENTORIES

Global Emission Inventory Activity (GEIA)

GEIA was created in 1990 to develop and distribute global emission inventories of gases and aerosols emitted into the atmosphere from natural and anthropogenic (human-caused) sources. The activity was initially documented as *Graedel et al.* [1993], and is maintained at the website: http://www.geiacenter.org/. The emission data sets can be downloaded in gridded form at 1º × 1º spatial resolution. The goal of GEIA is to assemble data for the year 1990; and emissions are presented at annual, seasonal, or monthly temporal resolution. GEIA accepts emission and related data bases provided they have undergone substantial peer review as reflected by acceptance for journal publication and agreement among the various GEIA project teams. Because the data sets are developed by different research teams, there is no consistency of methodology across species. Among the major species presently available in GEIA are NH_3, BC, CO_2, CO, CFCs, HFCs, PFCs, SF_6, Pb, Hg, CH_4, N_2O, NO, NO_x, SO_2, and VOC. GEIA has proved valuable to atmospheric scientists by providing uniformly presented inventories to drive computer models of the atmosphere. Support to field measurements and regulatory and policy development have also been provided. Data management and communication are coordinated by the GEIA Center in Boulder, Colorado, which is supported by the National Science Foundation.

Emission Database for Global Atmospheric Research (EDGAR)

EDGAR is a compilation of global emissions of direct and indirect greenhouse gases from anthropogenic sources on a country basis as well as on a 1º × 1º grid. The EDGAR database was developed jointly by the National Institute of Public Health and the Environment (RIVM) in the Netherlands and the Netherlands Organization for Applied Scientific Research (TNO), in cooperation with GEIA. The initial Version 2.0 of the database [*Olivier et al*, 1996] for the year 1990 has been used extensively in atmospheric modeling and other studies, but is now obsolete and replaced by Version 3.2 [*Olivier and Berdowski*, 2001], see http://arch.rivm.nl/env/int/coredata/edgar/. EDGAR Version 3.2 comprises an update of the 1990 emissions and new emission estimates for 1995. Unlike GEIA, emissions of all species are calculated in an internally consistent way from the same activity levels. Still under development, Version 3.2 of the database presently (May 2004) contains emissions for CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CO, NO_x, NMVOC, and SO_2. An historical inventory of global anthropogenic emissions from 1890-1990 at 10-year time steps, based on the EDGAR present-day emissions, is also available in gridded form and by world region [*van Aardenne et al.*, 2001].

Canadian Global Emission Interpretation Centre (CGEIC)

CGEIC was established by Environment Canada and Canadian ORTECH Environmental to provide emission inventories for a variety of modeling activities of concern to Canada. Persistent Organic Pollutants (POPs) and heavy metals were of special concern due to their ability to accumulate in areas of Canada extending to the Canadian High Arctic. CGEIC was also closely coordinated with GEIA. Gridded global inventories were established on the organization's website, http://www.ortech.ca/cgeic, which is no longer maintained. Inventories of SO_x, NO_x, Pb, hexachlorocyclohexane, and Hg are posted, but these have largely been adopted or superseded by more recent GEIA inventories.

Official Greenhouse Gas Inventories

Compilations of national emissions of greenhouse gases are being assembled as part of the implementation of the Kyoto Protocol. In accordance with the UN Framework Convention on Climate Change (UNFCCC), parties to the Convention submit national greenhouse gas inventories to the secretariat. These inventories have been compiled in an on-line searchable database for Annex I and non-Annex I parties (http://ghg.unfccc.int/). The site contains summary tables and an on-line database of emission estimates for the six main direct greenhouse gases: CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6, as well as for the indirect species CO, NO_x, NMVOC, and SO_2. These data are in general available for the period 1990-2000. The emission estimates are presented in accordance with the source categories of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (see below). Many important countries of the developing world, such as China and India, are not included in this database.

The IPCC established a Task Force on National Greenhouse Gas Inventories (TFI) in 1998 to oversee the IPCC National Greenhouse Gas Inventories Programme (IPCC-NGGIP). A technical support unit was set up at the Institute for Global Environmental Strategies (IGES) in Japan to run the IPCC-NGGIP. The purpose of this activity is to establish an internationally-agreed methodology for the calculation and reporting of national greenhouse-gas inventories and to encourage the use of this methodology by countries participating in the IPCC and by signatories of the UNFCCC. One product of the IPCC-NGGIP is a database on greenhouse-gas emission factors (EFDB), accessible at http://www.ipcc-nggip.iges.or.jp/EFDB/main.php. EFDB contains emission factor information from IPCC guidelines and from CORINAIR (see below). The IPCC Guidelines for National Greenhouse Gas Inventories, first published in 1995 and revised in 1997, contain recommended data and methodologies for calculating greenhouse-gas emissions from a wide variety of source types (http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm).

Regional Inventories

Regional Inventories: Europe

The United Nations Economic Commission for Europe (UNECE) sponsors a Task Force on Emission Inventories and Projections (TFEIP) to support a variety of emission activities and atmospheric modeling in Europe (http://tfeip-secretariat.org/unece.htm). There is an important inventory component of the task force's areas of responsibility. The United Nations Economic Commission for Europe/Co-operative programme for monitoring and evaluation of long range transmission of air pollutants in Europe (UNECE/EMEP) has established an emission database to support dispersion modeling and other analytical activities. The latest version of this database is WebDab 2003, available at http://webdab.emep.int. WebDab 2003 contains emissions by sector of the main pollutants (CO, NH_3, NMVOC, NO_x, and SO_x), nine heavy metals, 26 POPs, and size-differentiated particulate matter ($PM_{2.5}$, PM_{10}, coarse PM, and TSP). The database contains two kinds of data: national emission data submitted to the UNECE Secretariat to the LRTAP Convention and so-called "expert emissions," made to complete and/or correct the officially reported data for the purpose of creating uniform gridded emissions for the entire EMEP geographical area. Data are for a variety of years between 1970 and 2020. The greenhouse gases CO_2 and CH_4 were not historically included in WebDab, but after 2002 such estimates were developed and harmonized with the IPCC emission database. The two major citations for the Webdab data and methodology are *Vestreng* [2003] and *Vestreng and Klein* [2002].

The TFEIP has also recently taken over management of the EMEP/CORINAIR Atmospheric Emission Inventory Guidebook, published by the European Environment Agency [*EEA*, 2004]. The most recent version (3rd Edition, September 2003) is available at http://reports.eea.eu.int/EMEPCORINAIR4/en. This report is a detailed compendium of information on emission factors and related information organized by the SNAP nomenclature, similar to the U.S. EPA's AP-42. It is intended to support reporting under the UNECE Convention on Long-Range Transboundary Air Pollution and the EU directive on national emission ceilings.

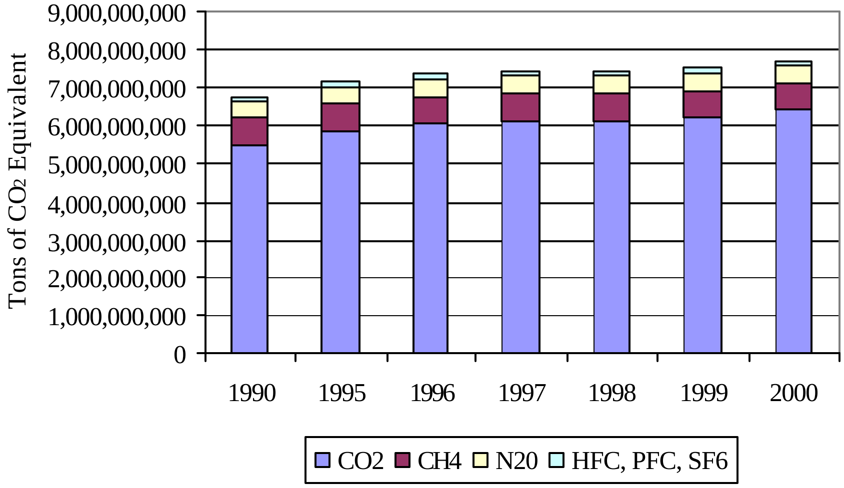
Regional Inventories: Asia

Regional inventories for Asia were first compiled in the early 1990s for use in atmospheric modeling and long-range transport studies [*Kato and Akimoto*, 1992; *Akimoto and Narita*, 1994]. Though these initial inventories were developed primarily for research purposes, they were widely used in Asian modeling studies. The Center for Global Environmental Research (CGER) at Japan's National Institute for Environmental Studies maintains an emission inventory of SO_2 and NO_x emissions for China, India, and Korea for 1990 and 1995 in gridded form (http://www-cger.nies.go.jp). To support the NASA TRACE-P and NSF/NOAA ACE-Asia field campaigns, *Streets et al.* [2003] developed an emission inventory for the year 2000 for all of Asia for the species SO_2, NO_x, CO_2, CO, CH_4, NMVOC, BC, OC, and NH_3. In addition, the NMVOC were speciated into 19 different classifications of organic compounds on the basis of reactivity and functional groups. The gridded and summary emissions contained in this inventory can be downloaded from http://www.cgrer.uiowa.edu/EMISSION_DATA/index_16.htm. Development agencies are trying to assist the less-developed countries of Asia in developing their own national inventories and assembling them into regional inventories. For example, the Regional Air Pollution in Developing Countries (RAPIDC) program, sponsored by the Swedish International Development Co-operation Agency (Sida) is helping the countries of South Asia develop national emission inventories using a standard methodology (see http://www.rapidc.org).

Regional Inventories: Africa and Latin America

In these two regions of the world there have been no systematic attempts to develop regional emission inventories, and indeed many countries in the regions lack reliable inventories of their own. The RAPIDC program funds APINA, the Air Pollution Information Network—Africa, one activity of which is to work toward a comprehensive regional emission inventory for southern Africa from both man-made and natural (wildfire) sources (http://www.york.ac.uk/inst/sei/rapidc2/apina/apina.html. In Latin America, inventory development has thus far focused on the air pollution problems of the major polluted cities of the region, such as Buenos Aires, Rio de Janeiro, Sao Paulo, and Santiago. The World Bank's Clean Air Initiative, for example, is helping to develop emission estimates, primarily for transportation, in the major cities of Latin America (http://www.worldbank.org/wbi/cleanair/). On both continents, more work is urgently needed to better understand national emissions and their contributions to regional and global air pollution problems through the development of reliable inventories.

Figure 3.4. U.S. GHG Emissions



3.2.1.2 Canada's Greenhouse Gas Emission Inventory

To support Canada's National Implementation Strategy on Climate Change, and Canada's commitments under the UNFCCC, national emission inventories on sources and sinks for GHG are compiled on an annual basis.

Canada has published greenhouse gas emission inventories for the past 11 years using the UNFCCC guidelines. This progression of GHG emission inventories is used to track Canada's progress towards reducing emissions to 6 percent below 1990 levels over the period of 2008 to 2012. The Canadian GHG emission inventory reports include analyses of the emission trends, factors affecting the trends, and detailed descriptions of the methods, models, and procedures used to develop and verify the data. The report documents emissions of the following pollutants:

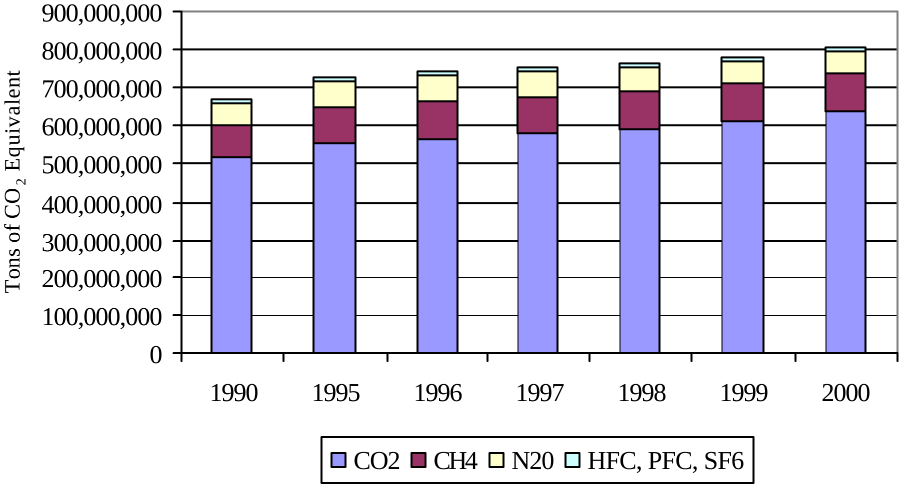
- CO_2
- CH_24
- N_2O
- SF_6
- PFCs
- HFCs.

The inventory uses an internationally agreed-upon reporting format that groups emissions into six sectors:

- Energy
- Industrial processes
- Solvent and other product use
- Agriculture
- Land-use change and forestry
- Waste.

More information on this emission inventory is available on the internet at: http://www.ec.gc.ca/pdb/ghg. Figure 3.5 provides a graphical representation of Canada's GHG emissions over the decade from 1990-2000.

Figure 3.5. Canadian GHG Emissions



3.2.1.3 Mexico's Greenhouse Gas Emission Inventory

A preliminary national GHG emission inventory for Mexico was developed by sector for the year 1990 with the first IPCC methodologies. This inventory was reported in the First National Communication to the UNFCCC in 1997. In 1998, Mexico signed the Kyoto Protocol, and subsequently in July 2001, the inventory was updated for years 1994, 1996, and 1998 and reported in the country's Second National Communication to the UNFCCC. Both of these National Communications are available at INE's website at http://www.ine.gob.mx/dgicurg/cclimatico/comnal.html and full reports are available at http://www.ine.gob.mx/dgicurg/cclimatico/inventario.html. The following agencies have supported the compilation of the National Greenhouse Gases Emission Inventory: the U.S. Country Studies Program, the U.S. EPA, the Global Environmental Facility by UNDP and the United Nations Environment Programme.

Only the 1996 inventory includes updated estimations for the land use change (LULUC) category. In terms of CO_2 equivalents of CO_2, CH_4, and N_2O emissions, the 1996 inventory totaled 691,318 gigagrams (Gg), and the contributions by sector (based on CO_2 equivalents) were:

- Fuel production and consumption = 31.7%
- Transportation = 14.5%
- Fugitive emissions = 7.2%
- Industrial processes = 6.2%

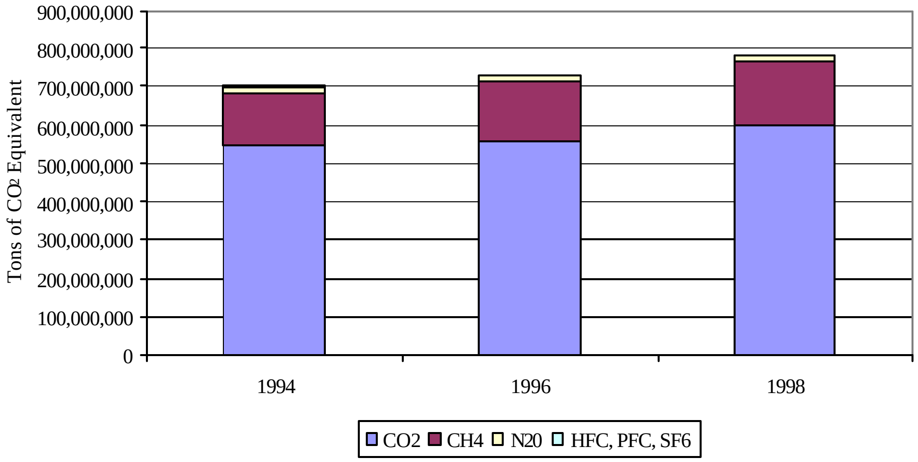
- Agriculture including livestock = 8.1%
- Forestry sector (i.e., LULUC) = 23.4%
- Waste management = 8.9 %.

The most significant changes in emissions during these years included an increase in fugitive emissions of 26% (from 1990 to 1998) and an increase in waste management (CO_2 equivalent) emissions from 526 Gg to 2,155 Gg; the latter change was attributed to a change to the IPCCC 1996 methodology and that some sectors were incorporated in this last inventory update. In the case of waste management, the change is attributed to the greater control of solid waste by new regulations that came into force.

A system was developed to store the GHG emission data for 1999 with the aim to systematize the national inventories and to make the results accessible to the general public through the web page at http://www.ine.gob.mx/dgicurg/cclimatico/inventario/intro.html. Figure 3.6 provides a snapshot of Mexico's GHG emissions in 2000.

INE's *Dirección General de Investigación sobre la Contaminación Urbana, Regional y Global* (DGICURG, General Directorate of Urban, Regional, and Global Air Pollution Research) coordinates a team of experts from academia and other government agencies and is responsible for compiling and updating Mexico's greenhouse gas inventory in compliance with its commitment to the Kyoto Protocol and UNFCCC reporting requirements. DGICURG has updated the greenhouse gas inventory to 2001 for the transportation and fugitive emission sectors, and is currently updating the agricultural sector (Personal communication between Paula Fields, ERG and Julia Martinez, INE/DGICURG, Directorate of Climate Change, May 25, 2004).

Figure 3.6. Year 2000 Mexico GHG Emissions



3.2.2 Carbonaceous Aerosols

Carbonaceous aerosols consist of fine particles, mostly less than 1 micrometer (µm) in diameter, which are usually classified as either black carbon (BC) or organic carbon (OC), in which the carbon is bonded to other elements. Because of the importance of carbonaceous aerosols to radiative forcing (Hansen et al. 2000; Hansen and Sato 2001; Andreae 2001; Penner et al. 2001; Jacobson 2001, 2002; Chameides and Bergin 2002), the impetus for developing aerosol emissions inventory has been the regional and global modeling community.

Worldwide it is estimated (Chameides and Bergin 2002) that uncontrolled burning of coal is a major source of BC emissions, with China and India contributing 25% of global BC emissions. Although both the magnitude and emissions factors for of BC emissions are highly uncertain, Streets et al. (2001) developed emissions factors for various combustion source types. While the emissions factors vary depending on operating conditions in different types of combustors, they estimated that the residential burning of coal in a traditional stove has a BC emission factor of 3.7 g kg^{-1}. In contrast, the BC emission factor for a large coal-fired boiler using an electrostatic precipitator is only about 0.0001 g kg^{-1}. Emissions are low because the very high temperatures and efficient mixing of air and fuel in large boilers readily oxidize any fine carbon particles leaving the combustion zone; it is primarily mineral matter that escapes and is captured in the particulate control device or passes through into the atmosphere.

BC emissions from fossil-fuel combustion and other anthropogenic activities in the United States are in the range of 300-400 Gg C yr^{-1}. Table 3.4 presents US emissions from the two recent inventories by emitting sector. The estimates are similar in total magnitude, but some significant differences are found at sub-sector level. One difference is believed to arise from different classifications of industrial nonroad diesel equipment. But worthy of further investigation are differences for on-road diesel vehicles, aircraft, and residential fuel combustion. A review and reconciliation of emission factors for the component source types would likely resolve the differences. A detailed discussion of the sources, magnitude, and uncertainties of global emissions of carbonaceous aerosols is provided in Appendix B.

Table 3.4. BC Emissions by Sector and Source Type

Source Type	BC Emissions (Gg C yr^{-1})	
	Bond et al. [2004]	Battye and Boyer [2002]
Transportation	***231***	***246***
Non-road diesel	33[a]	91[a]
On-road diesel	101	65
Non-road gasoline	0	20
Aircraft	47	17
On-road gasoline	25	16
Marine	10	16
Diesel locomotives	0	11
Miscellaneous fuel combustion	14	10
Open Burning	***61***	***116***
Stationary Fuel Combustion	***140***	***36***
Residential	79	22
Utility, industrial, commercial	61[a]	14[a]
Industrial Process, incineration	***9***	***9***
Fugitive Dust	n/a	***24***
Livestock	n/a	***5***
Total	***441***	***433***

Notes:
[a] Classification differences regarding industrial diesel nonroad equipment.

3.3 REGIONAL EMISSION INVENTORIES

3.3.1 U.S. RPOs

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 base year emission inventories to support development of future year inventories, air quality modeling, control strategy analyses, and implementation plan development. Initially, work focused on improving data for the 1996 or 1999 base year. However, for planning purposes, the final inventories will be prepared for the 2002 base year. For the most part, these inventories are for the criteria pollutants and their precursors, including ammonia. The 2002 inventories cover all geographic areas at the county or sub-county level for each sector. The inventories will also be used to support air planning activities for the ozone and fine PM National Ambient Air Quality Standards.

The RPOs focus on collecting the best temporally and spatially resolved activity data available from their member state, local, and tribal (S/L/T) agencies. They also focus on improving emission estimation methods and supporting data for categories determined to be significant contributors to visibility impairment and/or ozone and fine PM pollution, or for which previous emission estimates have a high degree of uncertainty. For mobile sources, this work has included populating EPA's MOBILE6.x and NONROAD models with county-or state-specific data (e.g., local VMT and temperature data, nonroad equipment populations). For stationary nonpoint sources, work has focused on improving emission estimates and the spatial and temporal distribution of emissions for subsectors that are important within each RPO (e.g., livestock waste, agricultural burning, wildfires, and residential wood combustion). The S/L/T agencies generally survey stationary point sources to obtain inventory data. Thus, inventory work has centered on quality assurance of the point source data (e.g., reviewing emission rates, operating schedules, stack parameters, geographic coordinates).

This section contains information on the individual RPOs and emission inventories that they have prepared. Summary data on individual emission inventories, as well as contact information for the various RPOs are presented in Table 3.5. Figure 3.7 provides a map depicting the geographical locales of all RPOs within the United States.

VISTAS

VISTAS developed 2002 emission inventories for mobile sources (including onroad and nonroad sectors) and stationary sources (both point and area). Much of the work to date has involved supplementing the 1999 NEI with local data (onroad and nonroad) and growing it to 2002. Point source emissions from the 1999 NEIv2 were quality assured and the inventory was checked for new and retired facilities. County-level ammonia emission estimates were developed using the Carnegie Mellon University (CMU) model. Data on 2002 fires were obtained from federal and state agencies. Work has also been conducted to improve spatial and temporal allocation of emissions. In addition to the 2002 base year inventory, VISTAS is developing a 2015 projection year inventory. VISTAS makes information regarding its emission inventories and other work available at: http://www.vistas-sesarm.org.

Figure 3.7. Map of U.S. RPOs

CENRAP

Similar to other RPOs, CENRAP's 2002 emission inventory efforts have involved supplementing the NEI with data supplied by state and local agencies. CENRAP has sponsored work on improving agricultural and prescribed burning and agricultural ammonia emissions. Work is ongoing to develop better activity data for nonroad and onroad sources, as well as agricultural dust. CENRAP also plans to sponsor work to improve point and area inventories for sources that are lacking data. Note that some of the emission inventory work sponsored by the WRAP below has included the states in the CENRAP region. CENRAP plans to have a comprehensive inventory for the region by October 2004. Information on CENRAP's activities and emission inventories is available at: http://www.cenrap.org.

MANE-VU

Inventory work conducted by MANE-VU includes the ongoing development of a regional mobile source inventory for 2002 for onroad and nonroad sources. For area sources, 2002 inventories of criteria and hazardous air pollutants were developed for open burning (residential solid waste, brush and leaf burning, land-clearing debris) and residential wood burning. Inventories of 2002 NH_3 emissions were developed for publicly owned treatment works, composting, cement plants, and industrial refrigeration. Ongoing work includes the development of a 2002 modeling inventory, which will include point source QA/QC and incorporation of CEM data, area source temporal and spatial allocation methods, and development of methods to incorporate fire emissions for the RPO and southeastern Canada. Information regarding MANE-VUs activities and emission inventories can be accessed at: http://www.marama.org/visibility/ and http://www.manevu.org/.

WRAP

WRAP has developed 1996 base year inventories for all sectors. The mobile source inventory contains criteria pollutant emission estimates for onroad sources (including paved road dust), as well as nonroad sources. Special studies have been conducted to estimate emissions for wind-blown dust, wildfires and prescribed burns, agricultural burning, unpaved roads, and NH_3. Both point and area source emissions cover the WRAP domain as well as the CENRAP domain (22 western states). The 1996 point source inventory (based on the 1996 National Emission Trends inventory) has been revised following a QA/QC project. The 1996 area source inventory was also revised based on input from state and local agencies. In addition to the 1996 inventory, WRAP has developed a 2018 projection year inventory. Information on WRAP and emission inventories that it has prepared are available at: http://www.wrapair.org/.

Midwest RPO

MRPO has developed gridded 2002 modeling inventories for use in regional haze and fine PM modeling. The “Base E” inventory includes all source sectors and covers the continental United States and southern Canada. MRPO has sponsored work to improve spatial and temporal allocation of several source sectors, including utility boilers and nonroad engines. Currently, work is ongoing in the development of a regional model to estimate process-based ammonia emissions from confined animal feeding operations. Work is also ongoing to develop a 2002 emission inventory for wildfires and prescribed burns. Information on the MRPO is available at: http://www.ladco.org/. Detailed project information is available at: http://www.ladco.org/mrpo.html.

Table 3.5. Listing of RPO Emission Inventories

Name	**Internet Location**	**Sponsor**	**Pollutants**	**Geographic Coverage**	**Spatial Resolution**	**Temporal Resolution**
MANE-VU RWC	http://marama.org/visibility/	MANE-VU MARAMA	Criteria and HAP from Residential Wood Combustion (indoor and outdoor equipment)	MANE-VU RPO	County level (based on census tract level estimates)	Annual averages, monthly, weekly, and daily profiles
MANE-VU Mobile Sources	http://marama.org/visibility/	MANE-VU MARAMA	Criteria Pollutants from Onroad and Nonroad Sources	MANE-VU RPO	County-level	Annual averages, monthly, weekly, and daily profiles
MANE-VU Open Burning	http://marama.org/visibility/	MANE-VU MARAMA	Criteria and HAP from Open Burning (Residential waste burning, yard waste burning, land clearing debris burning)	MANE-VU RPO	County level (based on census tract level estimates)	Annual averages, monthly, weekly, and daily profiles
MANE-VU Misc. Ammonia	http://marama.org/visibility/	MANE-VU MARAMA	Ammonia from cement plants, industrial refrigeration, POTWs, composting.	MANE-VU RPO	County level (POTWs, cement plants, based on point level data)	Annual averages
VISTAS Mobile Sources	http://www.vistas-sesarm .org/documents/index.asp	VISTAS	Criteria Pollutants for onroad and nonroad sources	VISTAS RPO	County-level	Annual averages, monthly, weekly, and daily profiles
VISTAS Point and Area	http://www.vistas-sesarm.org/ documents/index.asp	VISTAS	Criteria Pollutants for point and area sources	VISTAS RPO	County-level	Annual averages, monthly, weekly, and daily profiles

Table 3.5. Listing of RPO Emission Inventories (concluded)

Name	Internet Location	Sponsor	Pollutants	Geographic Coverage	Spatial Resolution	Temporal Resolution
Midwest RPO	http://www.ladco.org/ tech/emis/BaseE/BaseE_Reports.htm	MRPO	Criteria Pollutants ("Base E" inventory includes all sectors)	U.S. National and southern Canada	36-km grid (national) 12-km (regional)	Hourly
Midwest RPO	http://www.ladco.org/mrpo.html	MRPO	Criteria Pollutants (ongoing projects for nonroad sources, ammonia from livestock, wildfires)	Midwest RPO	County-level	Annual averages, monthly, weekly, and daily profiles
CENRAP	http://www.cenrap.org/	CENRAP	Criteria Pollutants (ongoing projects for Ag & prescribed burning, mobile sources, agricultural dust, and ammonia)	CENRAP RPO	County-level	Annual averages, monthly, weekly, and daily profiles
WRAP	http://www.wrapair.org/forums /ef/inventories/point/index.html	WRAP	Criteria Pollutants (for point sources)	WRAP and CENRAP RPOs (22 States)	Point	Annual, hourly
WRAP	http://www.wrapair.org/forums/ ef/inventories/mobile/index.html	WRAP	Criteria Pollutants plus EC/OC (for onroad, nonroad, road dust)	WRAP RPO	County-level	Annual average weekday, seasonal average weekday
WRAP	http://www.wrapair.org/forums/ ef/inventories/area/index.html	WRAP	Criteria Pollutants (for area sources)	WRAP and CENRAP (22 States)	County-level	Annual average
WRAP	www.wrapair.org	WRAP	Criteria Pollutants (for area sources)		Point and county-level	

3.3.2 Canadian Regional and Provincial Emission Inventories

Quebec Inventory

The province of Quebec compiles emission inventories for criteria air contaminants and GHGs on an annual basis. The emission inventories are compiled through an annual survey of industrial facilities, and supplemented with information for area, mobile, and natural sources compiled in collaboration with Environment Canada. Information on Quebec's emission inventory can be obtained at: http://www.menv.gouv.qc.ca/changements/ges-en/. This website provides a detailed and comprehensive summary and analysis of the Quebec's GHG emissions.

Ontario Inventory

The province of Ontario compiles emission inventories for criteria air contaminants on an annual basis. The latest emission inventory of criteria air contaminants available for Ontario is for the year 2000. Since July of 2000, Ontario has put in place a mandatory emission monitoring and reporting regulation which requires the owners and operators of approximately 5,000 facilities across the province in the industrial, commercial, institutional and municipal sectors to report on over 350 contaminants that they release to the air. The contaminants covered under this regulation encompass criteria air contaminants, GHGs, and air toxics such as metals, PAHs, dioxins and furans. As well as reporting this information to the provincial government, these facilities are required to make their reports available to any member of the public. The reporting organization (facility) is responsible for the validity and quality of its reported data. Information on this monitoring and reporting regulation is available at the following web location http://www.ene.gov.on.ca/envision/monitoring/monitoring.htm.

Ontario also prepared an air toxics emission inventory on the target substances for the Great Lakes Regional Air Toxics Emission Inventory Project for the 1999 calendar year. This 1999 emission inventory includes point and area sources only. In order to prepare the inventory, Ontario followed the Air Toxic Emission Inventory Protocol and the emission source methodologies agreed upon by the project's technical steering committee in the development of the inventory. Uncertainty is addressed in the inventory's report by acknowledging that emission factors have an inherent degree of uncertainty.

Alberta Inventory

The latest emission inventories compiled by the province of Alberta for criteria air contaminants and GHGs are for the year 2000. These emission inventories are comprehensive, in that they include all man-made and natural sources of emissions for these substances. Large industrial facilities, transportation, commercial operations, and agricultural operations are included in these inventories. The data were collected through a survey for the large industrial facility (point source) category. The data in this inventory supports many air-quality management programs, such as: the Canada Wide Standards for PM and ozone, the Alberta framework for management of acid deposition, the Canada-Wide Acid Rain Strategy for Post-2000, the management of regional air quality, and reporting to the public.

The focus of the 2000 inventory effort was on major industrial operations that emit significant amounts of the criteria air contaminants and GHGs. Some emission estimates have been reported through Alberta Environment's mandatory reporting process. Information on generic industrial processes, activity levels of these emission producing processes, emission quantities, and stack parameters for major stacks were also collected. To compile these comprehensive inventories, other sources of emissions, such as transportation and unregulated sources, were accounted for in supplementary projects and collaboration with Environment Canada.

The Government of Alberta and Alberta industry are currently working together to establish a formal mechanism and framework on how companies with large volumes of GHG emissions will track and report their emissions on an annual basis. The information gathered under this provincial reporting program will assist both the province and industry in characterizing emission sources, and in identifying opportunities for emission reductions.

Additional information on these emission inventories can be found at the following web location http://www3.gov.ab.ca/env/air/emissions_inventory.

British Columbia Inventory

British Columbia prepared an emission inventory for common air contaminants and GHGs for 2000. Common air contaminants included CO, NO_X, SO_X, total reduced sulfur (TRS), VOCs, PM, including both PM_{10} and $PM_{2.5}$. Greenhouse gases accounted for in the inventory included CO_2, CH_4 and NO_X. Source categories for which emissions are quantified in the inventory include: point sources, area sources, mobile sources, and natural sources. Additional information on this emission inventory can be found at the following web location: http://wlapwww.gov.bc.ca/air/airquality/.

Greater Vancouver Regional District Inventory

In 2000, the Greater Vancouver Regional District prepared an emission inventory for the Lower Fraser Valley Airshed. Contaminants inventoried included: PM, NO_X, SO_X, VOCs, CO, and NH_2. The inventory also quantified emissions of the greenhouse gases: CO_2, CH_4, and N_2O. Sources of emissions inventoried included: point sources, nonpoint sources, and mobile sources. Further information on this emission inventory can be obtained at: http://www.gvrd.bc.ca/air/inventory_reports.htm.

Great Lakes Toxic Emission Regional Inventory

The Great Lakes Toxic Emission Regional Inventory compiles emission data from eight Great Lakes states and the province of Ontario. As such, it is the largest multijurisdictional project of its kind in North America. The latest iteration of the emission inventory is based on data that was collected in 2001. Listing pollutants by type, quantity and source, the inventory categorizes emissions by more than 600 industrial classifications and more than 2,000 types of sources. The inventory includes point sources, mobile sources, and area sources. Additional information on this emission inventory can be obtained at: http://www.glc.org/air/.

The Border Air Quality Strategy Inventories

As part of the Canada-U.S. Air Quality Agreement, U.S. EPA Administrator Christine Whitman and Canada's Minister of the Environment, David Anderson, announced on January 6, 2003 the commitment by the two countries to build on the existing transborder air quality cooperation by developing new cooperative projects to reduce cross-border air pollution and enable greater opportunities for coordinated air quality management. Two pilot projects are currently in place and they are located in the Georgia Basin/Puget Sound International Airshed Strategy (which covers British Columbia and northwestern Washington State), and the Great Lakes Basin Airshed Management Framework (which covers the southeastern Michigan and southwestern Ontario).

The purpose of these pilot projects is for the United States and Canada, with partners from other levels of government, to engage in a joint investigation of local and sub-regional airshed management in a contiguous urban area that crosses the Canada-United States border. The goals are to: (1) exchange information on the emission sources and air quality measurements; (2) identify opportunities, challenges, and obstacles in developing a template for a coordinated airshed management approach, should it prove feasible. The template would be available for adaptation and adoption by local communities as their airshed management framework.

Detailed emission inventories are currently being compiled for these airsheds and should be completed during the next two years.

3.3.3 Mexican Regional Emission Inventories

Regional Criteria Pollutant Emission Inventories

Regional inventories for criteria air pollutants have been developed for geographic domains that include parts of Mexico and the United States. Most of these regional inventories were developed for input to models for assessing impacts on ozone levels in the U.S.-Mexican border region, and visibility impacts across the United States and into Canada.

Paso del Norte Ozone Study

Paso del Norte includes the area around El Paso, Texas, and Ciudad (Cd.) Juárez, Chihuahua. The Paso del Norte Ozone Study was conducted during the summer of 1996 to assist the U.S. EPA, the Texas Council on Environmental Quality (TCEQ) and others in collecting the data needed to perform reliable ozone modeling. Summary information on this study can be accessed at: http://www.epa.gov/earth1r6/6pd/air/pd-q/elpaso.pdf.

The Paso del Norte emission inventory was developed for the modeling domain (i.e., all of El Paso County in Texas, parts of Doña Ana and Otero counties in New Mexico, part of Hudspeth County in Texas, and the metropolitan area of Cd. Juárez in Chihuahua, Mexico). This inventory is not currently available on the internet. The inventory was developed primarily using existing emission inventory data for point, area, mobile, and biogenic sources. The exception was that EPA's Biogenic Emission Inventory System Version 2 (BEIS-II) was used to estimate the biogenic emissions (Haste et al., 1998).

For the U.S. portion of the domain, the inventory values were provided by a number of sources including TCEQ, the Emission Trends Database for 1995, and the Sunland Park (New Mexico)

SIP. A quality assurance review of these emissions determined that they were reasonable, and no adjustments were made.

For Cd. Juárez, 25 point sources, 32 major nonpoint sources, mobile sources, and biogenic sources were included in the inventory. Emissions for point, nonpoint, and mobile sources were provided by the *Instituto Mexicano de Investigación y Planeación* (IMIP) in Cd. Juárez. A QA review of the VOC and NO_x emissions from approximately one-half of the industrial sources in the Cd. Juárez inventory revealed some problems with the emissions as provided by IMIP (e.g., unexpectedly small VOC emissions from a pharmaceutical production facility, and unexpectedly large VOC emissions from an electrical accessory fabrication plant). Mobile source emissions were found to be consistent with gasoline sales data; however, heavy-duty diesel truck NO_x emissions may have been underestimated.

SCOS97-NARSTO Inventory

The 1997 Southern California Ozone Study-North American Research Strategy (SCOS97-NARSTO) was organized as a follow-up study to the Southern California Air Quality Study completed more than a decade earlier (Shah et al., 1998). The SCOS97-NARSTO emission inventory was developed for use as input to photochemical models for assessing the contributions of, and interactions among, air pollution sources in the region, and for developing, implementing, and tracking the progress of control strategies (Funk et al., 2001). The SCOS97-NARSTO emission inventory memo related to the Mexican portion of the domain is available on the California Air Resources Board (CARB) website at http://www.arb.ca.gov/research/scos/scospub.htm.

This modeling region for SCOS97-NARSTO, and thus the emission inventory, contains a portion of northern Baja California, including Tijuana, Tecate, and Mexicali. The SCOS97-NARSTO emission inventory for northern Baja California was developed using per capita scaling factors, and other inventories conducted in 1990 for northern Baja California and for 1996 in Mexicali (SAI, 1997 and Radian Corporation, 2000). The scaling factors provided a reasonable method to scale emissions that are highly uncertain and of unknown quality.

Border 2012 Inventory

The Border 2012 program was established by the U.S. EPA, Mexico's SEMARNAT, and other U.S. and Mexican environmental agencies as a successor to the Border XXI program. Border 2012 is designed to address environmental issues that exist in the U.S.-Mexico border region. Pursuant to the 1983 La Paz Agreement, the U.S.-Mexico border region is defined as following the border between the two countries from the Gulf of Mexico to the Pacific Ocean and extending 100 km from both sides of the border. To increase the understanding of emission sources located within the border region, and support an air quality assessment for Border 2012, an emission inventory was developed (ERG, 2004). Currently, the draft Border 2012 emission inventory is not available on the internet; however, after it is finalized it will be available on the EPA Border 2012 website at http://www.epa.gov/usmexicoborder .

The Border 2012 emission inventory combines existing criteria air pollutant emission inventories for the year 1999 from the U.S. NEI and the Mexico NEI using geographical information system

(GIS) techniques. This inventory includes annual emissions in tons per year for NO_x, SO_x, VOC, CO, PM_{10}, $PM_{2.5}$, and NH_3. Source types include point, area, on-road motor vehicle, and nonroad mobile sources.

In its current draft form, the Border 2012 emission inventory summarizes emissions in three ways:

- Based only on the portion of the counties/municipalities that lie within the 100 km border zone
- Based on the entire land mass of all counties/municipalities of which any portion lie within the 100 km border zone
- Based on state-level emissions for the 10 border states.

Future finalized versions of the Border 2012 emission inventory will include projections to years 2002 and 2012, as well as results provided in 4 km x 4 km grids for use in air-quality models.

BRAVO Inventory

The Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study examined visibility impairment at Big Bend National Park in Southwest Texas. To support BRAVO, an emission inventory for 1999 was developed for visibility pollutants and precursors (Kuhns et al. 2001). The BRAVO inventory was used as input into the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (Kuhns et al., 2003). Information regarding the BRAVO inventory is available at: http://www.epa.gov/ttn/chief/net/mexico.html. Figure 3.3 provides a graphic representation of PM_{10} emissions from the BRAVO inventory.

The BRAVO domain includes seven U.S. states (Texas, New Mexico, Colorado, Kansas, Oklahoma, Louisiana, and Arkansas) and 10 Mexican states (Baja California, Sonora, Chihuahua, Coahuila, Nuevo León, Tamaulipas, Sinaloa, Durango, Zacatecas, and San Luis Potosí). It also includes emissions from the three municipalities of Tula, Vito, and Apaxco (i.e., the largest industrial grouping of SO_2 sources in Mexico). The BRAVO inventory consists of emissions from point, nonpoint, onroad motor vehicle, nonroad mobile, and natural sources including the Popocateptl volcano (located in the Mexican state of Puebla). Windblown dust and forest fires were not included.

The Mexican portion of the BRAVO study emission inventory relied upon the previous inventories for Mexico including the Monterrey, Cd. Juárez, Mexicali, and Tijuana Air Quality Planning inventories. Nonpoint and mobile emission factors were calculated for these four cities based upon five activity indicators: population, number of households, total number of registered vehicles, agricultural acreage, and number of head of cattle. Activity data from Mexico's *Instituto Nacional de Estadística, Geografía e Informática* (INEGI) was used to estimate emissions from the uninventoried areas in Mexico. Point source emissions were estimated using data contained in the National Mercury Inventory and fuel consumption data provided by the CEC (Acosta-Ruiz and Powers, 2003).

The U.S. portion of the BRAVO study emission inventory used the 1999 NEI version 1.0 as a starting point. The TCEQ provided improved emission data for onroad motor vehicles, commercial ships, construction equipment, and oil field equipment in the state of Texas. Hourly emission data from CEMS on power plants were obtained from the U.S. EPA's Clean Air Market Program. These SO_2 and NO_x emission data were reconciled with the NEI datasets by matching facility process emissions in the NEI to stack emissions from the CEMS.

3.4 STATE AND LOCAL GOVERNMENT EMISSION INVENTORIES

This section presents information on smaller scale emission inventories. Many of these emission inventories are prepared by individual states or local agencies. Some of these emission inventories are also prepared for specific purposes. Brief descriptions of U.S., Canadian, and Mexican emission inventories are provided in this section. This is not a comprehensive list of emission inventories.

3.4.1 U.S. Local Emission Inventories

Most states in the United States produce their own emission inventories, and many local agencies also develop their own inventories. A listing of states and local governments is provided Appendix A. Information for this table was obtained from STAPPA/ALAPCO at: http://www.cleanairworld.org/scripts/stappa.asp. Many Native American Indian tribes develop their own emission inventories. A listing of Native American Indian Tribes is provided in Table 3.6. This section provides a snapshot of emission inventories that have been developed by states and local agencies. It is not a comprehensive listing, moreover it is meant to provide information to the reader on the sources and issues confronting state and local agency emission inventory developers.

Table 3.6 Native American Tribes

Tribe	Internet Address
Affiliated Tribes of Northwest Indians	http://www.atnitribes.org/
Confederated Tribes of Siletz Indians	http://ctsi.nsn.us/
Eastern Band of Cherokee	http://www.cherokee-nc.com/
Inter Tribal Council of Arizona	http://www.itcaonline.com/
Jamestown S'Klallam Tribe	http://www.jamestowntribe.org/
Mississippi Band of Choctaw	http://www.choctaw.org/
Navajo Nation EPA	http://www.cia-g.com/~nilchi/
Pueblo of Jemez	http://www.jemezpueblo.org/
Seminole Indians of Florida	http://www.semtribe.com/
Suquamish Tribe	http://www.suquamish.nsn.us/

Table 3.6 Concluded

Tribe	Internet Address
Taos Pueblo Environmental Office	http://www.laplaza.org/
Other Tribal Information/Sources	
National Tribal Environmental Council	http://www.ntec.org/
Inter-Tribal Environmental Council of Oklahoma and Texas	http://www.itecmembers.org/
Tribal Air Monitoring Support Center	http://www4.nau.edu/tams/
Tribal Operations Committee	http://www.epa.gov/indian/overtoc.htm
Institute for Tribal Environmental Professionals	http://www4.nau.edu/itep/

California

The California Air Resources Board (CARB) maintains a comprehensive statewide inventory of criteria and hazardous air pollutant emissions used for policy setting and air quality modeling. This inventory includes annual and daily emissions from point, nonpoint, onroad mobile, offroad mobile, and biogenic source categories. Point source emissions are developed by the California Air Districts from data reported by facilities. Nonpoint sources are estimated by CARB or by the Air Districts. Onroad and offroad mobile emissions are estimated using CARB emission models (EMFAC and OFFROAD). The most recently completed inventory is for 2003.

South Coast

The South Coast Air Quality Management District (SCAQMD), like other California Air Districts, is responsible for developing an inventory to submit to the state. CARB requires Air Districts to develop emissions for point sources and some offroad mobile and nonpoint source categories. Categories are designated as being the districts' responsibility when local data are more readily available. For categories for which CARB is responsible, districts have the prerogative to use their own methods to better reflect local conditions. The SCAQMD inventory covers the four counties in the district and includes criteria and hazardous air pollutants. The most recently completed inventory is for 2003.

Northern Front Range Air Quality Study

After California's South Coast Air Basin, the Denver area has had the most air-quality studies devoted to the understanding of high particulate matter concentrations and poor visual air quality concentrations, the most recent of which was the Northern Front Range Air Quality Study (NFRAQS). The NFRAQS objective was source apportionment of carbonaceous particles in the $PM_{2.5}$ size range, with source samples collected under ambient conditions similar to those experienced in the wintertime in the Denver area (Norton et al., 1998). The following sources were focused on as the most significant contributors to carbonaceous particles: (1) light-duty spark ignition (gasoline) and diesel vehicles; (2) heavy-duty diesel vehicles; (3) residential wood combustion; and (4) commercial meat cooking. Chemical data collected from each of these different source types was used to construct pollution source profiles to be used as input for receptor modeling with the chemical mass balance model.

In-use vehicle testing included a set of 111 vehicles in the summer of 1996 and 83 vehicles in the winter of 1997. Each vehicle was tested using the Urban Dynamometer Driving Schedule of the Federal Test Procedure driving cycle on a chassis dynamometer. In addition, other test cycles including the IM240 emission test were performed. To simulate real world conditions, both summer and winter study vehicles were tested outdoors at ambient temperatures and indoors at controlled temperatures. In addition, city/county/state officials also recruited 24 smoking vehicles and 22 light-duty diesel vehicles during the two periods. Chemical analysis of the collected PM samples from these vehicles was used to provide source profiles for light-duty vehicles for receptor modeling.

Chassis dynamometer testing of 21 heavy-duty diesel vehicles was performed to obtain a chemical source profile from heavy-duty diesel vehicles. The emphasis for vehicle recruitment was to obtain data for in-use, higher mileage vehicles because particle rates from these vehicles were thought to be significantly higher than corresponding new vehicle rates. Each vehicle was given a series of tests using the Central Business District, heavy-duty transient truck test, and the West Virginia University truck cycle.

To provide source samples from residential wood combustion and meat cooking, Desert Research Institute constructed a special dilution source sampler designed to collect combustion-formed particles at sampling temperatures representative of ambient conditions. Information on the Northern Front Range Air Quality Study can be obtained at: http://www.nfraqs.colostate.edu/nfraqs/.

Texas

The TCEQ Division of Air Quality inventories annual and daily emissions from point, nonpoint, onroad mobile, offroad mobile, and biogenic sources to be used in policy making and air-quality modeling. This statewide inventory covers criteria and hazardous air pollutants for all 254 counties in the state. Sources of data for estimating emissions come from various sources including facility reporting (for point sources), local surveys, and data available in the literature. A preliminary version of the 2002 inventory is expected to be completed by the first week of June.

Houston/Galveston Area

The Houston/Galveston Area Quality Science Evaluation, which is part of the Texas Air Quality Study (TexAQS, 2000), includes the development of an inventory of ozone precursor emissions and fine particulate matter emissions (both primary and precursor). As part of this project, speciation files and spatial allocation files were developed to further refine existing emission data. The inventory includes emissions for the 2000 base year and projection years. While the focus of the project is on the Houston/Galveston nonattainment area, other areas of Texas and some counties in Louisiana are included to provide information on transport.

3.4.2 Mexican Local Emission Inventories

Local inventories for industrial, area, on-road motor vehicle, and natural sources are an important part of the air quality plans or *Programas para Mejorar la Calidad del Aire* (PROAIRE Programs for the Improvement of Air Quality) developed for several metropolitan areas in Mexico. These inventories mostly have been developed by Mexico's SEMARNAT and INE in coordination with local environmental authorities, and several have been sponsored by EPA, WGA, and the Texas Commission on Environmental Quality (TCEQ). In addition, several other inventories are underway including inventories for the areas of Salamanca, Guanajuato and the La Laguna Region (Torreón, Coahuila; and Gómez Palacio and Lerdo, Durango), as well as the states of Tabasco, Hidalgo, and Puebla.

The following inventories can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas, except where otherwise indicated. A list of Mexican offices and officials involved in emission inventory and air quality issues is presented in Appendix A-2.

Mexico City Metropolitan Area (MCMA)

The Mexico City Metropolitan Area is the largest urban center in the country, comprising 1,347 square miles (i.e., 3,489 square kilometers) including parts of the states of México, Hidalgo, and Tlaxcala, and all of the Federal District. Approximately 18 million people live in the area.

The fourth biennial emissions inventory for 2000 was developed for the air quality plan for that area (Secretaria del Medio Ambiente 2004). This inventory can be downloaded from the Mexico's City *Secretaría del Medio Ambiente* (SMA Secretariat of the Environment) website at http://www.sma.df.gob.mx/bibliov/modules.php?name=News&file=article&sid=204.

The inventory includes NO_x, SO_x, CO, total organic compounds (TOC), volatile organic compounds (VOC), PM_{10}, $PM_{2.5}$, and NH_3 emissions from industries, on-road motor vehicles, area sources, and natural sources. Also, CO_2 and CH_4 are included for combustion sources. On-road motor vehicle emissions are the most significant source of pollution in this inventory, contributing more than 50% of the total NO_x, CO, PM_{10}, and $PM_{2.5}$ emissions. Point sources emit more than 70% of the SO_x emissions, and area sources (mainly industrial solvents and degreasing, and liquefied petroleum gas [LPG] combustion) and motor vehicles (mainly automobiles) emit the majority of the VOC emissions.

Metropolitan Zone of the Valley of México

Emission inventory experience in the Mexico City metropolitan area has some parallels with other major cities in North America. For example, ambient measurements in Mexico City showed discrepancies between ambient VOC/NO_x ratios and similar ratios estimated from emissions. The ambient ratios suggested that VOC emissions were underestimated by the emission inventories by a factor of 2 to 3. Overall results for Mexico City suggest that emission inventories need to be improved in three critical areas. First, it is necessary to develop an emission inventory for $PM_{2.5}$ focusing on the sources of primary organic and soot particulates. Second, it is important to resolve the serious underestimate of VOC emissions. Third, the NO_x inventory must be improved.

Mexico City researchers (Molina 2002) also suggest several approaches that should be employed simultaneously to verify emission inventories, namely:

- Develop a separate inventory for primary $PM_{2.5}$ (focusing on soot and organic aerosols), and segregate inventories for primary PM_{10} and $PM_{2.5}$ by chemical composition for each source
- Develop a fuel-based inventory using remote sensing data
- Develop a coherent energy-related database for the metropolitan area
- Conduct a detailed source receptor analysis (all exhaust and evaporative emissions)
- Improve characterization of the vehicle fleet and knowledge of driving cycles
- Develop VOC emission estimates that speciate emissions, and express emissions as weighted by reactivity or ozone-forming potential
- Conduct direct emission rate measurements and source profile measurements for vehicles, as well as for biogenic, industrial, and household sources.

The following measurements from special studies in Mexico City demonstrate useful techniques that could be applied in other urban areas:

- Routine hourly measurements of PM_{10}, O_3, NO, NO_2, and CO acquired from the Mexican Automatic Air Quality Monitoring Network (*Red Automatica de Monitoreo Atmosferico*) provide a long-term record to determine the temporal and spatial characteristics of air pollution.
- Remote sensing of emissions from individual vehicles, obtained from absorption spectra of IR and UV light projected through the exhaust plume, quantifies NO, CO, CO_2, and HC. These tests indicated that 4% of the automobiles contributed 30% of the tailpipe HC emissions, and 25% of the vehicles contributed 50% of the CO emissions in 1991.
- PAHs originate from emissions of motor vehicles, oil refineries, forest fires, and cooking. PAH concentrations along Mexico City roadways range from 60 to 910 ng/m^3. These levels are approximately five times higher than concentrations measured in the United States and are among the highest measured ambient values reported. The large concentrations are likely due to a combination of old diesel-powered vehicles and the city's relatively dirty light-duty vehicle fleet, half of which lacked catalytic converters in 2003.
- In the spring of 2003, an MIT-led multinational team of experts conducted an intensive, five-week field campaign in the Mexico City metropolitan area. The overall goal is to contribute to the understanding of the air quality problem in megacities by conducting

measurements and modeling studies of atmospheric pollutants in Mexico City and to provide a scientific base for devising emission control strategies (Molina, 2004).

Information on this emission inventory can be obtained from the following website: http://www.sma.df.gob.mx/bibliov/modules.php?name=News&file=article&sid=204

Guadalajara, Jalisco

The Guadalajara metropolitan area is the second largest metropolitan area in Mexico with 3.7 million inhabitants. The emission inventory for 1995 was developed as part of the air-quality plan for that area (SEMARNAT, 1997a). This inventory can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas.

This inventory includes NO_x, SO_x, CO, hydrocarbon (HC), total suspended particulate matter (TSP), and Pb emissions from industries, *servicios* (i.e., small industries and businesses), on-road motor vehicles, and soils and vegetation (i.e., wind erosion) sources. On-road motor vehicles emit more than 90% of the total NO_x, CO, HC, and Pb emissions. Industries emit 68% of the SO_2 emissions, and wind erosion generates more than 97% of the total TSP emissions.

Monterrey, Nuevo León

Monterrey is the largest city in any of the Mexican states bordering the United States, and third largest in Mexico. Although technically outside of the 100-km border zone as defined by the La Paz Agreement, air emission sources located within the Monterrey metropolitan area may contribute to air pollution within the U.S.-Mexican border area. An inventory for 1995 was developed for the Monterrey Air Quality Plan (SEMARNAT, 1997b). This inventory can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema6&dirTemas

This inventory includes NO_x, SO_x, CO, HC, TSP, and Pb emissions from industries, *servicios*, onroad motor vehicles, and soils and vegetation (i.e., wind erosion). Onroad motor vehicles emit more than 60% of the total NO_x, CO, HC, and Pb emissions, and industries emit 92% of the SO_x emissions. The quantity of annual PM_{10} emissions emitted by natural sources comes mostly from wind erosion of disturbed lands. The absence of area source SO_x emissions indicates that emissions from fuel combustion in the industrial, commercial, and residential sectors are not accounted for in this inventory.

Ciudad (Cd.) Júarez, Chihuahua

Cd. Juárez lies directly across the U.S.-Mexican border south of El Paso, Texas. It is the largest Mexican metropolitan area directly adjacent to the border. Cd. Juárez has been an area of focus for many regional air-quality studies related to impacts on criteria pollutant air-quality standards, visibility, and public health in the Paso del Norte region (i.e., Cd. Juárez, Chihuahua; El Paso, Texas; and Doña Ana County, New Mexico)(Parks et al., 1998, Yocke et al., 2001, and Parks et al., 2003). An inventory for 1996 was developed for the Cd. Juárez Air Quality Plan (SEMARNAT, 1998). This inventory can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas

The inventory includes NO_x, SO_x, CO, HC, and TSP emissions from industries, *servicios*, onroad motor vehicles, and soil (i.e., wind erosion). The inventory results indicate a significant contribution to the overall inventory by onroad motor vehicles for every pollutant except PM_{10}. Based on known significant activity by the maquiladora industry in Cd. Juárez during 1996, the point source emissions in this inventory are surprisingly low relative to area source SO_x emissions, indicating that point source fuel combustion may be under-reported. Also, recent projects sponsored by the TCEQ have focused on improving the area sources inventory (Eastern Research Group, 2003).

Mexicali, Baja California

Mexicali, the capital of the state of Baja California, lies directly across the U.S.-Mexican border south of Imperial County, California. An inventory for 1996 was developed for the Mexicali Air Quality Plan (SEMARNAT, 1999). The inventory was developed as a special task under the Mexico Emission Inventory Program sponsored by WGA, EPA, and INE (Radian International, 2000). This inventory can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas

The inventory includes NO_x, SO_x, CO, HC, and PM_{10} emissions from industries, area sources, onroad motor vehicles, and soil and vegetation (i.e., soil NO_x, vegetative VOC, and wind erosion). The inventory results for Mexicali show that motor vehicles generate the majority of the NO_x, VOC, and CO emissions. Area sources (mainly paved and unpaved road reentrainment) and natural sources (wind erosion) generate the majority of PM_{10}. The most significant PM_{10} area source categories are paved and unpaved road reentrainment, and wind erosion from disturbed areas (considered as a natural source in this inventory). The metallic and non-metallic mineral industries generate the majority of point source emissions of all pollutants.

Tijuana-Rosarito, Baja California

Tijuana lies directly across the U.S.-Mexican border south of San Diego, California. After Cd. Juárez, it is the largest metropolitan area directly adjacent to the border. This area's impact on ozone levels in Southern California has been studied for over a decade as part of the Southern California Ozone Study-North American Research Strategy for Tropospheric Ozone (SCOS-NARSTO).

An inventory for 1998 was developed for the Tijuana Air Quality Plan (Government of the State of Baja California et al., 2000). The municipality of Playas de Rosarito is also included in the inventory domain. This inventory can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas

The inventory includes NO_x, SO_x, CO, total organic gas (TOG), and PM_{10} emissions from industries, *servicios*, onroad motor vehicles, and soil and vegetation (i.e., soil NO_x, vegetative VOC, and wind erosion). As in Mexicali, motor vehicles generate the majority of NO_x, VOC, and CO emissions, while paved and unpaved road reentrainment, and wind erosion are responsible for the majority of the PM_{10} emissions.

Toluca, México

The Metropolitan Zone of the Valley of Toluca comprises the municipalities of Toluca, Metepec, Lerma, San Mateo Atenco, and Zinacantepec. The area has approximately 1.1 million inhabitants. An emission inventory for 1995 was conducted as part of the air quality plan for that area (SEMARNAT and INE, 1997). This inventory can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas

This inventory includes NO_x, SO_2, CO, HC, TSP, and Pb emissions from industries, *servicios*, onroad motor vehicles, and soils and vegetation (i.e., wind erosion, only) sources. Onroad motor vehicles emit more than 89% of the total NO_x, CO, HC, and Pb emissions. Industries emit 82% of the SO_2 emissions, and soils/wind erosion emit more than 97% of the total TSP inventory.

3.5 SPECIALTY INVENTORIES

Specialty emission inventories are prepared by agencies, groups, or facilities that may impact air quality, but do so over in smaller scales. For example, the U.S. Department of Defense prepares annual emission inventories for all of its bases, facilities, etc. This section does not provide a comprehensive listing of all specialty emission inventories. For example, many industrial facilities produce annual emission inventories as part of their air permits. These have not been included in this section. This section provides a snapshot of existing emission inventories that have been developed in the United States, Canada, and Mexico.

3.5.1 National Parks Emission Inventories

The U.S. National Park Service's Air Resources Division prepared criteria pollutant air emission inventories for 21 national parks in 2000/2001. Emission sources within each park included stationary, area, and mobile sources. Stationary sources include fossil-fuel-fired space and water heating equipment, generators, fuel storage tanks, and wastewater treatment plants. Area sources include wood stoves, fireplaces, campfires, wildfires, and prescribed burning. Mobile sources include vehicles operated by visitors, tour operators, Park Service employees and contractors, and nonroad vehicles and equipment. National Parks for which emission inventories have been prepared are identified in Table 3.7. Information on National Park emission inventories can be obtained at http://www2.nature.nps.gov/air/aqbasics/docs/In-parkEmissionInventorySum.pdf. Figure 3.8 presents emission data from some of the larger U.S. National Parks. Carbon dioxide is the predominant pollutant emitted by Park Service equipment.

Figure 3.8. 2000/2001 CO_2 Emissions from Select U.S. National Parks

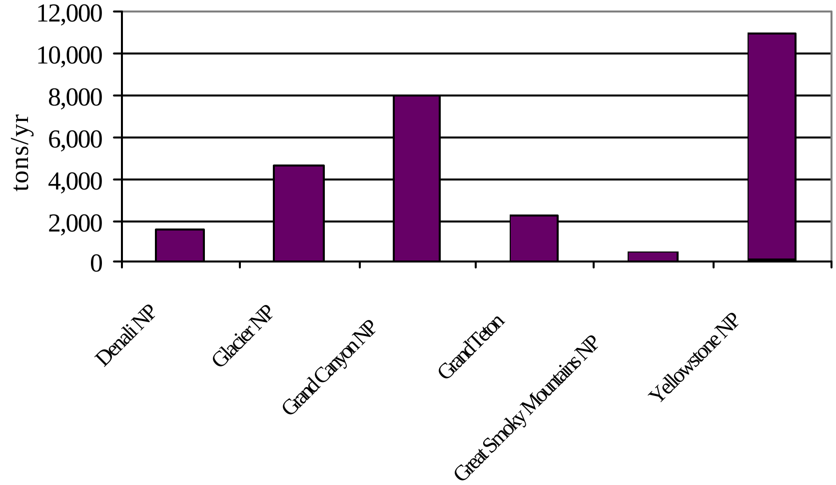


Table 3.7 Park Service Lands with Emission Inventories

Park Name	Location	Emission Inventory Type		
		Point	Area	Mobile
Badlands NP	South Dakota	✓	✓	✓
Big Cypress NP	Florida	✓	✓	✓
Carlsbad Caverns NM	New Mexico	✓	✓	✓
Chiricauha NM	Arizona	✓	✓	✓
Crater Lake NP	Oregon	✓	✓	✓
Craters of the Moon NP	Idaho	✓	✓	✓
Denali NP	Alaska	✓	✓	✓
Glacier NP	Montana	✓	✓	✓
Grand Canyon NP	Arizona	✓	✓	✓
Grand Teton NP	Wyoming	✓	✓	✓
Great Sand Dunes NM	Colorado	✓	✓	✓
Great Smoky Mountains NP	North Carolina and Tennessee	✓	✓	✓
Guadalupe Mountains NP	Texas	✓	✓	✓
Lake Mead NRA	Nevada and Arizona	✓	✓	✓
Mammoth Cave NP	Kentucky	✓	✓	✓

Table 3.7 Concluded

Park Name	Location	Emission Inventory Type		
		Point	Area	Mobile
Mesa Verde NP	Colorado	✓	✓	✓
Padre Island NS	Texas	✓	✓	✓
Theodore Roosevelt NP	North Dakota	✓	✓	✓
Wind Cave NP	South Dakota	✓	✓	✓
Yellowstone NP	Wyoming, Montana, North Dakota	✓	✓	✓

The 2000 emission inventory had four objectives. The first was to provide support for the development of the Breton National Wildlife Refuge Area current year outer continental shelf emission inventory. The second was to estimate historical outer continental shelf Gulf-wide emissions for 1977 and 1988 for the following air pollutants: CO, NO_x, SO_x, TSP, PM_{10}, $PM_{2.5}$, total hydrocarbons, and VOC. The third goal was to spatially resolve area and mobile sources to the grid-cell level, and point sources to specific coordinates. Finally, the fourth objective was to develop computer software tools to assist the MMS in collecting and managing the outer continental shelf emission inventory in the future.

Several conclusions were drawn from the inventories. No single source category is responsible for most of the emissions in the outer continental shelf area. Platform source emissions are greater than platform-related mobile source emissions. Among platform sources, engines, turbines, and boilers are the predominant source of emissions for NO_x, CO and PM. Venting of gas from wells represents the largest source of total hydrocarbons, followed closely by emissions from glycol dehydrators. MMS also found that flares are the largest sources of SO_2. Finally, among mobile sources, crew and supply boats are the single largest source category of all pollutants. Information on the MMS emission inventories can be obtained at http://www.gomr.mms.gov/homepg/regulate/environ/techsumm/2002/2002-073.html.

3.5.2 Military Emission Inventories

The U.S. Department of Defense (DoD) has six distinct services: the Air Force, Army, Marine Corps, National Guard, Navy, and specific Defense Agencies. The Clean Air Act Amendments of 1990 require that DoD installations prepare emission inventories. DoD installations have prepared both stationary and mobile source emission inventories. Many DoD installations are large and have varied sources of emissions. For example, typical stationary sources include boilers, paint booths, storage tanks, fuel transfers, energy plants, sandblasting operations, engine testing, arms firing, incinerators, woodworking, and wastewater treatment plants. Mobile sources include tanks, trucks, aircraft, government-owned and privately-owned vehicles, nonroad equipment, and ground equipment to service aircraft needs.

Approximately 66 Air Force, 80 Army, and 55 Navy installations prepare emission inventories on an annual basis. Each of the major branches of DoD publishes its own guidance documents for the preparation of emission inventories. Guidance for Air Force emission inventories is prepared by the Air Force Institute for Operational Health (available at: http://starview.brooks.af.mil/afioh/Environmental%20Programs/air_mission.htm). Army guidance is provided by the Center for Health Promotion and Preventive Medicine (available at: http://chppm-www.apgea.army.mil). Guidance for conducting Navy emission inventories is provided by the Chief of Naval Operations (available at: http://web.dandp.com/n451/programs/compliance/eqi/emissions.html#Air%20Emissions).

The military prepares air emission inventories to demonstrate compliance with rules and regulations affecting its operations. For example, emission inventories are used for determining whether a facility is a major or minor source. Furthermore, many Air Force installations are subject to the requirements of the Aerospace National Emission Standard for Hazardous Air Pollutants (40 CFR 63 Subpart GG). Boilers and storage tanks at bases may be subject to various New Source Performance Standards (NSPS). The military also prepares emission inventories for the preparation of air emission statements and annual emission fees. Emission inventories help DoD facilities quantify their emissions, and they also help quantify the levels of air pollutants emitted in communities and specific geographic locales.

3.5.3 Canadian Ammonia Inventories

Environment Canada has compiled a national emission inventory for atmospheric ammonia for the period of 1995 to 2000. The ammonia inventory provides estimates of ammonia on a national, provincial, and territorial basis for industrial and non-industrial activities. The emission inventory indicates that agricultural livestock and fertilizer application were among the main sources of ammonia emissions in Canada during that period. Emission estimates for these sectors were calculated using livestock statistics and recently developed emission factors. Furthermore, the estimates took into consideration Canadian manure management techniques and other farming practices, soil types, and climatic factors. The emission estimates for the other contributing sources were based on activity statistics such as population and vehicle kilometers traveled, and plant specific information collected through for the Criteria Air Contaminants Inventories, and the National Pollutant Release Inventory (NPRI).

3.5.4 Canada Heavy Metals Inventory

The Canadian heavy metals inventory combines three individual inventories: mercury, lead, and cadmium. These emission inventories are compiled on an annual basis to support the reporting requirements of the Heavy Metals protocol of the United-Nations Economic Commission for Europe, and the Canada-Wide Standards for Mercury.

3.5.5 Canada Persistent Organic Inventories

The Canadian persistent organic pollutants (POP) inventory combines three individual inventories: dioxins and furans, polycyclic aromatic hydrocarbons (PAH), and the hexachlorobenzene inventory. These emission inventories are compiled on an annual basis to support the reporting requirements of the Persistent Organic Protocol of the United-Nations Economic Commission for Europe, and the Canada-Wide Standards for dioxins and furans.

3.5.6 Mexican Hazardous Air Pollutant Emission Inventories

Special inventories of hazardous air pollutants (HAPs) have focused on transboundary impacts between Arizona in the United States, and Sonora in Mexico. Also, an emission inventory was sponsored by the North American Commission on Environmental Cooperation (CEC) to identify sources of mercury in Mexico.

Nogales, Sonora, and Nogales, Arizona

The Ambos Nogales HAP emissions inventory followed the development of HAP emissions inventories for four regions of Arizona under the Arizona Hazardous Air Pollution Research Program (Radian International 1997). This inventory was developed for the transboundary region of Nogales, Arizona and Nogales, Sonora, and included point, area, and on-road motor vehicle sources. The inventory currently is not available on the internet.

The Ambos Nogales HAP inventory was developed for the year 1994. The inventory domain measured 12 km x 19 km and was equally divided between Nogales, Arizona and Nogales, Sonora. The inventory included 113 individual HAPs drawn from the Arizona HAP Research Program list, as well as PM_{10} and $PM_{2.5}$. Reporting focused on 25 compounds of interest (COI) that were initially identified as having the greatest potential impact on human health within the inventory domain. The inventory results were allocated to 500 meter (m) grid cells by hour for each season for dispersion modeling and health risk assessment.

The Nogales, Sonora portion of the inventory included 49 point sources (primarily maquiladoras). Emissions were estimated for 23 area source categories, including some unique source categories such as residential biomass combustion, wire reclamation, and produce fumigation. On-road motor vehicle emissions were estimated using the MOBILE-Juárez emission factor model (Radian International 1996). Locomotives were estimated as an area source. All other non-road mobile source categories were not estimated.

The Nogales, Arizona portion of the inventory included three point sources. Emissions were estimated for 20 area source categories (including locomotives). On-road motor vehicle emissions were estimated using EPA's MOBILE5a and PART5 emission factor models. No-road mobile source emissions were obtained from the existing Grand Canyon Visibility Transport Commission (GCVTC) inventory (Radian International 1995).

Agua Prieta, Sonora, and Douglas, Arizona

Under the Arizona Hazardous Air Pollution Research program, the Arizona DEQ conducted an air quality monitoring program for Douglas, Arizona and Agua Prieta, Sonora, and a HAP emissions inventory (Meszler et al. 2002). The inventory results were allocated to [TBD] km grid cells for purposes of dispersion modeling and health risk assessment. The Douglas/Agua Prieta HAP inventory is not available on the Internet.

The inventory was developed for the year 1999. The inventory domain includes Douglas and Agua Prieta and it includes emissions of NO_x, SO_x, VOC, CO, PM_{10}, $PM_{2.5}$ and HAPs (343 compounds from EPA's HAP list and 740 compounds from EPA's Integrated Risk Information System [IRIS]).

The Agua Prieta portion of the inventory includes 71 point sources (i.e., maquiladoras, brick kilns, dry cleaners, a lime kiln, and a landfill). Emissions were estimated for only 11 area source categories (i.e., paved and unpaved road dust, degreasing, pesticide and consumer product use, residential butane combustion, residential wood combustion, printing operations, structural fires, automobile fires, trash fires, and charbroiling). On-road motor vehicle emissions were estimated by using EPA's MOBILE6 emission factor model. Non-road mobile source and biogenic emissions were also estimated.

Northern States Mercury Inventory

A preliminary inventory of mercury emissions was developed for the country of Mexico under sponsorship of the CEC (Acosta-Ruiz and Powers 2003). The inventory is available on the CEC website at http://www.cec.org.

The objectives of this inventory were to develop a comprehensive list of potential stationary sources of atmospheric Hg emissions in Mexico, to provide annual process throughputs for these sources, and to estimate Hg emissions using indirect approaches (e.g., emission factors). This inventory includes only industrial point sources of Hg.

The most significant sources of Hg were determined to be gold mining and refining, chloro-alkali plants, power plants, and ferrous and non-ferrous (i.e., copper, zinc, and lead) smelters. Mercury is a by-product of gold refining and ferrous/non-ferrous smelting, is used to produce chlorine gas in chloro-alkali plants, and is a component of the Maya crude oil used as feedstock to produce *combustóleo* that is used in thermal power plants and industrial/commercial boilers.

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CHAPTER 4. TOOLS FOR DEVELOPING EMISSION INVENTORIES

Numerous tools have been developed that assist in the preparation of emission inventories. These include emission models, processors, activity factors, and, of course, emission factors. Tools and techniques are also available to measure emissions for emission factor development efforts. This chapter discusses tools that are commonly used for the development of emission inventories. Wherever possible, the discussion focuses on tools that are used by all NARSTO member countries. Tools that have been modified for use in individual countries are also discussed.

4.1 EMISSION INVENTORY METHODS AND GUIDANCE

4.1.1 Emission Inventory Improvement Program (EIIP)

The EIIP is a jointly sponsored effort of the State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Official (STAPPA/ALAPCO) and EPA, and is an outgrowth of the Standing Air Emissions Work Group. The goal of EIIP is to provide cost-effective, reliable inventories by:

- Improving the quality of the emissions information
- Developing systems for collecting, calculating, and reporting emissions data.

The goal is approached by developing a set of preferred and alternative methods for all inventory associated tasks. This standardization improves the consistency of collected data and results in increased usefulness of emissions information.

EIIP documentation is available at http://www.epa.gov/ttn/chief/eiip/techreport/index.html. It consists of the 10 volumes described in Table 4.1.

Table 4.1 EIIP Document Descriptions

Volume	Title	Description
I	Introduction	Introduction
II	Point Sources	16 chapters describing methodologies for estimating emissions point sources
III	Area Sources	24 chapters, some of which have not been completed, on methodologies for estimating area sources.
IV	Mobile Sources	3 chapters that on methodologies for estimating emissions from mobile sources.
V	Biogenic Sources	Preferred methods for estimating emissions from biogenic sources.
VI	Quality Assurance/Quality Control	5 chapters and 6 appendices for ensuring quality assurance and quality control in emission inventories. Also contains a chapter on evaluating uncertainty in emission inventories.

Table 4.1 Concluded

Volume	Title	Description
VII	Data Management Procedures	2 chapters on a conceptual data model and an implementation guideline.
VIII	Greenhouse Gases	16 chapters on methodologies for estimating greenhouse gas emission from various sources.
IX	Particulate Emissions	A chapter on conducting PM2.5 emission inventories, and 22 documents that provide NEI methodology for estimating PM emissions from various source categories.
X	Emissions Projections	Information and procedures to assist State and local agencies in projecting future air pollution emissions.

4.1.2 EPWG

Canada has established the Emissions and Projections Working Group (EPWG). The mandate of the EPWG is to develop consistent standardized methodologies, processes and procedures for the timely and accurate preparation of emission inventories and projections of Canada's criteria air contaminants. The emission information developed by the EPWG supports various international, national, provincial/territorial and local air management initiatives.

The EPWG's main role is the compilation of emission inventories, backcasts, forecasts and trends for Canada's criteria contaminants. As such, the EPWG has five primary responsibilities:

1. Develop and publish emission inventory, forecast, backcast and trend information on Canada's CACs which consist of nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs), carbon monoxide (CO) and particulate matter (PM, PM_{10}, $PM_{2.5}$).
2. Improve the coordination of Federal, Provincial and Territorial inventory schedules for compiling emission inventories, and for performing emission projections and backcasts.
3. Evaluate, and where necessary, develop standardized methodologies for compiling emission inventories, and for performing projections and backcasts which are to be used by jurisdictions throughout Canada.
4. Develop the framework for national emission inventory, projection, and backcasting activities as directed by the NAICC.
5. Consult with stakeholders to inform them of emission inventory activities, and to solicit their input on these activities.

The EPWG also takes on a consultative role. There are various emission inventory type products (e.g. greenhouse gases, toxics, etc.) that are completed on an ad-hoc basis in Canada or are developed by other organizations. These are not always regularly scheduled products, and are often completed within a larger process such as the Canada Wide Standards. The EPWG is available to serve as a venue to review and provide comments on the emission estimates that are contained in these inventories. The EPWG's website can be accessed at: http://ccme.miupdate.com/initiatives/climate.html?category_id=34.

4.1.3 Mexican Emission Inventory Development Program

Since 1994, the Western Governors' Association (WGA), the EPA, and Mexico's *Instituto Nacional de Ecología* (INE–National Institute of Ecology) have led a comprehensive emissions inventory development program for the Country of Mexico. A primary goal of this program is to increase capacity within Mexico, among government, academic, and other emission inventory stakeholders, for the development of emission inventories. A major objective of the emission inventory capacity building work is the development of a set of 10 manuals. These manuals, some of which contain Mexico-specific emission factors and emission estimation methodologies, are designed to help guide the emissions inventory development process throughout the country. To date, the following manuals have been completed:

- Volume I: Emissions Inventory Program Planning
- Volume II: Emissions Inventory Fundamentals
- Volume III: Basic Emission Estimating Techniques
- Volume IV: Point Sources
- Volume V: Area Sources
- Volume VI: Motor Vehicles
- Volume VII: Natural Sources
- Volume VIII: Modeling Inventory Development.

Also, the *Advanced Training Workbook provides* sample calculations and case studies involving the use of emission factors and activity data especially for sources found in Mexico. Volume IX (*Emission Inventory Program Evaluation*) Volume X (*$PM_{2.5}$ Emissions Inventory Development*) are currently under development.

4.2 EMISSION FACTORS AND SPECIATION PROFILES

4.2.1 Compilation of Air Pollutant Emission Factors (AP-42)

An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere to an activity associated with the release of that pollutant. Emission factors are usually expressed as the weight of the pollutant divided by a unit weight, volume, distance, or duration of the activity (e.g., pounds of SO_2 per ton of coal burned). Emission factors are designed to be used in emissions inventories to estimate emissions from various sources of air pollution. These factors are usually simple averages of all available data that are of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category.

The principal repository of emission factors is EPA's Compilation of Air Pollutant Emission Factors, which is commonly referred to as AP-42. AP-42, which is available at (http://www.epa.gov/ttn/chief/ap42/index.html) contains 14 major categories of emission sources, and over 150 subcategories. The major source categories are listed in Table 4.2.

AP-42 emission factors are developed from emissions tests, mass balances, control equipment vendors specifications, and emissions models. Factors are assigned a rating from A through E, reflecting robustness of the factor. The assignment of factor ratings involves a two-step process. The first step involves an appraisal of the test data quality used to calculate an emission factor. The second step involves an assessment of the representativeness of the factor as a national annual average for the source category. Test data quality are rated from A through D as shown in Table 4.3.

Table 4.2 Major Source Categories Contained in AP-42

Chapter	Title
1	External Combustion Sources
2	Solid Waste Disposal
3	Stationary Internal Combustion Sources
4	Evaporation Loss Source
5	Petroleum Industry
6	Organic Chemical Process Industry
7	Liquid Storage Tanks
8	Inorganic Chemical Industry
9	Food and Agricultural Industries
10	Wood Products Industry
11	Mineral Products Industry
12	Metallurgical Industry
13	Miscellaneous Sources
14	Greenhouse Gas Biogenic Sources

Table 4.3 Emissions Test Data Quality Ratings

Rating	Explanation
A	Tests are performed by a sound methodology and are reported in enough detail for adequate validation.
B	Tests are performed by a generally sound methodology, but lacking enough detail for adequate validation.
C	Tests are based on an unproven or new methodology, or are lacking a significant amount of background information.
D	Tests are based on a generally unacceptable method, but the method may provide an order-of-magnitude value for the source.

Similar to the emission data ratings provided in Table 4.3, emission factors are rated from A to E as shown in Table 4.4.

Table 4.4 Emission Factor Ratings

Rating	Explanation
A (Excellent)	Factor is developed from A or B rated source test data taken from many randomly chosen facilities in the industry population. The source category population is sufficiently specific to minimize variability.
B (Above Average)	Factor is developed from A or B rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with an A rating, the source category population is sufficiently specific to minimize variability.
C (Average)	Factor is developed from A, B, or C rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if facilities tested represent a random sample of the industry. As with the A rating, the source category population is sufficiently specific to minimize variability.
D (Below Average)	Factor is developed A, B, or C rated test data from a small number of facilities, and there may be reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source population.
E (Poor)	Factor is developed from C and D rated test data, and there may be reason to suspect

AP-42 emission factors and support documents are available at http://www.epa.gov/ttn/chief/efinformation.html. AP-42 factors are also retrievable from a searchable FoxPro database, the Factor Information and Retrieval (FIRE) system, which is available at: http://www.epa.gov/ttn/chief/software/index.html. The EPA's conceptual future for its emission factor program is presented and described in Box 4-1.

4.2.2 SPECIATE

SPECIATE is EPA's repository of Total Organic Compound (TOC) and Particulate Matter (PM) speciated profiles for a variety of sources for use in ozone formation models, source receptor models, and other source apportionment studies. SPECIATE contains more than 1,000 speciation profiles of TOC and PM emission sources for use by the modeling community available in a user friendly data management system. The model and additional information can be obtained at: http://www.epa.gov/ttn/chief/software/speciate/.

4.2.3 FIRE

FIRE is a database management system containing EPA's recommended emission estimation factors for criteria and hazardous air pollutants and the master list for SCCs. FIRE includes information about industries and their emitting processes, the chemicals emitted, and the emission factors themselves. FIRE allows easy access to criteria and hazardous air pollutant emission factors obtained from AP-42, Locating and Estimating L&E) Documents, and the retired AFS Emission Factor (AFSEF) database and Crosswalk/Air Toxics Emissions Factor (XATEF) documents. The program and associated documentation for FIRE can be obtained at: http://www.epa.gov/ttn/chief/software/fire/.

4.2.4 Canadian Emission Factors

Several studies and measurement campaigns are conducted by the Canadian government, industries, and industrial associations for the development of emission factors that are specific to the Canadian climate, fuel types, and equipment in use in Canada. Canada makes use of AP-42 emission factors whenever Canadian emission factors are not available. In addition, it makes available a metric version of the U.S. EPA's FIRE database at: http://www.ec.gc.ca/pdb/npri/documents/2004ToolBox/docs/sect_2_5_4_e.cfm.

4.2.5 Mexico Emission Factors

Several special projects have been conducted to date to develop emission factors, activity data, and methodologies for Mexico-specific sources. The reports and manuals resulting from these projects are available on the EPA *Centro Información Sobre Contaminación de Aire* (CICA - Information Center on Air Pollution) website at http://www.epa.gov/ttn/catc/cica/cicaeng.html, unless otherwise noted.

Per Capita and Per Employee Emission Factors for Solvent Sources

As part of the development of the Mexico National Emissions Inventory (NEI), data were collected that provided the basis for development of Mexico-specific emission factors for some area source solvent categories. Per capita emission factors were developed for the architectural surface coating and graphic arts source categories; per employee emission factors were developed for the industrial surface coating, automobile body shop refinishing, and dry cleaning source categories. These emission factors are described in detail in Appendix C of the report "Mexico National Emissions Inventory, 1999, Final, Six Northern States (ERG, 2004)."

Box 4.1 The Conceptual Future of the EPA's Emission Factor Program

USEPA is currently exploring methods for restructuring its emission factor program. EPA has identified four primary reasons for restructuring the emission factor program. First, the existing process of developing emission factors for inclusion in AP-42 is labor intensive, time consuming, and expensive. Second, the existing emission factor rating system documented in Procedures for *Preparing Emission Factor Documents* is largely subjective in nature and provides limited information regarding the precision, accuracy and in-source variability of the emission factors. Third, the emission factors presented in AP-42 are arithmetic means and do not indicate the range of values that might be applicable for a given factor. Fourth, emission factors are being used for many applications for which they were not intended.

EPA is evaluating technology and innovative approaches to change the way the current emission factor program operates. For example, EPA is currently investigating methods and developing options for revising emission factor quality assessments. These new methods would provide a more objective assessment of emission factor quality and a more quantitative assessment of the precision, accuracy, and in-source variability of the emission factors.

EPA is also exploring methods for automating many parts of the emissions factor development and delivery process. For example, it is exploring the use of the eXtensible Markup Language (XML) to provide for data rich source test reports. The underlying rationale is that the sources and source test contractors would submit source test reports in a digital format that lends itself to data extraction and manipulation. The process of submitting data-rich source tests electronically to State agencies would save time and make the data contained therein more usable and manageable.

EPA is also exploring methods by which State agencies can make source test reports available for emissions factor development. The driving force here is that a wealth of source test data exists at state agencies that are not being used for the development of emissions factors. State and local agencies would be encouraged to make their source tests available online so that EPA can mine the reports for data used for the development of emissions factors. EPA is considering offering grant money to State and local agencies for the development of an online source test database base management system.

On its own end, EPA is considering the development of a state-of-the-art interactive website where users can download the latest emissions factors online. In addition to the emissions factors, conceptual plans call for the capability to obtain source test data online, as well as background data on existing emission factors.

It is hoped that a restructuring of its emissions factors program will result in a more streamlined process for developing and maintaining these factors. Another goal is to reduce the costs of the program while at the same time yield more up-to-date emissions factors.

The basis for the per capita and per employee solvent emission factors was national-level sales statistics of paints, inks, and dry cleaning solvents from *Asociación Nacional de Fabricantes de Pinturas y Tintas* (ANAFAPYT – National Association of Paint and Dye Manufacturers) and *Cámara Nacional de la Industria de Lavanderías* (CANALAVA – National Chamber of the Dry Cleaning Industry). Because these per capita and per employee solvent emission factors are based upon national-level sales statistics, they can be used throughout Mexico.

Automobile Body Shops

A study co-sponsored by EPA's Office of Air Quality Planning and Standards (OAQPS) and CICA examined the paint and solvent emissions from automobile body shops operating in Ciudad (Cd.) Juárez, Chihuahua, Mexico (EPA 1999). The study included a survey of a representative sample of automobile body shops in order to determine:

- Solvent content of various coatings (e.g., lacquer, enamel, water-based, urethane);
- Extent of solvents used in surface preparation and cleanup activities (e.g., thinners, petroleum distillates, blends, gasoline);
- Types of applications (e.g., spray booth, spray gun, open or enclosed area, ventilation techniques);
- Handling and disposal of waste (e.g., rags, sandpaper, paper, cans, tape); and
- Suitable types of control technologies.

The survey data were extrapolated across the entire population of automobile shops operating in Cd. Juárez. Also, potential control techniques were examined. Although emissions were estimated using EPA emission factors, the types of activity data collected by this project are useful in estimating emissions from automobile body shops in other areas within Mexico.

Street Vendor Cooking (Charcoal Grilling)

A study co-sponsored by EPA/OAQPS and CICA examined emissions from street vendor cooking devices, prevalent in the streets of Mexicali, Baja California (EPA 1999b) . (A related study made recommendations on emission estimation methods for charcoal grilling, as well as for open canal and sewage emissions (EPA 1999c)) Emissions from street vendors were examined experimentally by measuring levels of PM_{10} and $PM_{2.5}$, VOCs, semivolatile organic compounds (SVOCs), aldehydes, NO_x and SO_x from a test grill chosen to simulate the street vendor cooking devices in Mexicali. Nine test runs were made, and both chicken and beef were grilled. Charcoal from Mexicali and the U.S. was used (i.e., there was a shortage of Mexicali charcoal available for the tests). All of the emission parameters measure during the test runs appeared to be reasonable, with the exception of SO_2 measurements, which showed wide fluctuations due to an apparent equipment malfunction.

Emission rates (i.e., g/hour) and emission factors (i.e., g/kg of meat) were estimated. The emission factors are useful in the development of emission inventories for other areas in Mexico, and were used in an area source emission inventory for Cd. Juárez, and in the Mexico NEI (ERG 2003).

Scrap Tire Combustion

A study jointed sponsored by EPA/OAQPS, EPA/Office of Research and Development (ORD), and CICA examined air emissions from open burning of scrap tires and from tire-derived fuel (TDF) in well-designed combustors (EPA 1997). Existing laboratory test data were compiled for criteria pollutants and a list of 34 target compounds representing the highest potential for inhalation health impacts from open tire fires, along with test data on controlled burning of TDF in a rotary kiln incinerator simulator.

Emission factors (i.e., g/kg tire mass) were compiled for VOCs, SVOCs, polycyclic aromatic hydrocarbons (PAHs), and particulate matter (i.e., PM_{10}, organics, metals). Although these emissions data were developed from tests conducted in the U.S., the resulting emission factors are useful in the development of local emission inventories in Mexico where burning of tires in open pits and landfills may be prevalent. However, due to the difficulty in quantifying activity data (i.e., kg of tires burned), these emission factors may not be feasible for use in inventories covering larger geographic areas.

4.3 EMISSION ACTIVITY FACTORS

4.3.1 Onroad Sources

In the US, several different types of activity data may be used for calculating emissions from onroad sources. Vehicle miles traveled (VMT) is currently the most widely used activity factor for onroad sources. Other activity factors that are used in some cases include fuel consumed, time of operation (hours, minutes, or seconds), number of vehicle trips, soak length (for hot soak emissions), and others.

Environment Canada uses and compiles numerous activity factors from on-road sources in Canada for the estimation of emissions. Some of these activity factors are used as input in the emission factor estimation model MOBILE6.2C for criteria air contaminants (CACs). MOBILE6.2C makes use of activity factors such as vehicle kilometers traveled (VKT), annual kilometer accumulation rate, vehicle fleet and fuel characteristics. Technology fractions, fuel efficiency rating and fuel consumption are also used by Environment Canada.

Several approaches to estimating onroad activity are discussed below.

Top-down

The NEI uses a top-down approach to estimating onroad emissions. In this case, the VMT activity are based on VMT summaries by State and functional roadway class, and similar summaries for urban areas, collected by the Federal Highway Administration. The activity is then allocated to counties and functional roadway classes using a combination of county-level population and roadway mileage by county and functional roadway class as VMT surrogates. A similar top-down approach is applied in some cases using fuel sales data rather than VMT, and allocating accordingly. Top-down approaches to estimating activity for onroad sources have the advantages of applying a similar methodology and data source to a broad geographic area, such as the regional or national level. In the aggregate, these estimates are generally considered to be reasonable. However, when these activity data are examined for smaller geographic areas, such as at the county level, the estimates often vary significantly from actual activity.

For the most part, Canada's national Greenhouse Gas (GHG) Inventory is prepared using a "top down" approach, providing estimates at a provincial/territorial level of segregation. A vehicle fleet profile is established, based on model year and gross vehicle weight rating. To this fleet profile, ‘technology fractions’ are attached. The ‘technology fraction’ is a proxy for the emission control measures in the fleet (e.g., no catalyst, 3-way catalyst, advanced control diesel). This provides an estimate of average fuel consumption per vehicle class, per kilometer traveled. Fuel sales data, from Statistics Canada, is then used as a limiting factor. VKT is varied until all on-road fuel sales data is allocated. To these activity data, emission factors are applied and the GHG Inventory is derived. This top-down approach complies with the Inter-Governmental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCCC) guidelines for the estimation of GHGs. For further information on Environment Canada’s GHG Inventory, visit the website: http://www.ec.gc.ca/pdb/ghg/ghg_home_e.cfm.

Bottom-up

A more detailed approach to developing onroad activity is generally used in urban area modeling by metropolitan planning organizations. These organizations often use travel demand models to build link-level VMT databases. Inputs to these models include factors such as land use and employment by zone within the modeled region. The models are calibrated to actual traffic count data. In addition to VMT, these models can also provide other types of activity related to onroad sources including number of vehicle trips, or hours of vehicle travel. Such bottom-up models have the advantages of accounting for local detail and are generally considered the most accurate source of onroad activity for an urban area. These models sometimes have the capability to provide information on the temporal distribution of activity, by hour-of-day, day-of-week, or month-of-year, so that activity can be adjusted for any day of the year. The drawback to the bottom-up approach is the inability to apply this detailed methodology consistently to larger geographic areas, such as statewide or regionally.

In nearly every application, urban travel demand models are built using data from household surveys. The surveys typically gather demographic and economic information for each household, plus a travel diary recording all of the trips each household member made during the survey period (generally one day). The survey data are used to estimate the coefficients of a hierarchy of models that mirrors a theoretical hierarchy of behavior by travelers. Trips are separated by purpose (such as home-to-work/work-to-home and home-to-shop/shop-to-home), and each purpose receives separate modeling treatment.

While travel models produce VMT estimates, agencies and researchers may find it necessary to directly estimate VMT from traffic counts, or other types of empirical data. Probably the most widely used method is to extrapolate from Highway Performance Monitoring System (HPMS) data. However, some urban areas need to improve their existing HPMS sample of links to ensure representativeness. More approximate VMT estimation methods are used in some areas. For example, some estimates have been based on aggregate fuel sales and the estimated fleet-wide fuel economy corrected for off-road fuel consumption and out-of-state refueling and travel.

Special studies, including license plate surveys, focused counts, and special travel surveys, may be used to estimate VMT for traffic not included in regional models, such as through trips, and truck travel.

For the estimation of CACs from on-road activity, Environment Canada uses MOBILE6.2C. Generally, the data requirements for MOBILE6.2C can be broken into the following groups; external conditions (e.g. calendar year, altitude), vehicle fleet characteristics (e.g. age distributions, diesel sales fractions), vehicle activity (e.g. VKT, trip end distribution), fuel characteristics (e.g. sulphur level, gasoline volatility), and other parameters (e.g. Inspection and maintenance programs, technology penetration rates). This is considered a ‘bottom-up’ approach, and is aligned with the methodology employed by the United States Environmental Protection Agency (EPA). Harmonious emission estimation tools, techniques and methodologies are essential for meaningful comparisons to be made of emission estimates for trans-boundary air issues. MOBILE6.2C allows for the use of finer resolution data on activity factors. Local data can be used as input, and region-specific estimates can be compiled. Local surveys on roadways use, vehicle counts, fuel characteristics, and travel behaviour can all be incorporated into emission estimates. For further information on Environment Canada’s CAC Inventory, visit the website: http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm.

Mobile Activity Data for Canada

Compared to the United States, the availability of motor vehicle activity data in Canada is somewhat limited. Environment Canada does not have the ability to draw directly on vehicle registration data, as Canadian privacy laws restrict access. Private companies may purchase provincial/territorial vehicle registration files, aggregate the data and redistribute it. It is this data that Environment Canada uses for its emission estimates and vehicle fleet profile. Concern is drawn to the fact that the private companies that aggregate this data do so for purposes other than emission estimation, and aggregated classes do not always align with the needs of emission estimation modelers.

While there is a similar tendency in the U.S. and Canada to use travel demand models (TDMs) for urban planning and to estimate vehicle kilometers traveled, there are differences. As yet, no network has been established in Canada to pool this data for use in Environment Canada’s emission estimates. As the need for greater resolution on emission Inventories increases, county-level or municipal-level estimates may need to be established. Local TDM data will be invaluable for this effort. However, the current framework where individual urban areas model their respective regions for local purposes often excludes a consistent manner of data generation or compilation. For the time being, Canadian on-road emission estimation relies on aggregated activity data collected by private companies and Government Departments, at the provincial/territorial and national level.

Partnerships between Environment Canada, Transport Canada, NRCan and the use of Statistics Canada data have enhanced the ability to model on-road activity. Statistics Canada and Transport Canada developed and maintain the Canadian Vehicle Survey. This survey is an excellent source of fleet profile data, and makes use of travel diaries to capture driving behaviour and trends. Statistics Canada ensures that the sample size is representative, allowing for both local and aggregated uses of the data. Also, Transport Canada has provided data from the Company Average Fuel Consumption (CAFC) values. This data is used as fuel efficiency input data in MOBILE6.2C. Currently, Environment Canada's CAC division compiles annual emission Inventories at the provincial/territorial level. However, MOBILE6.2C does allow for finer resolution of estimates. The model has the capability to provide information based on the temporal and spatial distribution of activity (e.g., daily, intersection-level estimates).

Further partnerships with the two active inspection and maintenance (I/M) programs in Canada have recently allowed for corroboration of purchased data, data from other Government Departments and assumptions of Canadian-specific characteristics. AirCare in the province of British Columbia has been running since 1992 in the Lower Fraser Valley. Drive Clean has been in operation in Ontario since 1999. Pass and fail results from these programs allow for a partial validation of basic emission factors for MOBILE6.2C. Other information collected during the test (such as odometer readings) has been compiled into databases and can be formatted as annual kilometer accumulation rates for MOBILE6.2C. If links can be made between vehicles captured within the I/M programs and registered vehicles, local vehicle fleet characteristics can overwrite national level assumptions.

Mobile Activity Data for Mexico

Compared to the United States, the availability of motor vehicle activity data in Mexico is somewhat limited. In major U.S. metropolitan areas, travel demand models (TDMs) are typically used to estimate vehicle miles traveled (VMT). In Mexico, however, TDMs are not widely used; and the development of TDMs for the entire country is not technically or economically feasible.

In Mexico's current *Programas para Mejorar la Calidad del Aire* (PROAIRE– Programs for the Improvement of Air Quality) emissions inventories, vehicle kilometers traveled (VKT) are typically estimated using vehicle registration statistics combined with assumed daily VKT based upon limited traffic count statistics, informal surveys, and anecdotal information. Fuel sales data can be used to estimate VKT in situations where other VKT estimates are not available, if assumptions regarding fuel efficiencies for various vehicle classifications are made. However, fuel sales data are not currently available at the municipality-level for Mexico. Because of limited motor vehicle activity data in Mexico, a unique methodology was developed for the Mexico National Emissions Inventory (NEI) that utilized modeled traffic volumes and congestion levels at representative urban areas for different city size categories to generate daily per capita emission rates (ERG 2004, Wolf et al. 2004). The methodology can be obtained from a password-protected website (http://www.erg.com/mnei); however, in the future, the document will be available on the EPA's website and INE's website.

The first step in developing daily per capita emission rates was to identify seven urban area size categories with a representative urban area for each category. A basic assumption used in this methodology was that the daily per capita emission rates estimated for each of the representative urban areas are transferable to other urban areas of similar size. This assumption is reasonable because it has been shown that trip generation rates across different urban area locations and sizes are fairly stable when disaggregated by socio-economic conditions such as household size, income, and employment (Pearson et al. 1996).

Trip generation patterns were developed for each representative urban area based upon trip production and trip attraction rates from a well-documented transportation study conducted for Ciudad Juárez, Chihuahua (Instituto Municipal de Investigación y Planeación 1998). The trip generation patterns were developed for zone structures based upon census tracts called *Areas Geoestadísticas Básicas* (AGEBs). Relevant demographic and socio-economic information were obtained from the *Instituto Nacional de Estadistica, Geografía e Informática (*INEGI–National Institute of Statistics, Geography, and Computing) for each of the representative urban area zone structures. Total trips for a zone were obtained by multiplying the trip production rates by the number of households in each category of household size and income and by multiplying the attraction trip rates by the number of employees in the corresponding category of area type and economic activity.

A roadway network was developed for each of the representative urban areas in order to facilitate trip distribution. The networks were simplified versions of the current roadway infrastructure layout and only include freeways, main arterials, and collector roads. Local streets were modeled using artificial links called “connectors” which channel local traffic flows between the zones (represented at zone centroids) and the network system. Each link in the network was initially assigned a function class and flow direction based upon site visits and interviews with local transportation officials, and a link capacity and average speed based upon results from the Ciudad Juárez study. Individual link travel time was then computed using the assigned link speed. An iterative approach was used until the gravity model converged to a solution for the representative urban areas. A user-equilibrium algorithm was then used to assign traffic volumes to network links and then congestion levels between similar time alternatives using iteration.

Link-level VKT was estimated by multiplying each link’s traffic volume by the corresponding link’s length in kilometers. These link-level VKT estimates were combined with corresponding link-specific congested speed emission factors to estimate daily emissions on a link basis using PrepinPlus software. The link-specific congested speed emission factors were developed using MOBILE6-Mexico. The emission factors were developed for a generic set of scenarios with varied temperature ranges, altitude, and fuels. The speeds in the look-up matrices ranged from 4 to 100 kilometers per hour (kph) with 2 kph bins.

Total hourly emissions for each link were estimated by combining the link-specific emission factors with link-level VKT. Daily emissions for each representative urban area were estimated by summing up emissions for each hour over the entire roadway network. These daily emissions were then used to estimate per capita emission rates for the generic temperature/altitude/fuel scenarios for each of the urban area size categories. Annual municipality-level emissions were then estimated by combining per capita emission rates with populations for each municipality.

4.3.2 Nonroad Sources

Off-road engines/vehicles comprise a wide variety and sizes of diesel and gasoline engines being used in a variety of applications. Included in the off-road sector are: aircraft, locomotives, diesel and gasoline powered boats and ships, personal watercraft, lawn and garden equipment, agricultural and construction equipment, industrial and commercial equipment, and recreational vehicles. In response to the CAA Amendments of 1990, federal emission regulations have been developed for many of these engines types. With the increased recent interest in quantifying off-road engine/vehicle emissions, both the U.S. EPA and the California ARB have developed models to enable air pollution control agencies and researchers to more readily quantify emissions for many of these equipment types. These models contain estimates of equipment populations and usage patterns. Since the generic activity patterns in these models may not apply equally well in all areas, area-specific surveys of equipment populations and usage patterns are recommended for the most prominent equipment types in each area. Efficient survey techniques can vary significantly by equipment type/use because some equipment is used commercially and others by homeowners/consumers/recreators. Thus, activity is often based on non-economic factors.

Apportioning fuel use to off-road applications can be an effective tool for determining whether other emission estimation methods that have been applied have produced reasonable emission estimates. However, this requires that on-road and off-road fuel use be differentiated.

There are three off-road engine/vehicle types that are not included in the EPA and ARB models: aircraft, locomotives, and commercial marine vessels. For aircraft, there are large variations in LTO cycles from airport to airport. Although LTO times are similar for similar fleet mixes, the amount of idle varies significantly from airport to airport. This variance in taxi/idle time is the key factor in the variability of emissions from aircraft during airport operations.

Aircraft activity levels are normally expressed as landing and take-off cycles (LTOs), which consist of four aircraft operating modes: taxi and queue, take-off, climb-out and landing. Default values for the amount of time a specific aircraft type spends in each mode, or the time in modes, are normally included in Federal Aviation Administration's aircraft emissions model. Aircraft activity data in varying levels of detail may be obtained for all aircraft categories at airports with FAA-managed traffic control towers, which are required to keep detailed activity records on air carrier traffic and less detailed records for other aircraft categories (FAA 2004).

Emissions and activity for commercial marine vessels are normally categorized by five vessel types: ocean-going, tugs, ferries, dredges, and fishing vessels. Estimates of ocean-going vessel activity are available from the literature for a limited number of U.S. coastal and inland ports. Ocean-going vessel activity for other non-surveyed ports is typically estimated using an assignment process based on similar port characteristics. Key ocean-going vessel operating modes include cruise, reduced speed zone, maneuvering, and hotelling/dwelling (idling). For the non-ocean going commercial marine vessels, most of the emission inventory data collection effort is in estimating populations, with activity (hours of operation) and load factors based on typical usage profiles (EPA 1999d, EPA 1999e).

Locomotive activity is based on estimates of railroad locomotive diesel fuel consumption. In addition to line haul activity, rail switchyard operations should be inventoried. Unless a rail company operates in a limited geographic area, the fuel consumption data for locomotives is typically available for a larger area than the inventory area. For large Class I railroads, fuel consumption can typically be estimated using locomotive fuel rates coupled with miles of track and traffic density in the inventory area. Fuel consumption for small railroads (e.g., Class II/III locomotives, Amtrak) may be based on system-wide fuel estimates allocated based on the percentage of track length within the inventory area. Fuel consumption reported in public sources may form the basis of national or regional locomotive emission estimates, which can be assigned to counties or other sub-state areas based on a surrogate indicator, generally rail track length or rail freight density.

Canada Non Roads Data

Environment Canada compiles a CAC Inventory that includes the contribution of off-road engines/vehicles powered by a variety of fuel types (e.g., gasoline, diesel, compressed natural gas, liquefied petroleum gas, heavy fuel oil). Covered here are aircraft, marine vessels, locomotives and a variety of other applications such as residential and commercial equipment and off-highway vehicles. Emission estimates are handled distinctly for aircraft (sub-sector name 'Aviation'), for commercial marine (sub-sector name 'Commercial Marine') vessels, for locomotives (sub-sector name 'Rail'), and for all other off-road applications (sub-sector name 'Non-road'). The Non-road sector includes such things as recreational vehicles, lawn and garden equipment, and other commercial/residential engines and vehicles.

Aviation

Currently Environment Canada uses a set of emission factors for various aircraft types, based on landing and take-off cycles (LTOs). LTOs consist of four aircraft operating modes; taxi and queue, take-off, climb-out and landing. To these emission factors, activity level, in terms of number of LTOs, is applied. NAV Canada, Statistics Canada and Transport Canada all maintain databases on aircraft movement at Canadian airports, and it is this data that is used by Environment Canada for emission estimates for the Aviation sector.

Commercial marine

Considerable effort is being channeled into understanding the Commercial marine sub-sector, and its related emission sources. A recent study by Entec (*Quantification of Emissions from Ships Associated with Ship Movements Between Ports in the European Community*, 2002, Entec) is considered to be an excellent source of information. Drawing on a large sample size, emission factors are generated for certain vessel classes under various modes of operation and an entire emission estimation methodology is outlined. This methodology relies on the use of the Lloyd's Marine Intelligence Unit database (LMIU) for determination of average vessel characteristics. The LMIU can be used in conjunction with other vessel activity data contained in the databases of the Coast Guard to develop marine emission inventories either with or without temporal and spatial resolution. The Coast Guard data is ideally suited as it allows for temporal and spatial allocation of emissions. Shortly, the Coast Guard's data will become more attractive when it becomes entirely automated through the adoption of an Automatic Identification System (AIS). AIS is endorsed and recommended by the International Maritime Organization (IMO) and is currently being implemented in many other countries. Such an electronic database will be highly useful with GIS-based applications, and may facilitate a better articulation of marine emissions both nationally and internationally. Select Canadian port authorities, chambers of shipping and ship-owners associations have expressed interest in supplying survey data to help validate assumptions in terms of times in mode of operations and other shipping activities.

Rail

In 1995 the Railway Association of Canada (RAC) signed a memorandum of understanding (MOU) between Environment Canada and the RAC covering the period 1990 through 2005. Under the terms of the MOU, the RAC provides national level, annual traffic volumes and diesel fuel consumption for mainline, branchline, yard switching, and passenger service. Data from the annual Statistics Canada publication *Rail in Canada* (52-216) report is used to disaggregate RAC's national estimates to the provinces/territorial level required for the CAC Inventory. The Statistics Canada report does the apportioning of fuel use to provinces/territories, and the assumption is that emissions follow the same trend as fuel use. The sulphur content in diesel fuel can be obtained from the annual publication by Environment Canada's Oil, Gas and Energy Branch in the *Sulphur in Liquid Fuels* reports. The RAC's sulphur content is assumed to be 0.15% for all years and all provinces/territories.

Non-road

Environment Canada's CAC Inventory and related forecast for the Non-road sector has been compiled using the EPA's NONROAD model, with estimates used in support of proposed Canadian regulations. Canadian input data and other adaptations were implemented in the use of the NONROAD model. Due to the lack of a single source of data on the numerous engine applications modeled through NONROAD, an attempt was first made to compile the required engine population estimates. For many types of non-road equipment, the Canadian market relies almost exclusively on importation as there is only limited manufacturing of these products in Canada. Statistics Canada maintains an excellent importation database providing the annual quantity and value of imported goods organized under an international classification called *Harmonized System* (HS). When the HS coding is such that one can be fairly confident that all, or nearly all, goods classified under a given code are powered by internal combustion engines and correspond to a category of non-road equipment, the Statistics Canada database for this HS code can be used to estimate the corresponding off-road engine population in Canada. An important assumption in the allocation of non-road Canadian engine populations is that the distribution of Canadian engines with respect to different engine categories (i.e., 2-stroke, 4-stroke, and horse power range) and fuel types (i.e. gasoline, diesel, liquefied petroleum gas, and compressed natural gas) is directly proportional to the corresponding U.S. distributions

4.3.3 Stationary Nonpoint Sources

Because of the diverse nature of nonpoint sources, there are many types of emission activity factors used to develop nonpoint source emission inventories. This section focuses on three of the most important nonpoint source activity indicators: energy consumption/production, population, and employment.

Energy Consumption/Production Data

Because energy consumption and energy production are emission activities for many source categories, energy consumption/production data represent a key set of nonpoint source emission activity data. The Department of Energy's Energy Information Administration (EIA) develops databases and publishes reports that provide energy consumption and production data at various geographic levels. These databases and reports either focus on a particular energy sector (e.g., Residential Energy Consumption Survey), energy source (e.g., Annual Coal Report), or geographic area (e.g., State Energy Data). Depending on the particular resource, the EIA may report energy consumption/production on a national basis, by region (e.g., Census division), or by State (county-level data are not provided) (see http://www.eia.doe.gov/ for information on each available EIA resource). The EIA's State Energy Data (formerly the State Energy Data Report) is a particularly valuable resource because it provides energy consumption data at the most-specific geographic level available, and provides coverage of most energy sources and energy sectors.

The EIA's State Energy Data is a database that provides historical annual energy consumption, price, and expenditure data. All of the State Energy Data estimates are developed using the State Energy Data System (SEDS), which is maintained and operated by EIA. Energy consumption is estimated using data from existing surveys of energy suppliers that report consumption, sales, or distribution of energy at the State level (State Energy Data can be accessed from the following EIA web-site: http://www.eia.doe.gov/emeu/states/_use_multistate.html.

Population Data

For many nonpoint source categories, emissions are computed using per capita emission factors. For example, per capita emission factors are typically used to estimate consumer product emissions, if surveys cannot be conducted to develop local product use/sales data.

The Population Division of the Bureau of the Census develops annual July 1 population estimates at various geographic levels of detail for the U.S. and its territories. Population estimates are reported for the Nation, as well as by State, county, metropolitan area, and city/town. Each Census population data set can be downloaded from: http://eire.census.gov/popest/estimates_dataset.php. It is important to note that States, metropolitan areas, and cities may prepare population estimates for their own areas. Because these estimates may be developed using more specific local information, inventory preparers should investigate the availability of local population estimates as an alternative to using the Census values (Census 2004a, Census 2004b).

Employment Data

Employment data are frequently used to estimate nonpoint source emission activity. There are two main Federal agencies that compile employment data: the U.S. Department of Commerce's Bureau of the Census and the U.S. Department of Labor's Bureau of Labor Statistics (BLS 2004a, BLS 2004b).

The Bureau of the Census publishes County Business Patterns, which provides annual State and county employment data by industry. Beginning in 1998, County Business Patterns data are reported by 1997 North American Industrial Classification System (NAICS) industry. Data for 1997 and earlier years are reported using the Standard Industrial Classification (SIC) system. No data are published that would disclose the operations of an individual employer and County Business Patterns excludes data on self-employed individuals, employees of private households, railroad employees, agricultural production employees, and most government employees.

County Business Patterns employment data are available for download from the following Census web-site: http://www.census.gov/epcd/cbp/view/cbpview.html.

The BLS develops both occupational and industry employment estimates. The BLS' Occupational Employment Series reports National, State-, and metropolitan area-level non-farm employment estimates on an annual basis for each of over 700 occupations. The BLS also produces occupational employment and wage estimates for over 450 industry classifications at the national level. The industry classifications correspond to the 3, 4, and 5-digit NAICS industrial groups (pre-2001 data are reported by 4-digit SIC code). The BLS data do not cover the self-employed, owners and partners in unincorporated firms, household workers, unpaid family workers, or farm workers. The BLS occupational employment data can be obtained from: http://www.bls.gov/oes/home.htm.

The Quarterly Census of Employment and Wages (QCEW) program compiles employment data by industry sector that excludes members of the armed forces, the self-employed, proprietors, domestic workers, unpaid family workers, and railroad workers covered by the railroad unemployment insurance system. Available data include monthly employment by NAICS industry and county. These data are also aggregated to annual levels, to higher industry levels, and to higher geographic levels (national, State, and Metropolitan Statistical Area [MSA]). At the State and MSA level, the QCEW program publishes employment data down to the 6-digit NAICS industry level, if disclosure restrictions are met. BLS withholds publication of employment data for any industry level when necessary to protect the identity of cooperating employers. More information is available on the QCEW program from the following BLS web-site: http://www.bls.gov/cew/home.htm.

Because the Bureau of the Census and the BLS do not report comprehensive employment data, it is worthwhile to supplement these data, if possible, with estimates from market research companies. There are several private market research companies (e.g., Dun and Bradstreet, Inc.) that compile and report employment estimates for all sectors/firms. Unlike the Census and BLS, however, a fee must be paid for access to these data (e.g., options for obtaining Dun and Bradstreet estimates are described at http://www.dnb.com/us/dbproducts/sales_marketing/index.html.

Information on these three nonpoint source activity indicators are compiled and published in Canada by its national statistical agency called Statistics Canada. As an example, the Canadian energy consumption and production information is available on a monthly basis, and is provided as energy balance sheets in natural units and heat equivalents in primary and secondary forms, by province. Each balance sheet shows data on production, trade, interprovincial movements, conversion and consumption by sector. Information on natural gas liquids, electricity generated from fossil fuels, solid wood waste and spent pulping liquor are also made available in these balance sheets.

4.3.4 Point Sources

Activity indicators for point sources can range from fuel consumption, to the amount of product produced, to the amount of throughput, to the size/capacity of a storage tank. These activity indicators, or Source Classification Code units, are designed to provide the linkage between activity and the quantity of air pollution emitted. What the point source activity indicators have in common is that they are a direct measure of the input or output of an industrial process. Information about pollution-generating activity is typically (and most reliably) collected directly from each individual site/facility via surveys. Such surveys are normally performed by State/provincial air pollution control agencies, with such authority delegated to local air pollution control agencies in some large metropolitan areas.

There are also sector-specific data sources – many of which are mentioned in the non-point source discussion above – that can be used as supplements to the point source surveys, and as top down checks to ensure that all fuel use in a sector is being captured in the point source inventory. Within the point source sector, the most prominent and widely studied sub-sector is electric utilities (electricity generating units [EGUs]). The history of how activity indicators (i.e., fuel consumption) have been estimated for the electric utility sector and this evolution/improvement with time is illustrative of the different methods that can be applied to estimate pollution generating activity.

In the United States, the responsibility and authority for performing point source activity surveys has resided with the States. The execution and data submittals from these surveys to EPA were not performed consistently, which made it very difficult for regulators and researchers to quantify electric utility emissions and activity, and to track changes with time. In the early 1980s, the use of annual power plant survey data collected by the Department of Energy on fuel purchases and fuel consumption were used to develop methods for providing consistent longitudinal estimates of SO_2 emissions from electric utilities. These methods were applied to estimate electric utility air pollution emissions for major research efforts in the 1980s and early 1990s, such as the National Acid Precipitation Assessment Program (NAPAP), and to establish a baseline for measuring progress toward meeting the Title IV requirements of the 1990 Clean Air Act Amendments.

More recently, researchers have taken advantage of the emissions and activity information that is available hourly for the electric utility units that are now required to have continuous emission monitors (CEMs). The activity information available for CEM equipped units is heat input. Because not all EGUs are required to have CEMs, State point source surveys and fuel consumption information submitted to the Department of Energy continue to be valuable resources for quantifying pollution generating activity for this sector.

As trading programs are implemented to achieve regional or local goals for meeting Clean Air Act mandates, it is expected that continuous monitoring will be required for some non-EGU point sources. This will improve our ability to quantify activity indicators for these sectors and sources.

In Mexico, industrial facilities (i.e. point sources) operating in specific geographical "federal zones" or having potential significant interstate impacts or complex operating characteristics are under federal jurisdiction (i.e. SEMARNAT is in charge of regulating them). These facilities include the following:

- Those within 100 kilometers (km) of the Mexican border (as indicated under the La Paz Agreement);
- Those included under Article 111 of the LGEEPA:
- Public transportation terminals;
- On- and off-shore federal lands (e.g., federal coastal zone, federal islands, reefs, and keys);
- Federal government facilities;
- Mexico City Metropolitan Area
- Facilities or activities in one state that affect another state; and
- Facilities that require federal intervention due to their nature and complexity.

In addition to these, there are 11 specific industrial sectors under federal jurisdiction. Facilities that fall within these sectors are under federal jurisdiction regardless of where they are located (i.e., inside or outside of a federal zone). The 11 federal jurisdiction industrial sectors include:

1. Petroleum and petrochemical
2. Chemical
3. Paints and dyes
4. Metal
5. Automotive
6. Pulp and paper
7. Cement and lime
8. Asbestos
9. Glass
10. Electrical energy generation
11. Hazardous waste treatment.

State, Federal District, and municipal jurisdictions exclude industrial facilities under federal jurisdiction (i.e., those contained within the 11 federal industrial sectors and/or located within federal zones). However, they are responsible of the regulation, administration, enforcement, and sanctions for stationary industrial sources within their geographical jurisdictions, including the development of emissions inventories for these sources.

4.4 EMISSION INVENTORY MODELS

4.4.1 CMU Ammonia Model

The Carnegie Mellon University Ammonia Model is an emission factor model and database of activity data for ammonia emissions. It stores county specific activity data at the national scale and emission factors for a variety of ammonia emission sources, including livestock, fertilizers, wastewater treatment facilities, mobile sources, natural biogenic sources, etc. Examples of stored activity parameters include livestock populations by animal type, fertilizer consumption rates, wastewater plant process rates, vehicle miles traveled by vehicle class and technology types, and land coverage by land use categories. This model and associated documentation can be retrieved at: http://www.cmu.edu/ammonia/.

4.4.2 MOBILE6

U.S. MOBILE6

MOBILE6 is a computer model developed by the U.S. EPA (http://www.epa.gov/otaq/m6.htm) for estimating emissions from on-road motor vehicles. The model provides criteria and HAP emission factors for highway motor vehicles such as passenger cars, trucks, and buses. MOBILE6 calculates emission factors for 28 individual vehicle types in low and high altitude regions of the United States (EPA 2002a, EPA 2002b). MOBILE6 emission factors depend on various conditions, such as ambient temperatures, travel speeds, operating modes, fuel volatility, and mileage accrual rates. Many of the variables affecting vehicle emissions can be specified by the user through the use of an input file. MOBILE6 will estimate emission factors for any calendar year between 1952 and 2050. Vehicles from the 25 most recent model years are considered to be in operation in each calendar year. Emission factors generated by MOBILE6 are multiplied by vehicle miles traveled (VMT) estimates to produce emissions estimates.

MOBILE6 uses statistical relationships based on thousands of emission tests performed on both new and in-use vehicles. In addition to standard testing conditions, many vehicles have been tested at non-standard temperatures, with different fuel grades, and under different driving cycles. Relationships have been developed for vehicles at varying emission control levels, ranging from no control to projections of in-use performance of new technology vehicles.

Even though systematic emission measurements have been performed on the in-use vehicle fleet in the U.S., there is substantial uncertainty about the applicability of these results. The primary sources of uncertainty are the sensitivity of vehicle emissions to the driving cycle, the wide variety of driving patterns, and the effects of sampling error. Remote sensing surveys indicate that a small fraction of high emitters in the fleet produce a large fraction of total vehicle emissions. Their representation in a survey sample has a big influence on resulting emission rates/factors.

Since MOBILE6's release in January 2001, there have been two studies sponsored to evaluate and validate the model—one sponsored by the Coordinating Research Council and the U.S. Environmental Protection Agency, and another sponsored by the American Association of State Highway and Transportation Officials.

The CRC project (ENVIRON, 2004) compared MOBILE6 HC, CO, and NO_X emission estimates with various real-world data sources, including tunnel studies, ambient pollutant concentration ratios, emission ratios from remote sensing devices, and heavy-duty vehicle emissions data based on chassis dynamometer testing. Compared with tunnel studies, the CRC study found that MOBILE6 over predicts fleet average emissions, with the over prediction being most pronounced for CO; NO_X emission estimates from MOBILE6 most clearly matched the tunnel data. The CRC data also showed that MOBILE6 likely overestimates CO emissions, particularly for newer vehicles. Compared with ambient data, the HC/NO_X ratios developed from MOBILE6 appear to be reasonably accurate, and the CRC data generally supported the HC deterioration rates in MOBILE6.

The AASHTO study (Sierra, 2004) evaluated several components of MOBILE6 including (1) PM emission factors, (2) air toxic emission factors, (3) assessment of emission factors when compressed natural gas is the fuel, and (4) methods to estimate CO2. It was found that MOBILE6 appears to overestimate exhaust PM emissions from newer vehicles. However, for pre-1990 model years, MOBILE6 predictions fall within the range of recent test program expected values. The AASHTO study also found that MOBILE6 may be underestimating PM-10 emissions from heavy-duty diesel trucks. They also found that MOBILE6 brake wear emission factors likely underestimate brake wear emissions from the heavier vehicle classes.

Canadian MOBILE6

Environment Canada has developed a Canadian version of the U.S. EPA's MOBILE6.2 model. The model created was based on reviewing the underlying MOBILE6.2 method and documentation, reviewing current and past Canadian inventory methods, modeling documentation and other related studies, and discussions with Canadian vehicle manufacturers to determine differences between U.S. and Canadian vehicle fleets.

In brief, the Canadian model does not change the functionality of MOBILE6.2 or its commands. Certain data needed to be changed from the U.S. default to properly reflect Canadian conditions, and those data were handled in two ways: either through available MOBILE6.2 input commands (the preferred method) or through code modifications (when input commands could not be used). In this manner, the model is designed to allow for the continued use of the U.S. MOBILE6.2 User's Guide and all commands in MOBILE6.2 would be executed similarly in Canadian and U.S. versions. Input files may be more elaborate in Canadian modeling, as the pre-existing defaults in the U.S. version of the model are not always reasonable for Canadian conditions. Moreover, those code changes that were completed were implemented to address the differences in the light-duty U.S. and Canadian fleets prior to the 1988 model year. All code changes are invisible to the user. This excerpt is from the full report on the Canadian conversion of the model, *Development of the Canadian Version of the MOBILE6.2 Model*, 2004, Air Improvement Resource and SENES Consultants.

The MOBILE6.2C model, all available data and resources, along with a graphic user interface in both official languages of Canada will be made freely available from Environment Canada's website shortly (http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm).

Mexican MOBILE6

In 1995, tailpipe testing of 200 vehicles in Ciudad (Cd.) Juárez, Chihuahua was conducted using EPA's portable dynamometer. These data were used to modify EPA's MOBILE5a model and develop the MOBILE-Juárez emissions factor model (Radian International 1996). This first-generation Mexican mobile model generated emission factors for NO_x, VOC, and CO. MOBILE-Juárez was revised in 1999 to include the ability to estimate tailpipe exhaust PM emissions (ERG 2001a, ERG 2001b).

Although MOBILE-Juárez was originally designed for use in Cd. Juárez, with no intention to use it in other Mexican cities, it was suitable for use in other Mexican border cities with some minor modifications. However, extensive modifications were required for the model to generate accurate emission factors for non-border cities. The need for a "national" model led to the development of MOBILE5-Mexico. The development of the MOBILE5-Mexico model was the next logical development step following MOBILE-Juárez (ERG, 2000). The MOBILE5-Mexico model was based upon EPA's MOBILE5a model and incorporated data from various regions within Mexico to more accurately represent the Mexican vehicle fleet. MOBILE5-Mexico was divided into five modules, which were used to model five different regions that were thought to have distinct fleet characteristics and regulatory structures. The MOBILE5-Mexico model utilized existing testing data from Mexico City and Cd. Juárez, as well as new testing data from Aguascalientes. The user's guide and model software are available on the EPA *Centro Información de sobre Contaminación de Aire* (CICA - Information Center on Air Pollution) website at http://www.epa.gov/ttn/catc/cica/cicaeng.html.

A goal of the North American Commission for Environmental Cooperation (CEC) is a standardization of emissions estimation methodologies among the three countries of North America. In 2000, the EPA had replaced MOBILE5a with MOBILE6 as the regulatory mobile model for estimating mobile source emissions by state environmental regulatory agencies. Thus, to be consistent with the CEC's goals, MOBILE5-Mexico was replaced with MOBILE6-Mexico (ERG 2003). Currently, MOBILE-6 Mexico is available on a password-protected website (http://www.erg.com/mnei); however, in the future, the inventory will be available on the EPA's website.

MOBILE6-Mexico has more flexibility and can predict emissions for more pollutant types than the previous MOBILE5-Mexico emission factor model. It also has more up-to-date assumptions about how quickly vehicle emission control systems deteriorate and about how much lower the emissions levels of future vehicles will be when compared to current vehicles.

The basic structure of the MOBILE6-Mexico model is based upon the EPA's MOBILE6 emission factor model. MOBILE6-Mexico estimates HC, CO, NO_x, PM, and carbon dioxide emission factors for 28 gasoline- and diesel-powered on-road motor vehicle types. The specific emission factor estimates depend upon various conditions such as ambient temperatures, average travel speed, vehicle operating modes, fuel volatility, and mileage accumulation rates. Nearly all of the required input variables can be specified by the user; however, "default" values have been provided which should be appropriate for most areas of Mexico. MOBILE6-Mexico can be used to estimate emission factors for any calendar year between 1952 and 2050. For each calendar year, the overall vehicle fleet consists of the 25 most recent vehicle model years.

The first use of the MOBILE6-Mexico emission factor model in Mexico is for the development of on-road motor vehicle emission estimates for the Mexico National Emissions Inventory (NEI)(ERG 2004).

4.4.3 EMFAC2000

In the United States, California is the only state that has the authority to establish its own motor vehicle emission standards. California's emission standards have to be of equal or greater stringency than the Federal standards for the other 49 states. In order to properly account for the effects of their state's emission standards, the California ARB has developed its own emission factor model—EMFAC 2000. The model produces emission rates for exhaust and evaporative hydrocarbons, carbon monoxide, oxides of nitrogen and particulate matter associated with exhaust, tire-wear and brake-wear. Hydrocarbon emissions estimates are produced for total hydrocarbon, total organic gases, and reactive organic gases. Particulate matter estimates are made for total suspended particulate, particulate ten microns in diameter or less, and particulate 2.5 microns in diameter or less. The model also estimates emissions of oxides of sulfur, lead, and carbon dioxide. The carbon dioxide inventory is used to estimate fuel consumption. Although the estimation of toxic air contaminants is currently performed outside of EMFAC2000, efforts are underway to include this capability in the next version of the model. The model, as well as information can be obtained at: http://www.arb.ca.gov/msei/on-road/latest_version.htm (ARB 2002).

4.4.4 MOVES

To keep pace with new analysis needs, new modeling approaches, and new data, the EPA's Office of Transportation and Air Quality (OTAQ) is currently working on a new modeling system termed the Motor Vehicle Emission Simulator (MOVES). This new system will estimate emissions for on-road and nonroad sources, cover a broad range of pollutants, and allow multiple scale analysis, from fine-scale analysis to national inventory estimation. The foundation of the multi-scale approach is a common set of modal emission rates disaggregated by driving mode, which are then re-aggregated based on representative activity data to estimate total emissions at any scale over any driving pattern. The MOVES concept for defining modal emissions is a binning approach using vehicle specific power and instantaneous speed as the variables used to identify driving modes. This has produced a 17 bin approach that segregates idle and deceleration, and splits the remaining cruise and acceleration operation into 15 bins defined by combinations of speed (less than 25, 25 to 50 and greater than 50 miles per hour) and vehicle specific power (EPA 2002c). Additional information regarding the MOVES model can be obtained at: http://www.epa.gov/otaq/ngm.htm.

4.4.5 NONROAD

The NONROAD emissions model, which is currently in draft form, predicts emissions for nonroad equipment ranging from lawn and garden equipment to heavy-duty commercial vehicles. The model includes more than 300 basic and specific types on nonroad equipment that use gasoline, diesel, compressed natural gas, and liquefied petroleum gas. NONROAD estimates emissions for hydrocarbons, NO_X, CO, CO_2, SO_X, and PM (EPA 2004a, EPA 2004b).

The geographic extent of each model run is user-defined and ranges from national total emissions to subcounty emissions. The subcounty level requires the user to supply the necessary input to distribute the emissions. Although requiring more of the user, this level allows the model to estimate emissions for nonattainment areas that consist of multiple counties or part-counties. NONROAD can estimate emissions for the current year, as well as project for future year emissions out to 2045 and backcast past year emissions to 1970. The model includes growth and scrappage rates for equipment. Emissions are calculated for annual, seasonal, or monthly time periods, with estimates reported for the total period or for a typical day of the week in the period selected. The NONROAD model can be obtained at: http://www.epa.gov/otaq/nonrdmdl.htm.

Canadian NONROAD

Environment Canada has developed Canadian off-road engine population databases for use with the U.S. EPA's draft NONROAD 2004 emissions inventory computer model. At present, no sub-region or county level data is incorporated into the Canadian engine population database. However, to provide for compatibility with these and other aspects of the model, Canada, the provinces and territories are mapped to certain American states and FIPS (Federal Information Processing Standards) codes. Environment Canada has also created modified spillage factor files, NOx deterioration files, and technology files to reflect the difference in Canada and the U.S. Full details of the changes to these files are outlined in the report, *User's Guide for the Canadian Adaptation of the U.S. EPA's Draft NONROAD2004 Emissions Inventory Model*, 2004, by Roland Vaivads for Environment Canada.
All available data, resources, modified files and documentation will be made freely available from Environment Canada's website shortly (http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm).

4.4.6 Biogenic Emissions Inventory System

First developed in 1988, BEIS estimates volatile organic compound emissions from vegetation and nitric oxide emissions from soils. Because of resource limitations, recent BEIS development has been restricted to versions that are compatible with the Sparse Matrix Operational Kernel Emissions (SMOKE) system. There have been multiple releases of BEIS, with the most recent release being version 3.12.

According to EPA, versions of BEIS include the following:

> BEIS 3.12: This is the most recent version of BEIS. It is assembled as a stand-alone module to the SMOKE system for generating gridded, hourly emissions in a format consistent with air quality modeling.
>
> BEIS 3.11: This is an forerunner to version 3.12 of BEIS. BEIS 3.11 is a stand-alone module to the SMOKE system for generating gridded, hourly emissions in a format consistent for air quality modeling. BEIS3.11 revises the soil NO algorithm in BEIS3.10 to better distinguish between agricultural and nonagricultural land, and to limit adjustments from temperature, precipitation, fertilizer application, and crop canopy to the growing season and to areas of agriculture. A leaf shading algorithm is added for estimating methanol emissions from non-forested areas.

BEIS-2: This is an older version of BEIS. It calculates emissions from vegetation using 75 tree genera, 17 agricultural crop types, and urban grasses. There are several data requirements that are necessary inputs to the BEIS-2 model, including spatially gridded land-use and plant cover data, vegetation-specific emission factors for hydrocarbon and NO_X, and hourly gridded temperature data.

Documented physico-chemical effects remain largely unaccounted for in the BEIS models. For example, the effects of plant stress and dew on biogenic emission rates are not accounted for in the model. Since the effects of these conditions are accounted for in existing dry deposition models, these data are available for incorporation into BEIS models. Relative humidity and carbon dioxide concentrations also affect biogenic emission rates. Data to support these physico-chemical effects are available for incorporation into the BEIS models. The model can be obtained at: http://www.epa.gov/asmdnerl/biogen.html.

4.4.7 GLOBEIS

The Global Biosphere Emissions and Interactions System (GLOBEIS) allows users to estimate biogenic emissions of volatile organic compounds, carbon monoxide, and soil NO_X for any scale and domain. GLOBEIS runs in Microsoft Access on a PC platform. Emission rates are a function of landcover and environmental conditions, which are characterized by from user-supplied data using the most updated emissions algorithms. The developers of GLOBEIS state that this system has the following advantages:

- Ability to use high resolution land use data GIS data or BELD 3 database;
- Updated emission factor algorithms. The GLOBEIS3 algorithms reflect the latest science compared to the BEIS2 algorithms;
- The ability to compare different emission factor algorithms in the same model;
- VOC speciation for the CB4 or SAPRC99 chemical mechanisms;
- The ability to base isoprene emissions on solar radiation data supplied from GOES satellite images. This accurately represents the impacts of clouds on biogenic emissions inventories with hourly temporal resolution;
- The ability to model effects of drought and prolonged periods of high temperature;
- The ability to use satellite-based leaf are index data to determine the spatial distribution of emission and/or leaf age; and,
- It includes a leaf temperature model.

GLOBEIS 3.1 has been adopted by Environment Canada to estimate biogenic emissions. Environment Canada uses the GIS based Spatial Emissions Distribution Information System (SEDIS 2.0) for the integration, processing, and the geographic distribution of the criteria air contaminants emissions from the inventories. This system generates the various input files required to run the GLOBEIS 3.1 model such as:

1. Domain definition and specification of geographic units; including the identification, latitude, longitude and total area of each geographic unit (grid system or administrative regions);

2. Land use distribution by geographic unit and by land use code; including land use and land cover information based on AVHRR Land Cover map of Canada;
3. Hourly temperature data for all stations across Canada; and,
4. Hourly cloud opacity data for all stations across Canada.

Some modifications to the emission factors and other related information in the GLOBEIS 3.1 model were also updated to reflect the Canadian information available. Information regarding the GLOBEIS model can be obtained at: www.globeis.com/.

4.4.8 TANKS

TANKS estimates VOC and HAP emissions from organic liquid storage tanks. It is based on theoretical physico-chemical principles of evaporation and models emissions by simulating them as an evaporation process. The American Petroleum Institute developed the underlying equations to TANKS and licensed their noncommercial use to EPA for the software and AP-42 documentation. Required inputs include tank construction information, environmental conditions, and physico-chemical data about the mixture of liquids contained in the tanks. The TANKS software, as well as users guide can be obtained at: http://www.epa.gov/ttn/chief/software/tanks/index.html.

4.4.9 WATER9

WATER9, the wastewater treatment model, is a Windows based computer program and consists of analytical expressions for estimating air emissions of individual waste constituents in wastewater collection, storage, treatment, and disposal facilities; a database listing many of the organic compounds; and procedures for obtaining reports of constituent fates, including air emissions and treatment effectiveness.

WATER9 is a significant upgrade of features previously obtained in the computer programs WATER8, Chem9, and Chemdat8. WATER9 contains a set of model units that can be used together in a project to provide a model for an entire facility. WATER9 is able to evaluate a full facility that contains multiple wastewater inlet streams, multiple collection systems, and complex treatment configurations. WATER9 provides separate emission estimates for each individual compound that is identified as a constituent of the wastes. The emission estimates are based upon the properties of the compound and its concentration in the wastes. To obtain these emission estimates, the user must identify the compounds of interest and provide their concentrations in the wastes. The identification of compounds can be made by selecting them from the database that accompanies the program or by entering new information describing the properties of a compound not contained in the database.

WATER9 has the ability to use site-specific compound property information, and the ability to estimate missing compound property values. Estimates of the total air emissions from the wastes are obtained by summing the estimates for the individual compounds. The model, as well as documentation, can be obtained at: http://www.epa.gov/ttn/chief/software/water/.

4.5 EMISSIONS PROCESSORS

Emissions processing tools are used to prepare and manipulate existing emissions and related data (e.g., temporal profiles, chemical speciation profiles, and control strategies) for input to air quality simulation models. The principal emissions processors are described below.

4.5.1 SMOKE

SMOKE, which stands for Sparse Matrix Operator Kernel Emissions, efficiently processes emissions data using matrix-vector multiplication. It performs the core functions of emissions processing including spatial allocation, temporal allocation, chemical speciation, control technology application, and generation of biogenic emission estimates. SMOKE contains a driver for the MOBILE6 model and also uses a reorganized versions of UAM-BEIS-2. Alternative mobile source models such as EMFAC2000 and biogenic models such as BEIS-3 may be run external to SMOKE and their results incorporated into the SMOKE processing stream. SMOKE can be obtained at: http://www.cep.unc.edu/empd/EDSS/emissions/.

4.5.2 EPS2

One of the most widely used emissions processing tools is the Emissions Processing System (EPS)2.0/2.5. EPS initially was developed under EPA sponsorship as a FORTRAN-based emission processing system to be distributed free of charge. EPS was designed to prepare county-level seasonal or annual emission inventories for use in UAM and was released as version 1.0. As a result of the CAA Amendments of 1990, a growing emphasis on the use of urban airshed models (UAM) led to a series of enhancements. EPS2.0 provides expanded capabilities to handle the CAAA requirements with all the necessary modules to prepare spatially, temporally, and chemically detailed emission inventories. Advantages and disadvantages exist for any methodology, but overall, the use of EPS2 is the most cost effective solution for UAM applications because it is publicly available and it allows the development of emissions inventory inputs for UAM with a minimum of additional data since it comes with a set of national defaults for many of its required inputs.

Canadian EPS1.0

Canada has developed its own emissions preprocessor, which is based on the US EPA's EPS2 and on BEIS2. The CEPS1.0 was developed to process current Canadian and US annual national inventories of criteria air pollutants and to generate emission input files for each air quality model as required. CEPS1.0 differs from its US counterpart mainly in the form of regional and country specific modifications. Areas where the US EPS2 and BEIS2 were changed include: data structure, input files for the accommodation of different map projections and arbitrary grid windows, grid orientations, and grid increments. Further changes were required to the base programs as follows: chemical mechanisms other can CB-IV, multiple time zones, updated and enlarged spatial allocation factor fields, various major/minor point-source partitioning options and the use of gridded meteorological fields in calculating mobile and biogenic emissions.

4.5.3 EMS

The Emissions Modeling System (EMS-95 and EMS-2000) are state-of-the-science processing systems that compute model-ready emission estimates for point, area, mobile, and biogenic sources. EMS is based on the Geocoded Emission Modeling and Projections (GEMAP) system developed for the California Air Resources Board (CARB) during the early 1990s and includes a number of enhancements and extensions to the original GEMAP system. EMS is comprised of six primary modules: the Grid Definition Model, the Point Source Model, the Area Source Model, the Motor Vehicle Emissions Estimates Model, the Biogenic Model for Emissions Estimates, and the Speciation Model. While its approach to generating emission inventories for regional scale air quality modeling is flexible and comprehensive, the software requirements (SAS, ESRI's geographic information systems software, ArcInfo, and a FORTRAN compiler) make it an expensive system to use. EMS is specifically designed to perform the following activities:

- Modify emission parameters and inputs efficiently,
- Define a modeling grid,
- Process point and area source emission estimates, based on annual average or day-specific emissions,
- Calculate on-road mobile source emissions estimates,
- Calculate biogenic emission estimates,
- Calculate crude oil storage tank emission estimates,
- Spatially distribute, temporally allocate, and speciate emissions for use in photochemical modeling, and;
- Develop projected emission inventories for future-year scenarios.

EMS-HAP, designed initially to process the 1996 National Toxics Inventory (NTI), is a system of computer programs that process emission inventories for use in the Assessment System for Population Exposure Nationwide (ASPEN) or the Industrial Source Complex (ISC3) Dispersion Models (ISCST3) air quality models. It differs from EMS-95 in that it is specific to the NTI and ASPEN/ISCST3. It also is capable of estimating future year emissions data for these models. EMS can be obtained at the following location: http://64.27.125.175/tech/emis/index.html.

4.6 EMISSION PROJECTIONS

Emission projections are performed in support of several goals, such as providing a basis for developing control strategies for State Implementation Plans (SIPs), conducting attainment demonstration analyses, tracking progress towards meeting air quality standards, and evaluating future year impacts associated with national rulemakings. Emission projections are a function of change in activity (growth or decline) combined with changes in the emission rate or controls applicable to the source. The methodologies, tools, and data sources that are used to prepare future year emission inventories are specific to the inventory sector. The following sections identify key emission projection concepts, and tools and data sources that have been developed and used in preparing emission projections. Additional background projection information is available in the following documents prepared in support of the Emission Inventory

Improvement Program: http://www.epa.gov/ttn/chief/eiip/techreport/volume10/x01.pdf and http://www.epa.gov/ttn/chief/eiip/committee/projections/evaltools.pdf.

4.6.1 Emission Activity Forecasts

Because source-specific future year emission activity forecasts are difficult or impossible to obtain, projection year inventories are typically based on forecasts of population, industrial activity, or other surrogates for emission activity changes. The EPA has developed the Economic Growth Analysis System (EGAS) to support emission activity level forecasting. The latest version of EGAS (4.0) provides default emission activity growth factors for the period 1996-2020 (Pechan 2004). This Windows-based software tool provides growth factors for nearly 10,000 source classification codes (SCCs) for each county in the continental United States based on forecasts for surrogate emission activity growth indicators such as output by industry sector. It is important to note that the growth factors in EGAS are defaults and that forecasters should rely on more specific information whenever it is available. The following link on EPA's Emissions Modeling Clearing House (EMCH) provides the EGAS 4.0 installation files, reference manual, and user's guide: http://www.epa.gov/ttn/chief/emch/projection/egas40/index.html. The EPA is currently developing EGAS 5.0, which will extend projections capability through at least 2025, and include activity growth indicators for all 50 States and the District of Columbia.

Although EGAS provides emission activity growth factors for every emission sector, the NONROAD model has been developed in the U.S. to support emission projections for most nonroad source categories. The NONROAD model and associated documentation is available from: http://www.epa.gov/otaq/nonrdmdl.htm#model. For fuel combustion sectors, EGAS 4.0 incorporates energy consumption projections prepared by the Energy Information Administration (EIA) in *Annual Energy Outlook 2001* (EIA 2004a, EIA 2004b). Because the EIA updates their energy consumption projections on an annual basis, emission forecasters can obtain EIA's current energy consumption projections from the following link: http://www.eia.doe.gov/oiaf/aeo/index.html. Vehicle miles traveled (VMT) is the emission activity associated with onroad mobile sources. The two main methods that have been used to prepare VMT projections are through travel demand forecasting (preferred) and through extrapolation of historical VMT trends.

The importance and complexity of the electricity generating unit (EGU) sector in the U.S. has lead to the development of computer simulation models to evaluate the effects of air pollution control strategies and other important changes influencing this sector (Pechan 1984). These models seek to represent generation, transmission and pricing of electricity subject to fuel prices, the costs of capital and domestic investment, and electricity load shape and demand. Such models also typically include a linear programming component to allow evaluations of the cost and emissions impacts of proposed policies to limit EGU sector emissions of SO_2, NO_x, CO_2, and mercury via trading programs. In the U.S., the Integrated Planning Model (IPM) has been developed for preparing EGU emission projections in the contiguous United States (ICF 2004). The IPM is a proprietary model maintained by ICF Consulting (ICF). Therefore, it is necessary for potential users to solicit IPM runs from ICF. More information on IPM is available from ICF at: http://www.icfconsulting.com/Markets/Energy/ipm.asp. Information on recent EPA IPM modeling runs is available from the following EPA Clean Air Markets Division link: http://www.epa.gov/airmarkt/epa-ipm/.

4.6.2 Emission Rate/Control Forecasts

In the U.S., future year emission rates for most source sectors are maintained in sector-specific models (e.g., EGU emission rates in IPM; onroad mobile source rates in MOBILE, and nonroad mobile source rates in NONROAD). These models produce emission forecasts that incorporate the impact of equipment turnover on the emission rates of new vehicles/equipment.

Because there is no emission estimation model for the non-EGU stationary point and nonpoint sectors, there is no single resource that provides future year emission rates for these sectors. To assist in identifying future year stationary source emission rate/control assumptions, forecasters can obtain emission inventory forecast documentation prepared in support of rulemakings. This documentation generally includes estimates of the emission reduction(s) associated with the mandated control for one or more future implementation years. The percentage emission reduction(s) can then be calculated from these reductions and applied in preparing non-EGU stationary source emission forecasts. A potential source of emission reduction information for some stationary sources in AirControlNET (Pechan 2003), an EPA relational database that contains emission reduction and cost information for a series of mandatory and discretionary point and nonpoint source emission control strategies. Information on AirControlNET is available from the following EPA link: http://www.epa.gov/ttn/ecas/AirControlNET.htm.

There is also no tool available in the U.S. for modeling the impact of equipment turnover on future non-EGU stationary source emission rates. Although this is not likely to have a significant impact on short-term projections, emission forecasters should consider incorporating the impact of stationary source equipment turnover whenever possible. A recent example of a stationary point source emission projection effort that modeled this effect is the Western Regional Air Partnership (WRAP) 2018 year forecast. More information on the WRAP emission projections methodology can be found at: http://www.wrapair.org/forums/ef/documents/2002-12_PECHAN_FinalReport_Base-Annex-Bart.pdf.

4.6.3 Canadian Emission Projections

Similarly to the EPA, Environment Canada compiles emission projections on a regular basis to support the development of federal and provincial emission control strategies (federal and provincial implementation plans), to evaluate their future impact on the air quality, and to support the reporting requirements of domestic and international programs and agreements.

Using the latest emissions inventory available, the Canadian projections for industries and power generating utilities are developed using annual growth factors, which are calculated from surrogate data or indicators obtained from the energy outlook compiled by Canada's ministry of natural resources, Natural Resources Canada (NRCan).

NRCan has adapted the US National Energy Modeling System (NEMS) for the development of the Canadian energy outlooks. NEMS is an energy-economy modeling system, designed and implemented by the Energy Information Administration of the US Department of Energy. NEMS projects the production, imports, consumption and prices of energy, subject to various assumptions such as macroeconomics, resource availability and costs, costs and performances of energy technologies, behavioral and technological choice criteria and demographics.

Emission projections for the on-road transportation vehicles are developed using the Canadian emission estimation models, MOBILE 6.2C. Emission projections for the non-road transportation vehicles (excluded aviation, marine and rail), emissions are calculated using the Canadian version of the U.S. NONROAD model. These model takes into account the Vehicle Kilometer Traveled each year (VKT), the turnover of vehicle fleets, the characteristics of the gasoline and diesel fuel being used, as well as future impacts of current energy policies and emission reduction programs.

A Base Case Forecast is developed using the provincial and territorial projections compiled by Environment Canada. The Base Case Forecast is a "business/policy as usual" projection. This means all current energy, environment and related policies are held constant over the projection period. The impacts of modified or additional control regulations that have not been officially implemented (at the time the forecast is prepared) are not included in a base case. The base case is thus a reference case, against which control scenarios can be built to compare the impacts of new emission reduction measures if emissions projected into the future do not meet predetermined levels or caps. A review of the Base Case Forecast is performed through consultations with industrial sector experts, provincial and territorial governments, industry associations, and other interested parties.

Environment Canada is currently in the process of validating and improving the Energy 2020 Model to project the emissions for both CAC's and GHGs. Energy 2020 is an integrated energy system that calculates the energy demand, the energy supply and the associated emissions. The model projects end-use energy demands in major sectors (residential, commercial, industrial, agriculture and transportation) based on macroeconomic assumptions. It also dynamically simulates the supply of various types of energy (electricity, oil, gas, biomass) to meet these end-use demands. Finally it calculates the CAC and GHG emissions associated with these demands and supplies of energy. Being an integrated model, Energy 2020 can estimates how changes in energy demand behaviors in one sector can impact other sectors via fuel consumption, fuel supply and fuel prices.

The Energy 2020 model is widely used in Canada, the United States, Europe, and around the world, with each region or jurisdiction configuring the model to meet the detail levels specific to the country. Environment Canada has adapted the model to cover the 10 provinces and 3 territories. Other enhancements to the Energy 2020, to take into account the particularities of Canada, include additional categories in the transportation sector, the regulate/deregulate supplies of electricity, disaggregation of fuel types, CAC emission factors, etc.

The Canadian version of the Energy 2020 model will be used as a starting point for future emission projections. It will become a policy tool to analyse the impacts of current and future environment policies, energy options and control measures to reduce future CAC and GHG emissions. It will be calibrated to the energy outlooks prepared by Natural Resources Canada (NRCan) on a regular basis.

4.7 EMISSION TEST METHODS

Over the past 30 years EPA has developed emissions test methods to ensure compliance with New Source Performance Standards (NSPS), National Emissions Standards for Hazardous Air Pollutants (NESHAPS), and Maximum Achievable Control Technology (MACT) standards. These methods provide the basic emissions data for inventories, emission factors, compliance determinations, State data collection requirements, and control technology research and development.

Table 4.6 lists EPA's promulgated, proposed, and conditional test methods and alternative approved methods by criteria and hazardous air pollutant. Links to these methods can be found at: http://www.epa.gov/epahome/index/.

Method numbers or Performance Specifications between 1 and 100 are for New Source Performance Standards (NSPSs). These methods, which apply to criteria pollutants, are found in 40 CFR Part 60, Appendix A.

Method numbers in the 100 series are for the National Emission Standards for Hazardous Air Pollutants (NESHAPs). These methods are found in 40 CFR Part 61, Appendix B.

Method numbers in the 200 series are used to develop data for State Implementation Plans (SIPs). These methods are found in 40 CFR Part 51, Appendix M.

Method numbers in the 300 series are for the Maximum Achievable Control Technology (MACT) standards for hazardous air pollutants. These methods are found in 40 CFR Part 63, Appendix A.

All methods include specific quality control and quality assurance requirements that must be met and provide estimates of method precision. The pollutant-specific methods are generally applicable to multiple categories of stationary source categories. Methods specific to a particular source category are given a letter suffix. It should be noted that essentially all of the test methods apply to point sources. There are no methods for many area/fugitive sources such as PM from dirt roads or agricultural burning. In addition, there are no promulgated or proposed methods for PM_{10} or $PM_{2.5}$ or natural sources.

A major limitation to using EPA test methods for inventory or emission factor development is that each test is conducted at a specific set of operating and ambient conditions. It is therefore difficult to assess the representativeness of the test results. In particular, emissions tests are generally not conducted during periods of startup, shutdown, process changes, or malfunctions, when emissions may be higher than during steady state operation.

4.7.1 Continuous Emissions Monitoring Systems (CEMS)

Continuous emissions monitoring is the continuous measurement of pollutants emitted to the atmosphere from a point source. A continuous emissions monitoring system (CEMS) is combination of a gas or particulate pollutants analyzer with a manual or software calculation tool that calculates and reports emissions in units of a standard or mass emissions. The two principal uses for CEMS are to ensure continuous compliance with emissions limits and to integrate total emissions over a period of time. The great advantage of CEMS over stack testing is that emissions are measured under all operating conditions, including startup and shutdown, not just during a one steady state operating condition. CEMS typically collect and report hourly emissions. The data can be summed to calculate daily, weekly, monthly, seasonal, or annual emissions, or used as recorded for air quality modeling. While opacity monitors fall under the category of CEMS, they do not provide quantitative emissions data and are thus not considered in this section.

Table 4.4 EPA Test Methods

Pollutant	EPA Promulgated Test Methods	EPA Proposed Test Methods	EPA Conditional Test Methods (numbers not assigned)
Carbon Dioxide and Oxygen	3, 3A, 3B, 3C		CTM-034
Methane	3C		
Particulate Matter	5, 5A, B, D, E, F, G, H, 5I, 17, 201, 201A, 202, 315		CTM-002
$PM_{2.5}$, PM_{10}	201, 201A, 202		CTM-039
Sulfur Dioxide	6, 6A-6C, 8		
Nitrogen Oxides	7, 7A-7E, 20		CTM-022
Sulfuric Acid Mist	8		
Opacity	9, 22	203, 203A-C	CPS-001
Carbon Monoxide	10, 10A, 10B		
Hydrogen Sulfide	11, 15		
Lead	12, 29		
Fluoride	13A, 13B. 14, 14A		
Carbonyl Sulfide, Carbon Disulfide	15		
Total Reduced Sulfur	15A, 16A, 16B		
Sulfur	16		

Table 4.4 Continued

Pollutant	EPA Promulgated Test Methods	EPA Proposed Test Methods	EPA Conditional Test Methods (numbers not assigned)
Volatile Organic Compounds	18, 21, 25D, 204A-F, 305, 307		CTM-028 CTM 042
Dioxin and Furan	23		
Nonmethane Organic Compound	25, 25C		CTM-035
Gaseous Organics	25A		
Metals (Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, P, Se, Ag)	29		
Hydrogen Chloride, Halides, Halogens	26, 26A, 321	322	
Mercury	29, 101, 101A, 102, 105	324	
Beryllium	29, 103, 104,		
Vinyl Chloride	106, 107, 107A		
Arsenic	29, 108, 108A, 108B, 108C		
Polonium-210	111		
Radionuclides	114		
Radon-222	115		
Chromium	29, 306, 306A		
Methanol	308		
Hexane	310A, 310C		
HAPS	311		not assigned
Styrene	312A-C		
Formaldehyde	316	323	CTM-027
Isocynates		207	
Butadiene			CTM-001
Acrylonitrile			CTM-008
Halogenated Organics			CTM-011
Benzene			CTM-014

Table 4.4 Concluded

Pollutant	EPA Promulgated Test Methods	EPA Proposed Test Methods	EPA Conditional Test Methods (numbers not assigned)
Ammonia			CTM-027
Methylene Diphenyl Isocyanate (MDI)			CTM-031
Phenol and Cresol			CTM-032
Hydrogen Cyanide			CTM-033
Toluene Diisocynate			CTM-036

Listed below are pollutants monitored by CEMS to comply with State and federal emissions limitation and provide data for allowance trading program in the United States. The most widely used technology for each is also listed. It should be noted that Fourier Transform Infrared Spectroscopy (FTIR) is emerging as an alternative to many of the standard techniques listed below. As FTIR becomes more price competitive, it will likely be used on many sources as a multi-pollutant CEMS.

NO_x-chemiluminesence (CI)
SO_2 -ultraviolet absorbance
CO_2-non-dispersive infrared (NDIR)
CO- NDIR/gas filter correlation (GFC)
TRS-flame photometric detection
VOCs/THC-flame ionization detection
PM-particle counters
O_2-paramagnetic detection
HCl-NDIR/GFC
NH3-

The largest users of CEMS in the United States are electrical generating units (EGUs) mandated by Title IV of Clean Air Act (the Acid Rain Program or ARP) to reduce emissions of SO_2 and NO_x. The ARP uses an allowance trading program (each allowance is equal to one ton of SO_2 emitted during a year) among EGUs to ensure compliance with the emissions reductions. Hourly CEMS data from EGUs provide the assurance that each allowance represents one ton. The ARP requires each EGU larger than 25 megawatts (with certain exceptions) to install CEMS for SO_2, NO_x, volumetric flow, and either O_2 or CO_2. The CEMS are subject to stringent certification requirements, QA/QC procedures, and record keeping rules (40 CFR Part 75). EPA's Clean Air Markets Division (CAMD) receives hourly data each quarter from over 3,000 units. These data are summed to calculate annual mass emissions of SO_2 for the ARP allowance trading program and used to provide annual emissions for the NEI, State, and RPO inventories from EGUs. The hourly data are available for use as inputs for atmospheric dispersion and deposition models.

EPA has recently established the NO_x Budget Trading Program to reduce ambient ozone levels in the eastern United States. This program, which affects EGU's and industrial boilers and turbines >250 mmBtu/hr (and cement kilns in New York), receives hourly NO_x emissions data from more than 1,000 units each quarter. These hourly data can be used in the same manner as the ARP hourly data

CEMS are also required for 20 National Emission Standards for Hazardous Air Pollutants (NESHAPS) categories under 40 CFR Part 63 and four New Source Performance Standard (NSPS) source categories under 40 CFR Part 60. Pollutants monitored under these standards are SO_2, NO_x, CO, TRS, VOCs, and THC. Performance specifications for these CEMS are specified in Appendix F to 40 CFR Part 60. In addition, many States require continuous emissions monitoring of sources in addition to the Federal requirements. For example, Pennsylvania requires the operation of about 500 CEMS in addition to those required under the ARP, NESHAPS, and NSPS programs. Because CEMS used for NESHAPS, NSPS, and State mandates are used to monitor continuous compliance with emissions standards, they generally measure pollutant concentrations, not mass emissions. Although the concentration data, in many cases, could be used to calculate mass emissions, this is generally not done and these data are not used in calculating emissions factors or in emissions inventories.

CEMS implementation in Canada is generally specified by the certificate of approval or permit of the facility, which is issued by provincial regulatory agencies. The majority of CEMS are required to monitor process conditions linked to emissions, such as O_2 and CO at municipal solid waste incinerators, wood waste combustors, cremators, and other sensitive sources. Mass emission rate CEMS are installed at major sources such as thermal power stations, primary smelters, and cement plants.

Technical guidance for CEMS installation, certification, operation and data reporting is provided by the federal “Protocols and Performance for Continuous Monitoring of Gaseous Emissions from Thermal Power Generation” Report EPS 1/PG/7. Although this is a thermal power guideline, the general principles can be adapted to other processes and have been referenced on numerous permits for other sectors. 1/PG/7 is currently under review, to update QA/QC provisions associated with SO_2 and NOx budget programs.

Alberta has developed guidelines similar to 1/PG/7, named “CEMS Code”, and expanded their scope to include in-stack opacity, total reduced sulphur (TRS), and CO.

All generating units with greater than 73 MW gross heat input are required in Alberta and Ontario to report SO_2 and NOx emissions on the basis of CEMS measurements.

4.7.2 Canadian and Mexican Emission Measurement Methods

Most of the Canadian methods for stationary emission sources are very similar to those used in USA. Some, like those for Vinyl Chloride, Arsenic, TRS, and semi-volatile Organic Compounds, preceded or were developed in parallel to their US EPA counterparts, and retained some significant differences.

The mercury method developed by former Ontario Hydro has been adopted by ASTM as D6784-02 Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal–Fired Stationary Sources.

Some Canadian methods were developed as companion to specific regulations (such as the Ontario total hydrocarbon regulation for incinerator and the ambient odor guideline) or programs (such as Method EPS 1/RM/15 as companion to the National Emission Guidelines for Commercial / Industrial Boilers and Heaters).

Environment Canada's Reference methods for stationary sources are summarized in Table 4.6, whereas that Alberta and Ontario Methods are listed in Tables 4.7 and 4.8.

Environment Canada is currently working on the following emission measurement methods:

- Update EPS 1/PG/7 (CEMS for NOx and SO_2 budgets)
- Revision of RM/15 (addition of low level SO_2 and NO_2)
- Ethylene Oxide control efficiency from sterilizers
- Integrated NOx sampling method
- Dilution sampling method for condensable particulate matter
- Mercury emissions from landfills
- Ozone depleting substances from low pressure chillers.

Environment Canada's measurement methods for mobile sources are identical to US EPA Methods. Currently Ontario is evaluating methods for isocyanate emissions from automotive coating (manufacturing and repairs), in cooperation with stakeholders. Environment Canada's measurement methods for mobile sources are identical to US EPA Methods.

Worldwide there are many countries that have their own stack test methods. The majority of them have adopted EPA methods. However the European countries, most notably Great Britain and Germany have extensive stack-test methods. The European Union is currently working to adopt a standard set of stack test methods for all the countries in the Union.

A listing of Mexico's reference methods for stationary sources in provided in Table 4.9.

Table 4-6 Environment Canada Reference Methods for Stationary Sources

Method	Parameter
EPS 1-AP-74-3	Sulphur Dioxide from Stationary Sources (absorption in H_2O_2 followed by Ba thorin titration)
EPS 1-AP-75-1 EPS 1-AP-75-1A	Asbestos from Asbestos Mining and Milling Operations S-3, Sampling of Drill Baghouse Exhaust Emissions (Isokinetic sampling followed by optical phase-contrast microscopy)
EPS 1-AP-75-2	Opacity of Emissions from Stationary Sources (Trained observer and transmissometer versions)
EPS 1-AP-77-1	Vinyl Chloride from Vinyl Chloride and Polyvinyl Chloride Manufacturing (Tedlar bag sampling followed by GC/FID analysis)
EPS 1-AP-77-3	Nitrogen Oxides from Stationary Sources (grab sample followed by colorimetric wet chemical analysis)

Table 4-6 Concluded

Method	Parameter
EPS 1-AP-79-1	Arsenic from Gold Roasting Operations
EPS 1/RM/1	Gaseous Hydrogen Chloride from Stationary Sources (impinger absorption followed by IC analysis)
EPS 1/RM/2	Selected Semi-volatile Organic Compounds from Stationary Sources (isokinetic sampling with XAD /Ethylene Glycol Impingers)
EPS 1/RM3	Analysis of PCDDs, PCDFs and PCBs (high resolution GC/MS analysis)
EPS 1/RM/4	Carbon monoxide Emission from Stationary Sources (Tedlar bag sampling follow by NDIR determination)
EPS 1/RM/5	Mercury Emissions from Mercury Cell Chlor-Alkali Plants (permanganate impinger sampling followed by analysis by CVAA)
EPS 1/RM/6	Total Reduced Sulphur Compounds from Pulp and Paper Operations (dried Tedlar bag sample followed by GC/FPD analysis)
EPS 1/RM/7	Lead in Particulate from Stationary Sources (isokinetic sampling followed by aqua regia digestion and AA analysis)
EPS 1/RM/8	Particulate matter from Stationary sources, Traverse Points, Molecular Weight, Moisture (isokinetic sampling followed by gravimetric determination)
EPS 1/RM/15	Gaseous Emissions from Fossil Fuel-fired Boilers (electrochemical analyzer method for NOx, SO_2, CO and O_2)
EPS 1/RM/23	Internal Quality Assurance Requirements for the Analysis of Dioxins in Environmental Samples
EPS 1/PG/7	Protocols and Performance Specifications for Continuous Emission Monitoring of Gaseous Emissions from Thermal Power Generation (CEMS summary equivalent to CFR part 60 and CFR part 75)

Table 4-7 Alberta’s Emission Test Methods for Stationary Sources

Method	Parameter
1	Traverse Points
1a	Traverse Points, Small Ducts
2	Stack Gas Velocity & Flow Rate
2c	Flow, Small Duct, Standard Pitot
3	Stack Gas Molecular Weight

Table 4-7 Concluded

Method	Parameter
4	Moisture Content
5	Particulate Emissions
5a	Condensible Particulate Emissions
7	NOx Emissions
7a	NOx Emissions: Ion Chromatography
7c	NOx Emissions: Colorimetric
8	Sulfuric Acid Mist &/or SO2 Emissions
10	CO Emissions
18	Gaseous Organic Emissions
25	Nonmethane Organic Emissions
26	Hydrogen Halide & Halogen Emissions
26a	Isokinetic Hydrogen Halide & Halogen Emissions
	Total Reduced Sulfur, Pulp & Paper
	Total Reduced Sulfur, Sour Gas Plants
	Chlorine & Chlorine Dioxide Emissions
	Vinyl Chloride Monomer Emissions
	Lead Emissions
	Volatile Organic Compound Emissions
	Semi-volatile Organic Compound Emissions
CEMS Code	Continuous Emission Monitoring System Code

Table 4-8 Ontario's Emission Test Methods for Stationary Sources

Method	Parameter
1	Traverse Points
2	Stack Gas Velocity and Flow Rate
3	Stack Gas Molecular Weight
4	Moisture Content
5	Particulate Emissions
	Odour Emissions (dinamic dilution sampling on Tedlar bags followed by forced choice sensory panel)
	Total Hydrocarbon Emissions (heated continuous FID)

Table 4-9 Mexico's Reference Test Methods for Stationary Sources

Method No.	Parameter	US EPA Equivalent
NMX-AA-009-1993-SCFI	Stack gas flow (pitot tube method)	Method 2
NMX-AA-010-SCFI-2001	Particulate Matter (Isokinetic sampling with in-stack filter)	Method 5
NMX-AA-035-1976	CO_2, CO and O_2 (Orsat analysis of combustion gases)	Method 3
NMX-AA-054-1978	Stack gas Moisture (Gravimetric impinger method)	Method 4
NMX-AA-055-1979	SO_2 (midget impinger absortion in H_2O_2 solution, followed by Ba-thorin titration)	Method 6
NMX-AA-056-1980	SO_2, SO_3 and H_2SO_4 mist (isokinetic sampling, hot filtering, isopropanol absorption of SO_3 and H_2SO_4, thorin titration)	Method 8
NMX-AA-069-1980	H_2S (absorption in $CdSO_4$ solution, followed by iodometric titration)	Method 11
NMX-AA-070-1980	Chlorides and Cl_2 (chlorides absorbed in water impinger. Chlorine absorbed in arsenite solution. Followed by photocolorimetric determination of chlorides)	-
NMX-AA-085-1986	Calibration of dry gas meter with wet gas meters or spirometer	Method 5 QA/QC
NMX-AA-086-1986	Rotometer calibration	-
NMX-AA-090-1986	Phosphoric acid mist (Isokinetic sampling without filter, color development with Mo-Va reagent , followed by spectrophotometric determination)_	-
NMX-AA-095-1986	Cyanides (Isokinetic sampling in dilute Zn acetate solution, followed by buffering and by pyridine-pyrazolone addition. Spectrophotometric determination)	-
NMX-AA-096-1986	Benzene, Toluene, Xylene and Styrene (Colorimetric determination of benzene absorbed in a concentrated formaldehyde/H_2SO_4 solution. Colorimetric determination of toluene+xylene in a concentrated KIO4/ H_2SO_4 solution. Colorimetric determination of styrene in a concentrated H_2SO_4 solution)	-
NMX-AA-097-1986	NH_3 (Absorption in dilute H_2SO_4 solution followed by phenol-nitroferrocyanide addition and colorimetric determination)	-
NMX-AA-098-1996	Trichloroethylene (Absortion in pyridine impingers. Colour development by hot-mixing with sodium hydroxide/ethanol solution. Colorimetric determination)	-
NMX–AA-114-1991	Opacity by smoke stain in a filter	-

4.7.3 Other Emission Measurement Methods

There are several bodies in the United States and worldwide that have developed emission measurement methods. Some of the first US stack testing methods were developed by the American Society of Mechanical Engineers (ASME). These and other ASME methods are called Performance Test Codes (PTCs). One of the first PTCs related to the abatement of atmospheric pollution was PTC 21, *Dust Separating Apparatus."* PTC 21 was published in 1941. That was followed in 1957 by a stack testing method, PTC 27, *"Determining Dust Concentration in a Gas Stream)."* PTC 27 and the similar Western Precipitation WP 50 procedure collected particulate matter isokinetically using a ceramic (alundum) thimble filter media. These methods were used for performance evaluations of particulate removal equipment and for determining particulate matter emission concentrations and mass emission rates. In 1965, ASME published PTC 28, *"Determining the Properties of Fine Particulate Matter."* This method included procedures for characterizing the properties of the particulate matter.

ASTM International (ASTM), originally known as American Standards for Testing and Materials, was formed over a century ago. It is one of the largest voluntary standards development organizations in the world. ASTM has developed stack testing methods for a number of years, and continues to do so today. Some of the more recent ASTM stack testing methods are:

- D6060-96(2001) Standard Practice for Sampling of Process Vents with a Portable Gas Chromatograph
- D6216-03 Standard Practice for Opacity Monitor Manufacturers to Certify Conformance with Design and Performance Specifications
- D6331-98 Standard Test Method for Determination of Mass Concentration of Particulate Matter from Stationary Sources at Low Concentrations (Manual Gravimetric Method)
- D6348-03 Standard Test Method for Determination of Gaseous Compounds by Extractive Direct Interface Fourier Transform Infrared (FTIR) Spectroscopy
- D6420-99 Standard Test Method for Determination of Gaseous Organic Compounds by Direct Interface Gas Chromatography-Mass Spectrometry
- D6522-00 Standard Test Method for Determination of Nitrogen Oxides, Carbon Monoxide, and Oxygen Concentrations in Emissions from Natural Gas-Fired Reciprocating engines, Combustion Turbines, Boilers, and Process Heaters Using Portable Analyzers
- D6735-01 Standard Test Method for Measurement of Gaseous Chlorides and Fluorides from Mineral Calcining Exhaust Sources – Impinger Method
- D6784-02 Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro Method)
- D6831-02 Standard Test Method for Sampling and Determining Particulate Matter in Stack Gases Using an In-Stack, Inertial Microbalance

These methods are produced by the ASTM D22 Subcommittee. The D22 Subcommittee has Work Groups that are assigned to specific methods. The EPA has been involved on some of the ASTM D22 Work Groups and has adopted some of the most recent methods as Reference or

Alternative Methods. In addition to the published methods, ASTM D22 Work Groups are currently working on:

- Practice for Certification of Opacity Monitors for Low Level (<10%) Applications
- Continuously Monitoring Low Levels of NO_x, Carbon Monoxide and Ammonia
- Test method for Determination of PM 2.5 Mass and Species Emissions from Stationary Combustion Sources by Dilution sampling

In addition to the consensus groups, ASME and ASTM, several US state and local agencies have developed their own stack testing methods. Examples are the State of California Air Resources Board, the Commonwealth of Pennsylvania, and the California South Coast Air Management District. Other states adopt EPA Methods with some variation such as Maryland that requires the use of 70º F as standard temperature instead of 20º C (68º F) as used by the EPA. Many states have guidelines for stack testing and although they may not have specific methods, some of the state guidelines interpret how the EPA Methods are applied.

Section 12(d) of Public Law 104-113, the *National Technology Transfer and Advisory Act of 1995* directs Federal agencies to use voluntary consensus standards, such as the ASME and ASTM standards noted above, in lieu of government developed standards where possible. This Law is implemented by Office of Management and Budget (OMB) Circular A-119.

4.7.4 Predictive Emissions Models (PEMS)

Predictive Emissions Models (PEMS) can be used in certain applications as a less expensive alternative to continuous emissions monitors (CEMS) to provide more frequent hourly emissions data. PEMS were developed as an outgrowth of process control software that monitors and adjusts operating parameters to maximize process efficiencies. For environmental applications, the software can be modified to predict emissions of pollutants of interest from the same parameters monitored for system performance. In 2001 over 75 PEMS had been installed, the vast majority on gas-fired combustion turbines, with the remainder on gas- fired boilers and internal combustion engines. About 80 percent of the PEMS were used to predict emissions of NO_x. The majority of approved PEMS have been installed in Texas.

PEMS can be classified as first principles, statistical regression, and neural network models. A first principles model calculates emissions based on the chemical kinetics and thermodynamics of the combustion or other process using the operating parameters of the system. Uncertainty analysis is generally not a part of a first principles method. Regression models establish the relationship between emissions of a pollutant of interest, process operating parameters, and ambient conditions such as temperature and humidity based on a probability model. An error structure for the model is assumed (usually based on a normal distribution), allowing the estimation of error in the coefficients in the model and the propagation of error through the model into predictions made with the model. The method consists of two steps: (1) a model-fitting step that estimates model coefficients, and (2) a prediction step, where the model is used to estimate emissions. This method facilitates conducting an uncertainty analysis at different levels, including model prediction error, parameter error, and random error. A neural network method infers emissions based on an established set of logic commands and causal linkages between emissions, operating and ambient parameters. Some neural network applications involve statistical techniques. In a network, emissions are inferred from a set of linkages (defined by the user) that establish the relationship between how a combustion source is operated and the expected emissions. Unlike first- principles methods, neural networks require the user to establish "fault trees" or "event trees" consistent with standard engineering techniques. Uncertainty analysis is not generally performed in a neural network framework, but is conceptually possible.

EPA's Office of Air Quality Planning and Standards, Clean Air Markets Division, the Texas Commission on Environmental Quality, and California's South Coast Air Quality Management District have established are developing PEMS performance requirements. All protocols require comparison of PEMS predictions to measured emission tests, relative accuracy tests, sensor drift limitations, and quality assurance procedures.
Technical issues related to the accuracy, precision, and reliability of PEMS predictions include: the amount of paired PEMS/CEMS (or manual test) data to be collected at each condition for accuracy determinations; defining the operating envelope over which PEMS predictions are reliable; startup, shutdown, and transient conditions (PEMS are designed for predicting emissions at steady state); the duration and timing of the demonstration period (e.g., combustion turbine operations differ by season); frequency of relative accuracy testing daily calibrations are not applicable).

4.8 DATA MANAGEMENT

Emission inventory data management systems have changed dramatically over the last 20 years from older mainframe systems (such as the U.S. EPA's National Emissions Data System [NEDS] which later became the Aerometric Information Retrieval System [AIRS]) to simple spreadsheets (used initially to develop the U.S. EPA's National Emission Trends). AIRS can be accessed at: http://www.epa.gov/Compliance/planning/data/air/afssystem.html. NEDS data format was used to store U.S. EPA emissions data including data developed for the 1985 National Acid Precipitation Assessment Program (NAPAP). Current emission 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. However, emissions data are still managed with smaller systems including spreadsheets and smaller relational systems such as MS Access.

The Canadian emission inventories are maintained into two different databases for storage, retrieval, and processing. The CAC emissions collected annually from industrial and commercial facilities through Environment Canada's National Pollutant Release Inventory (NPRI) are stored into the NPRI database. The NPRI database is a relational database available in MS Access and in MS SQL server for main storage. Copies of this point source database which includes releases for more than 323 pollutants, including the CACs and heavy metals, can be downloaded at the following location http://www.ec.gc.ca/pdb/npri/npri_dat_rep_e.cfm. The database can also be accessed using online querying and mapping tools available at the following locations http://www.ec.gc.ca/pdb/npri/npri_online_data_e.cfm, http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm.

The comprehensive emission inventories for Criteria Air Contaminants, heavy metals, and persistent organic pollutants compiled to support the development of emission reduction policies, air quality modelling, and emission trends are stored in a separate relational database system called the Residual Discharge Information System (RDIS II). This database system was designed in 1998 and incorporates many of the features available from provincial and state database systems available at that time. This MS SQL database was designed to handle multi-media releases and the provincial emissions inventory information submitted, which are submitted in various file formats. The database is not publicly available due the confidentiality of the historical point source information. Efforts are currently underway to export the Canadian emission inventory data in the latest NEI Input Format (NIF).

A new MS SQL database called OWNERS is currently being developed in Canada. This new database will provide a one-window for the Canadian industries to report their releases and other information required under different regulations on-line using a new electronic reporting form. The database will also merge the information from the NPRI and the RDIS II databases, and is expected to be ready in 2005.

Data management encompasses data input, manipulation, quality assurance checking, storage, accessibility, and dissemination. Significant issues related to emission database management systems include:

- Data transparency
- Data applicability
- Data quantity
- Data quality
- Data accessibility
- Data dissemination
- Data lag time.

Each of these items along with examples is discussed below.

4.8.1 Data Transparency

Data transparency refers to the ability to easily describe, understand, and assimilate emissions data into a variety of database management systems. Several efforts are currently underway to provide data transparency. In most data management systems, the first step towards understanding data is the development of metadata. Metadata is “data about the data”. Metadata describes the data in a database and assists users in understanding what the data elements represent.

Generally the next step is the development of a data dictionary. This step frequently depends upon how “formal” the database management system will be. If the data are likely to be stored in a spreadsheet or a stand alone PC-based database management system, this step may not be undertaken. However for relational databases, this step is virtually mandatory.

For example the U.S. NEI is hosted on an Oracle relational database. Data entry into the NEI is enabled by the NEI Input Format (NIF). The NIF fully defines the data fields and their attributes necessary to submit and store data in the underlying database. U.S. EPA has developed the NIF format in a precise manner so that data submitted by State, local, tribal and other reporting agencies can be stored in the database management system. Use of the NIF creates a relational, normalized data set that conforms to the relational standards and structure of EPA's Oracle database that stores the NEI data. This format avoids duplication of information that may otherwise occur in a flat file format and reduces the size of the resulting database. It also provides flexibility to support the changing requirements of a national inventory over time. The NIF is currently one of the most widely used formats by State, local and Tribal agencies to report emission data to EPA.

The NIF is divided into four source groups – point, area and nonroad mobile, onroad mobile, and biogenic. The table structure for the current NIF is shown in Table 4.10. The number of fields per table is shown in parenthesis. These tables and fields contain the detailed information on emission sources, such as processes associated with the emissions, location, periods of operation, pollutants emitted to the atmosphere, and control technologies. Key fields provide the linkage between the many tables in the relational structure.

Table 4.10 NIF 3.0 Source Tables

Source	Tables[a]	
Point	Transmittal (19) Site (20) Emission Unit (15) Emission Release Point (29)	Emission Process (23) Control Equipment (18) Emission Period (21) Emission (33)
Area and Nonroad mobile	Transmittal (19) Emission Process (21) Emission Period (18)	Control Equipment (12) Emissions (27)
Onroad Mobile	Transmittal (19) Emission Period (12)	Emissions (17)
Biogenic	Transmittal (19)	Biogenic (13)

[a] The values in parenthesis indicate the number of fields in the table.

While the national data format is precisely defined, state, local, and tribal agencies may maintain their emissions database in a format that meets their own particular needs and still report data to the EPA using the NIF format. This is an example of data transparency. The format and characteristics of the data are fully described so that either submitters or users of the data may easily and straightforwardly send or receive data from the database management system. Such transparency can be important for entities outside of the United States. For example, data transparency may be of particular importance for Canada and Mexico and their development of national emission inventories. If all three countries used the NIF, it would be possible to develop a tri-national emissions inventory. However, the use of the NIF by other countries is subject to each country's regulations and needs.

Other entities have gone different routes to ensure that their data are fully understood and to make sure that the user can readily obtain and use the emissions data. For example, the Global Emission Inventory Activity (GEIA) has developed a uniform data format in which to store emissions data in. Information on that format can be found on the GEIA data website at http://www.geiacenter.org/emits/geiadfrm.html. In addition to a description of the data format, GEIA also provides a tool to read their data into a series of arrays that can be used for pre-processing. Information on that tool is available at http://www.geiacenter.org/emits/geiadfrm.html#Program.

4.8.2 Data Applicability

One of the biggest issues with respect to development of emissions data management is the applicability of the data. Some emission inventory data management is relatively straightforward because the usage (applicability) is simple. In other cases the usage is multifaceted and complex. For example, the U.S. NEI provides an example of the complexity associated with data management issues of large, complex emissions inventories. The NEI database was developed for air quality modeling, human exposure modeling, risk assessment, regional compliance strategy development, and emissions trends tracking. Because of these many demands on NEI, the data input requirements and data base have become very complex.

Other data applicability issues result from temporal, spatial and species related applicability. For example the focus of the NEI has largely been on criteria pollutants at either an annual, seasonal, or daily basis. More recently HAPs have been added to the NEI resulting in modifications to the database structure since the original structure wasn't completely applicable to the inclusion of HAPS in the database. Emissions in the NEI are limited to the U.S. States and territories, with point sources specifically located using latitude/longitude (or UTM) coordinates and area and mobile sources located within counties.

For GEIA, the focus is on global emissions of a wide variety of compounds/species that are available on a one degree grid for the entire world. The data are in annual, seasonal or monthly resolution. Most data are provided for the surface level, but there is vertical resolution for some chemical emissions.

Recent evaluations of the use of the NIF for specifically locating wildfire emissions have shown some limitations of the format for these types of emissions. While the NIF as currently structured will largely work for most aspects of fire emissions, current thinking is that they should generally be considered more like point sources than they have in the past where they were typically treated as area sources. This has created issues with the current NIF structure particularly the way that the NIF structure would handle plume characteristics of fires.

Other entities have found other limitations to the NIF structure. The Western Regional Air Partnership (WRAP) has recently embarked on the development of an Emissions Data Management System (EDMS) which is largely based on the NIF structure. However, in that work effort, WRAP has developed modifications to the NIF structure to handle fires, meteorological and geographic information.

As another example, the current NIF structure is not particularly well suited for handling link-based mobile source data. Most mobile source inventory data stored in the NIF currently is housed at the county level.

Under most current regional air quality modeling systems, emissions data must currently be "pre-processed" for use in the model. Thus most data management systems are not currently set up to handle "model" ready data in the sense that the data must still be processed prior to use in the various models.

Clearly, the application of the emissions data plays a large role in determining the overall requirements of an emissions data management system. However, it is important to also remember that even when most of the applications of the data are known, frequently, the data will also be used in applications beyond those originally intended. This can be clearly seen from the changes that the NIF has undergone over the last few years.

4.8.3 Data Quantity

The total amount of data that a database management system must store will frequently determine the characteristics of the system. Data requirements depend upon the types of data being stored, the period of time the emissions cover, and the data usage. For example, the amount of data received by EPA from submitters to the NEI can be significant. A decade's worth of emission inventory data contained within the NEI requires on the order of 50 gigabytes. This amount of data requires advanced data management systems and capabilities. Local inventories for a county or municipality can effectively be housed in a spreadsheet or a MS Access (or similar) database management system especially if the use of the data is limited to simple inventory needs rather than air quality modeling.

Current trends have been towards larger and larger datasets. This is largely related to three things. First, the amount of computing power and data storage capacity that an individual or group has at their disposal has significantly increased over the last decade. Second, the tools with which to manage larger amounts of data have significantly improved. Finally, the uses of the data have typically expanded. These factors have generally led to a significant increase in the quantity of data that many emission database management systems must handle.

4.8.4 Data Quality

Data quality has become an issue of increasing concern for emission inventory developers. Estimates of uncertainty and an understanding of the lineage of the data have become increasingly important for current inventory practices. This is particularly true for the NEI. For the NEI, State/local/industrial/Tribal agencies frequently either do not collect the necessary data or do not have access to it. In those cases, EPA may use surrogate data or use default values to fill in missing data. For example, for HAPs, Toxic Release Inventory (TRI) data are often used to fill in missing or incomplete information. Data used for the development of Maximum

Achievable Control Technology (MACT) standards have also been used as inputs for the NEI HAP data. Growth factors are sometimes applied to old NEI data in order to calculate emissions for more current years for NEI submittals. This data mix has resulted in a large emission inventory having inconsistent data of uncertain quality and inconsistent lineage.

Several attempts have been made to improve the understanding and of and the actual quality of emission inventories. For example, EPA developed the Data Attribute Rating System (DARS). That system was designed to assign quantitative rankings to the various aspects of inventory development (emission factors, activity data, etc.) so that the overall quality of individual data elements could be ascertained. Specific guidance for applying the numeric ratings to these data elements was developed and the results were typically used to understand which sectors of the inventory were of higher or lower quality than others.

Since implementing the NIF, EPA has also attempted to provide quality assurance tools for the actual data submitted to the NEI. As part of this attempt, EPA has developed a program called the Basic Format and Content Checker. Based on ASCII text or MS Access database inventory files, the program generates multiple reports identifying missing and invalid information in the submitted inventory. This allows the submitter to make necessary data corrections early in the process, when the information is more readily available. After submittal, work is done to further QA the data, fill in data gaps, and prepare the data for loading into the NEI database, so that the majority of State submittals still require extensive data manipulation efforts in order to be placed in the NEI. While this tool provides a significant mechanism for ensuring that the data submitted are within likely bounds, and that the data are amenable to use in a relational database system (e.g., by checking for widowed and orphaned records), it does not address the lineage of the data received, nor does it address the mixture of data levels that can be submitted to the inventory. In addition, it is intended only for the NIF format and does not provide QA tools for other inventory data.

Environment Canada does not provide a quantitative estimate of the uncertainty for its emission inventories. Qualitative estimates are available and were included in the NARSTO PM Assessment.

Different QA/QC tests are performed on the information contained in the NPRI and RDIS II databases. For example the information collected through the NPRI is verified using a series of validation functions which are triggered within the electronic reporting form used by the industries. Similar validation functions are also applied to the information reported by the industries before it is transferred into the main database for storage and querying. These validation functions include:

- The verification of all required fields;
- Reported values are verified to ensure that they are within expected ranges;
- New data is compared to previously reported data for each facility.

Data outliers are identified and facilities are contacted to correct the data anomalies.

Verification of the information contained in the RDIS II database is also performed on a regular basis. The provincial information received usually includes process level information and undergoes the same validation functions as for the NPRI data. Additional validation is performed on this information which include:

- Verification that all CAC contaminants were estimated or reported;
- Emissions levels are within the expected levels and ratios;
- Emission methodologies and emission factors reflect the most up to date information available.

4.8.5 Data Accessibility

In current systems, accessibility (and data dissemination) are largely issues of making emissions data more readily available on a quicker schedule than in the past to a wide variety of users in a format that is relatively transparent (or easily understood).

Under current capabilities, the primary mechanism for data access and dissemination is by the use of the Internet. NEI data and documentation are made available through the EPA's website at: http:/www.epa.gov/ttn/chief/eiinformation.html. NEI data files on this website are in MS Access format, and can therefore be used by people having access to the Internet and a PC. The amount of data present in the NEI requires the use of a robust PC and knowledge of MS Access. The data are also available using file transfer protocol (FTP) sites. For large data sets, this is the quickest means of accessing complete data sets.

EPA has also developed a series of programs with which NEI data can be accessed over the Internet. For example, EPA has developed a user-friendly web-querying tool called NEON (NEI on the NET). This system allows users to access data down to the process level from the NEI. For example, NEON allows users to select the information that they wish to see, and the data can be output on screen or downloaded in MS Excel spreadsheet format. In coordination with the SAS Institute, EPA has developed the AirData system that provides color-coded geographic maps displaying varying intensities of air pollution. The SAS software allows users to map air pollution to the county level for all states for which data is present in the NEI. However, NEON is currently only available internally via the EPA intranet to EPA personnel. Future plans call for access to the public.

4.8.6 Data Dissemination

While the NIF defines a particular format, agencies may submit the inventory in one of several different electronic formats: flat file, Access database, and eXtensible markup language (XML). XML is designed to store any kind of structured information and improve the functionality of the Internet by providing more flexible and adaptable information identification. XML makes it possible for diverse computer systems (and data applications specifically) to share easily data stored in different formats across multiple computer platforms. XML makes it easy for a computer to generate data, read data, and ensure that the data structure is unambiguous across platforms, formats, and applications. XML enables a user to define a custom markup language for transferring data.

Dissemination of emissions data at this point is largely via the Internet through any of the mechanisms listed in this section and the data accessibility section.

4.8.7 Data Lag Time

A major issue facing emission inventory data management is data lag time. As usage of the Internet and other "data now" capabilities increase, the expectation is that emission inventory data should also be available in real time. Current practices within EPA generally show a lag time of several years between the actual date and the most recent inventory year of record. For example, the most current version of the NEI is for calendar year 2002, a lag time of approximately two years. This concurrency issue is perhaps one of the biggest facing inventory data management in the future. How to build the infrastructure necessary to successfully collect and calculate emissions from various sources in a time frame that is close to real time. Real time emissions data management is unlikely for many types of sources (especially smaller area sources). However, real time emission estimates for some point sources is becoming an increasing reality. The use of continuous emissions monitors (such as those called for under the Acid Rain provisions of the Clean Air Act Amendments) provide one example of the potential for real time reporting of emissions values. They also provide further support for the increase in the amounts of data being reported to regulatory and other agencies.

These issues, data transparency, data applicability, data quantity, data quality, data accessibility, data dissemination, and data lag time means that there are no simple solutions to solving the data management issues. Certainly, there are many lessons to be learned from the issues associated with managing the NEI and other emissions data management solutions, and with sufficient time, experience, and technological improvements, significant progress will be made towards addressing these data management issues.

4.9 QA/QC METHODS

The Intergovernmental Panel on Climate Change (IPCC) provides definitions for both QA and QC as it relates to emissions inventories. The IPCC defines emissions inventory QA as follows:

> *Quality Assurance (QA) activities include a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process. Reviews, preferably by independent third parties, should be performed upon a finalized inventory following the implementation of QC procedures. Reviews verify that data quality objectives were met, ensure that the inventory represents the best possible estimates of emissions and sinks given the current state of scientific knowledge and data available, and support the effectiveness of the QC program) (IPCC, 2000).*

The IPCC provides a rigorous definition for QC as it pertains to emission inventories. Specifically, the IPCC definition sets forth three goals for QC systems:

> *Quality Control (QC) is a system of routine technical activities, to measure and control the quality of the inventory as it is being developed. The QC system is designed to:*
>
> *(i) Provide routine and consistent checks to ensure data integrity, correctness, and completeness;*
> *(ii) Identify and address errors and omissions;*

(iii) Document and archive inventory material and record all QC activities.

> *QC activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardized procedures for emission calculations, measurements, estimating uncertainties, archiving information and reporting. Higher tier QC activities include technical reviews of source categories, activity and emission factor data, and method (IPCC 2000).*

In June 1997 the Emission Inventory Improvement Program (EIIP) (IPCC, 1997) published a guide of quality assurance and quality control methodologies that can be employed for emissions inventories (EIIP is a jointly sponsored effort by STAPPA/ALAPCO and the US EPA). EIIP methodologies include, in order of decreasing complexity, reality checks, peer review, sample calculations, automated checks, sensitivity analysis, statistical checks, independent audits, and emissions estimation validation.

The format of the emissions inventory is a key driver in determining how QA/QC routines are applied. For example, an emissions inventory that is built on the basis of a spreadsheet will have different QA/QC requirements than an emissions inventory that is built around a database. The size of the emissions inventory is also a driver to the type of QA/QC routines that are used. For example, automated routines may not be necessary for small inventories but are essential for regional or national ones.

Large emission inventories contained in databases are of particular concern due to their size and complexity. Three useful QA/QC methods for assessing the quality of an emissions inventory are 1) examining the content of supplemental fields, such as SIC and NAICS codes, geographic location, and pollutant, 2) if there are multiple tables in a relational database, then one can check that correct parent-child relationships exist, and 3) evaluating the emissions numeric values.

In the former, one can check that those fields in the inventory that are required to have an entry do have an entry, whether it is valid or invalid. As a second step for those fields that are restricted to certain values, the entry can be compared to values in a lookup table. For example, the NAICS codes, SIC codes, and pollutants in the inventory can be compared to an acceptable list of codes or names. For locational data, the x- and y-coordinates of a point source can be checked to see if they lie within the boundaries of a geographic entity such as a county or State.

If the inventory is defined in terms of relationships between tables, in which there is an association between common fields in two tables, then these relationships can be checked to ensure that correct parent-child relationships exist. For example, if there is a relationship between a table with geographic information for point sources and a table with emission values for those point sources, one can check that for each record in the table of geographic information there is at least one record in the emissions table.

Another method of assessing an emissions inventory is to examine the actual emissions data by filtering the data with different criteria. These methods can be simple lists, statistical comparisons, or graphical methods. Lists of top emitters (facilities or sources at facilities) by pollutant can be compiled to determine if any of the emissions appear to be too large relative to the emissions of other facilities or points. Similar lists can be compiled by geographic region to determine if one region's emissions exceed those of other regions. If this appeared to be the case, then the list of top emitters, as described above, in that region could be examined. Emissions by a specific classification group, such as the NAICS, can be examined. Not only can the emission values be checked, but if specific pollutants are known to be associated with a classification, then the inventory can be checked to be sure there are no pollutants that do not belong to the classification. Graphical methods include frequency histograms to provide graphical representations of the distribution of the emissions that illustrate the distortion and spread of the data, as well as the presence of outliers. Another graphical aid displays emission density maps to see where the majority of the emissions occur. These ideas can be applied to a single inventory or comparing two inventories, such as one year to another, or one region (e.g., county) to another.

USEPA has developed two programs that perform varying QA/QC checks on incoming state NEI submittals. The first program, called the Basic Format and Content Checker is designed to QA/QC MS Access or ASCII submittals in Version 3 of the NEI Input Format. This program checks to ensure that mandatory fields are filled, that tables and field names are correct, and it also checks for duplicate data records. In addition, the program performs referential integrity checks to ensure that relationships between tables are correct. Finally, as an option, the program can also perform contents checks. In this case, it compares reported values against those provided by lookup tables.

USEPA has also developed the Extended QA tool which is designed to review hazardous air pollutant and criteria air pollutant related data in NEI submittals. The Extended QA tool is used to examine actual emissions data contained in NEI submittals. The tool can be used to identify top emitting facilities by geographic region or by NAICS/SIC code. Depending upon the availability of data, the tool can also analyze multi year emissions data. This tool is particularly useful for identifying outliers within data submittals.

While objective methods for assessing an emissions inventory can be developed, the analysis of the results from those methods require the intervention of someone familiar with the inventory to ultimately decide whether or not the data in the inventory are valid or need to be modified. Consequently, QA/QC tools are of importance, but the ultimate checks must be performed by those familiar with the sources and magnitudes of emissions.

4.10 NEAR-TERM INVENTORY NEEDS

The diversity of inventory-related needs among the three NARSTO countries should be noted. Stemming from geographical and industrial differences as well as varying states of inventory development, this diversity suggests that Canada, the United States, and Mexico should place different emphases on immediate development efforts in several specific areas. Table 4.11 provides an indication of these varying emphasis levels for the three NARSTO countries.

Table 4.11. Important Inventory Limitations and Associated Needs for Immediate Emphasis in Canada, the United States, and Mexico.

Mexico	Canada	United States	Resolution	Potential for Support –New Methods
Complete detailed national inventory, emphasis on the northern sectors.	Refine national inventory with resources available.	Upgrade NEI and components, with improved AP-42, and emissions models.	Use established methodologies with assistance of modeling techniques, and error identification.	Improved use of measurements combined with calculation methods open opportunities
Particular attention to carbon (VOC, OC, BC), $PM_{2.5}$, NH, Biomass, toxics	Particular attention to Carbon (VOC, OC, BC), $PM_{2.5}$, NH wildfires, toxics	Particular attention to Carbon (VOC, OC, BC), NH_3, fires, HAPS	High priority for measurements and EF, Activity development	New measurement methods and reconciliation needed to address emerging issues
Estimate uncertainties and priorities for improvement	Quantify uncertainties in estimates, especially industrial sources, fire, and transportation	Quantify uncertainties in NEI, especially transportation and area sources	Difficult problem, requires combined measurements, and improved estimation techniques	Measurement uncertainties and reconciliation methods applied systematically.
Air quality model support for cities driver	Air quality model support an important driver	Air quality model an important driver with fine spatial and temporal resolve.	Emissions models continue to develop as part of modeling evolution-attention to transportation and diffuse sources.	Modeling requirements need to be met with new emissions models and focus on emerging pollutant specs.
Transboundary exchange secondary driver	Transboundary exchange secondary driver.	Extremes in space and time scales for models crucial for health effects and for intercontinental assess.	Seek reasonable uniformity in reporting emissions by country; attention to improved estimates by scale and time.	Modeling continues to push extremes of spatial and temporal scales with improved emissions estimation.
Regional applications become more important	Urban focus in US-Canada boundary concern for health and welfare.	Multiscale applications will increase with stakeholder and international needs.	Model applications combined with emissions models will continue to evolve with more sophistication as needed.	Expect methods reconciliation to continue improvement. Improved definition and application of uncertainty analysis.
Increase accessibility for stakeholder use	Increase accessibility for stakeholder use within legal constraints	Increased efficient stakeholder access important	Adoption of improved data management methods for user friendly access	Application of new, efficient means of data base management.
Provide for regular update with consistent methodology	Provide for regular update for progress tracking	Measure of progress critical element for NEI	Requirement for continued stakeholder interaction and efficient use of data management skills.	Updates require continuing stakeholder attention and support, use of new methods may help obtain data more rapidly.
Improve ability to make emissions projections	Improve ability to make emissions projections.	Improve ability to make projections important element of planning	Requires integration of local and regional socio-economic and technology outlooks.	Projections problematic, but need for more attention to looking a to progress relative to predictions for improvement.

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CHAPTER 5. STRENGTHS AND WEAKNESSES OF CURRENT INVENTORIES AND MODELS: SENSITIVITIES, UNCERTAINTIES AND EVALUATION PROCEDURES

5.1 INTRODUCTION

Chapter 2 summarizes the development of emission inventories, which generally involves a combination of direct measurements, emission factors, activity factors, and emission models. However, because of random sampling error, measurement errors, unrepresentative samples of pollutant sources, and possibly other errors, uncertainty is introduced. In order to maximize the usefulness of emission inventories, it is important to understand and quantify the uncertainty in those inventories. ***Uncertainties are rarely, or not rigorously, quantified in emission inventories and models.***

This section introduces basic concepts and terms used in uncertainty analysis of emission inventories, which are presented in the textbox on the following page; a conceptual framework for quantifying variability and uncertainty in emission inventories; and the distinction between uncertainty analyses versus sensitivity analyses, and concepts regarding evaluation, verification and validation of emission models and inventories.

5.1.1 Conceptual Framework for Quantifying Variability and Uncertainty in Emission Inventories

In order to quantitatively characterize variability and uncertainty in emission inventories originating from variable and uncertain emission factors and activity factors, typically a probabilistic approach is used. In the probabilistic approach, probability distributions are developed for emission factor and activity factor data sets or elicited from expert judgment. These probability distributions often represent variability. Since emission inventories are typically aimed at estimate the sum of emissions for many source categories, the use of average emission factors is appropriate. Because of random sampling error, measurement error, or lack of representativeness of the available data, there can be uncertainty regarding the true value of each estimated average emission or activity factor. Consequently, there can also be uncertainty regarding the true but unknown frequency distribution regarding inter-unit variability among sources within the population of all sources in a category. As a result, there is uncertainty in any estimate of any statistic of the population, such as the average emission factor and average activity factors. The uncertainty in emission and activity factors can be propagated through the emission inventory to simulate the uncertainty in the estimate for the total emissions from a population of emission sources, typically based upon Monte Carlo simulation. Figure 5.1 shows the conceptual framework for propagation of variability and uncertainty in emission inventory model inputs to quantify the uncertainty in the estimate of total emissions (Frey et al., 1999).

Definition of Terminology

Accuracy	Agreement between the true value and measured observations of a quantity.
Bias	A bias exists when there is a discrepancy between the true value and the average result obtained from a model. Bias is also referred to as constant error or systematic error.
Precision	Agreement among repeated measurements of the same quantity
Precision vs. Accuracy	Figure 5-a and 5-b illustrates the difference between precision and accuracy. A model may be accurate but not precise. In contrast, a model may be biased but may produce precise

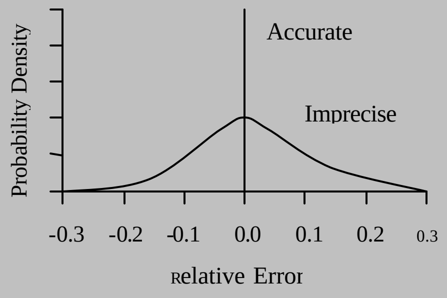


Figure 5-a. Accurate and imprecise model

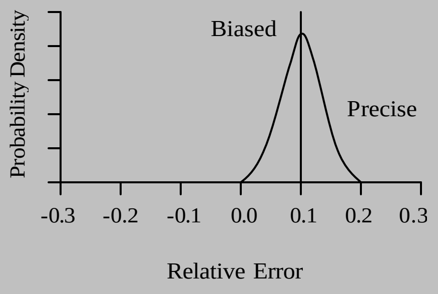


Figure 5-b. Biased and precise model

Random Error	The deviation of individual measurements from the average of the population of measurements. Random error in the context of measurements is inversely related to precision
Sensitivity Analysis	A study of how the variation in the outputs of a model can be attributed to, qualitatively or quantitatively, to different sources of variation in model inputs (Saltelli et al., 2000).
Systematic Error	If the error remains constant or arises from consistent and repeatable sources (like an offset in calibration), it is referred to as systematic error.
Variability	Variability is the heterogeneity of a quantity over time, space or members of a population (Morgan and Henrion, 1990; Cullen and Frey, 1999). Variability may arise, for example, due to differences in design from one emitter to another (inter-plant variability) and in operating conditions from one time to another at a given emitter (intra-plant variability). There may be inter-vehicle or inter-unit variability, temporal variability over time and spatial variability across geographic areas.
Uncertainty	Uncertainty refers to a lack of knowledge about the true value of a quantity (Cullen and Frey, 1999). For example, there exists uncertainty in average emission factors for a source category due to random sampling and measurement error and uncertainty in emissions for a given point time due to temporal variability.
Uncertainty Analysis	A study of how uncertainty or errors in model inputs are characterized and propagated to model outputs

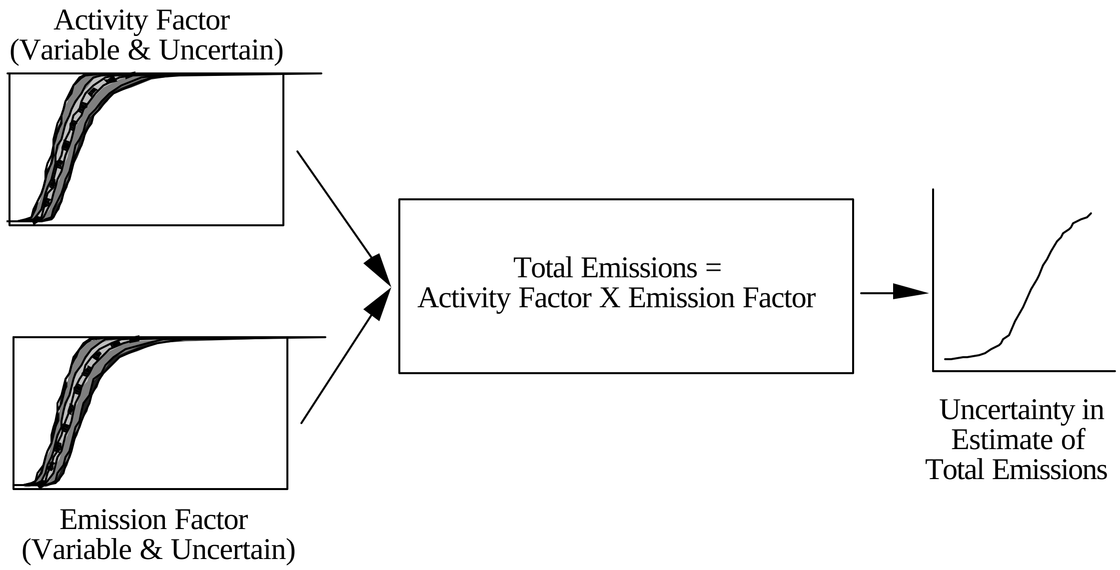


Figure 5.1. Conceptual Framework for Propagation of Variability and Uncertainty in Emission Inventory Inputs to Quantify the Uncertainty in the Estimate of Total Emissions.

5.1.2 Uncertainty Analysis vs. Sensitivity Analysis

Both uncertainty analysis and sensitivity analysis are important components in probabilistic emission inventory development. Although uncertainty and sensitivity analysis are highly complementary, they are actually two different types of analysis. In uncertainty analysis, the objective is to quantify uncertainty in a predicted quantity of interest, such as total emissions for many source categories for a specific time period and geographic area. In sensitivity analysis, the objective is to determine which specific inputs to the estimate contribute the most to the overall estimate of uncertainty (Cullen and Frey, 1999).

Sensitivity can be expressed in terms of a *derivative*, $s_{i,j} = \frac{\partial q_i}{\partial \alpha_j}$, which reflects the change in some quantity q_i caused by a change in some variable α_j (e.g., the change in emission rate of species *i* caused by a change in process temperature). *Uncertainty* is typically expressed in terms of a *pdf* or (as indicated in Figure 5.1) a *cumulative distribution function (cdf).* This concept can be used to express (local) uncertainty of a single phenomenon as well as (global) uncertainty arising from joint contributions of a number of phenomena.

Uncertainty analysis is typically used to characterize uncertainty in total emissions. Sensitivity analysis is used to identify the key input uncertainties that contribute the most to the overall uncertainty in the inventory. Because uncertainty arises because of lack of perfect knowledge of the true but typically unknown value of actual emissions, uncertainty can be reduced by obtaining better information and improved knowledge. Therefore, insights regarding key sources of uncertainty can be used to assess priorities for collecting additional data or information in order to reduce uncertainty. Sensitivity analysis is typically used to (1) assist in verification/evaluation of emission inventory models, (2) identify key sources of variability and uncertainty; and (3) evaluating the importance of key assumptions during emission inventories development (Russell and Dennis, 2000).

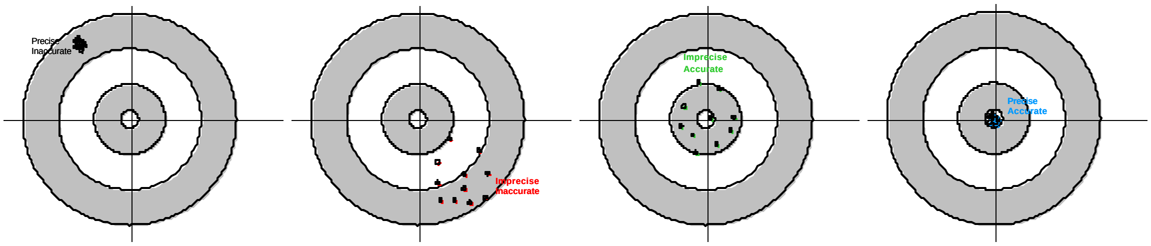
Uncertainty analysis is typically implemented with the use of error propagation techniques including analytical Taylor series expansion, or, more typically, numerical analysis methods such as Monte Carlo simulation and its variants. Sensitivity analysis can be implemented in several ways. For example, when a Monte Carlo simulation or similar technique (e.g., Latin Hypercube sampling) is used for the uncertainty analysis, sensitivity analysis is typically conducted using statistical methods such as correlation coefficients, regression analysis, analysis of variance, categorical and regression trees and others.

5.1.3 Evaluation, Verification and Validation

Evaluation of emission inventories includes evaluation of emission data and emission models used for development of emission inventories. Evaluation typically pertains to seeking internal checks regarding the consistency of the inventory and external checks regarding the validity of the inventory. As a matter of good practice, it is assumed that appropriate quality assurance and quality control (QA/QC) procedures are followed when developing the inventory. Such procedures assist with verification of the inventory but do not necessarily address the validity of the inventory. For example, according to one definition, evaluation of emission models is an assessment of the adequacy and correctness of the science represented in the emission model through comparison against empirical data, such as laboratory test, in situ test (Russell and Dennis, 2000). Here, emission model and inventory evaluation can be done through model verification and validation.

Model verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model (Russell and Dennis, 2000). Verification of emission models can help determine the consistency, completeness, and correctness of the fundamental equations or methods, and of computer codes of emission model systems compared to design criteria and objectives of model development. Model verification typically includes the following steps: (1) ensuring that mathematical model is correct; (2) making sure that the computerized version of mathematical model is correct; and (3) ensuring that the values of the inputs are correctly specified (Cullen and Frey, 1999). Model verification can be done through comparison of computer code calculations to hand calculation or with an alternative calculation scheme and another independent version of computer code of the model. However, model verification can not ensure that model design correctly and sufficiently represent real world emission systems.

Model validation is the process of determining whether a model is an accurate representation of the real world from the perspective of the intended uses of the model (Oreskes et al., 1994). Model validation can be done by comparing the model results to observations from the system being modeled. Ideally, if there are independent data available for model inputs and systems, it is possible to assess the accuracy and precision of a model. A model that is accurate will generate a prediction, on average, that is equal to the "true value" of the quantity. Precision refers to the agreement among repeated predictions (Cullen and Frey, 1999). Figure 5.2 depicts some possible combinations of precision and accuracy, based upon analogy with a dartboard. It is possible to have a model that is accurate but imprecise, precise but inaccurate, both inaccurate and imprecise, or both precise and accurate. A known systematic error (or bias) can be corrected to convert an inaccurate prediction to an accurate prediction.



(a) (b) (c) (d)

Figure 5.2. Conceptual Diagram of Precision and Accuracy of Hitting a Target, Analogous to the Ability of a Model to Predict a True but Unknown Quantity: (a) Inaccurate but Precise; (b) Inaccurate and Imprecise; (c) Accurate but Imprecise; and (d) Precise and Accurate.

Comprehensive validation of emission models or inventories can be very difficult because of complexity of emission models, and cost and difficulty in collecting emission data. For example, with respect to validation of vehicle emission factor models, independent observed data may be available only for small numbers of vehicles or for conditions that are not the same as the driving cycles used to develop the model (e.g., tunnel studies of steady-state driving on a short link versus area-wide trip-average emission estimates from MOBILE). Thus, validation may be possible for only parts of the models or can be made only approximately, since there are known differences between the basis of the model and the basis of the available independent data. Situations in which models are tested against data for only parts of model domain are known as partial validation. It may be possible to make theoretical arguments for asserting that partial validation implied that overall validity of the model (Rish, 1988). For example, a sensitivity analysis may reveal that only parts of a model are critical to making a particular prediction. Therefore, it is more important to have validation for the most sensitive or critical parts of a model.

5.1.4 Organization of This Chapter

This chapter begins by reviewing some tests of the strengths and weaknesses of current emission inventories. These tests are “top-down”, i.e., tests conducted outside the structure of the emission inventory. They do not explicitly consider individual components (emission factors, activity factors) that go into the development of inventories from the “bottom-up”. Rather they consider completely independent information. Thus, a “top-down” approach can also be thought of as a verification or validation, at least partially, of the inventory. For example, measured ambient concentrations, under at least some conditions, can be directly related to the emissions responsible for the ambient levels, and hence provide a test of the inventory of those emissions. These tests are important because they provide an indication of the accuracy of existing inventories. However, generally they do not provide clear guidance regarding the specific cause of any indicated inaccuracies.

The remainder of the chapter deals with systematic approaches for quantifying inventory uncertainty from the “bottom-up”, i.e., working within the structure of the inventory to derive a quantitative measure of the inventory uncertainty through uncertainty analysis and sensitivity analysis. These approaches are complementary to the top down tests, because they can apportion the uncertainty of an inventory to the various components that go into the inventory. Such apportionment is critical for identifying the most effective approach for improving inventories. Finally, key findings, conclusions and recommendations applied to future emission inventory development are summarized.

5.2 STRENGTHS AND WEAKNESSES OF CURRENT EMISSION INVENTORIES: TOP-DOWN TESTS

This section has two major goals: first, to introduce various “top-down” techniques for evaluating the strengths and weaknesses of current inventories, and second, to provide evaluations, in so far as possible, of important sectors of current inventories. It implicitly assumes that the ambient measurements or other independent information used in the evaluations are accurate, and that they are correctly interpreted. Any discrepancies uncovered are assumed to be due to weaknesses in the inventories, and, where possible, suggestions for the modification of the inventories are made so as to resolve the discrepancies. However, it must be kept in mind that the accuracy and interpretation of the measurements may have weaknesses themselves. As reflected in the Emission Inventory Flow Diagram (Figure 2.1), the discussion presented here must be considered as only the first step in a repetitive process of improving both the inventories and their evaluation through these top-down tests. The ultimate goal is to bring the inventories and their evaluations into agreement.

5.2.1 Evaluation of Road Transport Emissions

Road transport emissions are perhaps the most important in the inventory because they account for a major share of VOC, NO_x and CO emissions. Additionally, these VOC emissions provide the majority of the most photochemically reactive VOCs, and road transport emissions are localized in urban areas, which account for the majority of the NAAQS ozone violations. Accurate estimates of these emissions are difficult since they must integrate the emission factors (e.g., grams/ mile driven) for a diverse, constantly evolving vehicle fleet multiplied by highly variable activity factors (e.g., average miles driven per unit time for each vehicle type). In this section we examine the reported road transport emissions for internal consistency over the past ~20 years, and for inconsistencies with ambient measurements, which may indicate weaknesses of the inventories.

<u>5.2.1.1 History of temporal trends of road transport emissions in NEI</u>

Each year the U.S. EPA reports estimated road transport emissions and their trends over the previous decades. Our goal here is to examine a sample of these reports (Saeger et. al., 1989; EPA, 1990; 1995a; 2000; 2004) to determine if the derived estimates are converging to more precisely defined values, or if there is a significant element of scatter in the estimates that may indicate fundamental uncertainties in the methods underlying the estimates.

Figure 5.3 presents estimated road emissions for the three major classes of vehicle emissions; it is clear that the different inventory development techniques that have been used over the years have yielded results that differ in some important respects. For 1998 (the last year reported in the 2000 Trends Report) only minor changes of 10 and 11% increases are noted in the VOC and NO_x emissions, respectively, between the 2000 and 2003 reports. However, the estimate for CO increased by 45%. A further curiosity is evident in the 2003 estimates; CO increased by 10% from 2000 to 2001 while VOC decreased by 9%; since CO and VOCs are controlled by the same techniques, such a divergent change must be questioned. These comparisons suggest that the most recent emission estimates are uncertain by at least ~10% for VOC and NO_x and ~50% for CO.

Of perhaps greater concern is the larger variability apparent in the estimates for earlier years. For example, for 1985 (the one year with estimates from all five inventories) the 2003 report estimate is higher than all previous estimates by factors of up to 1.35, 1.6 and 2.5 for VOC, NO_x, and CO, respectively. These relatively large factors indicate that the road emission estimates for the past two decades are significantly less certain than the estimates for more recent years.

5.2.1.2 Temporal trend of road transport CO emissions in NEI compared to ambient observations

Careful analysis of ambient measurements of emitted species can, in many instances, provide valuable insights into the magnitude and temporal trends of the emissions that produce the ambient concentrations. Our goal here is to use the temporal trend of ambient CO concentrations in U.S. urban areas to test the temporal trends of CO emissions included in inventories.

Figure 5.4 shows the emissions from Figure 5.3 for the two most recent trends reports compared with measured mean CO ambient levels. The latter are the means over more than 300 U.S. urban sites for the second highest annual maximum 8-hour average. It is appropriate to compare these quantities since road transport emissions are responsible for the maximum urban levels reflected in these measurements.

The trend of the mean ambient concentration follows the trend in the 2003 report much more closely than that in the 2000 report. This conclusion is supported by the average 1980-1999 yearly decreases; 4.4 %/yr for the ambient concentrations compared to 4.2 and 2.7 %/yr for the 2003 and 2000 Trends Reports, respectively. However, while these comparisons indicate that the temporal trend in the 2003 report is much more consistent with ambient measurements than that in the 2000 report, they provide no information regarding the accuracy of the absolute emissions in any particular year or report.

One difference between the ambient trend and the trend in the 2003 report is apparent in Figure 5.4 for the most recent years. The ambient data show no indication for the slowing and reversal of the decrease in emissions from 2000-2001 – the curiosity noted in the preceding section. When the ambient data from 2002 are available, this comparison should be more definite.

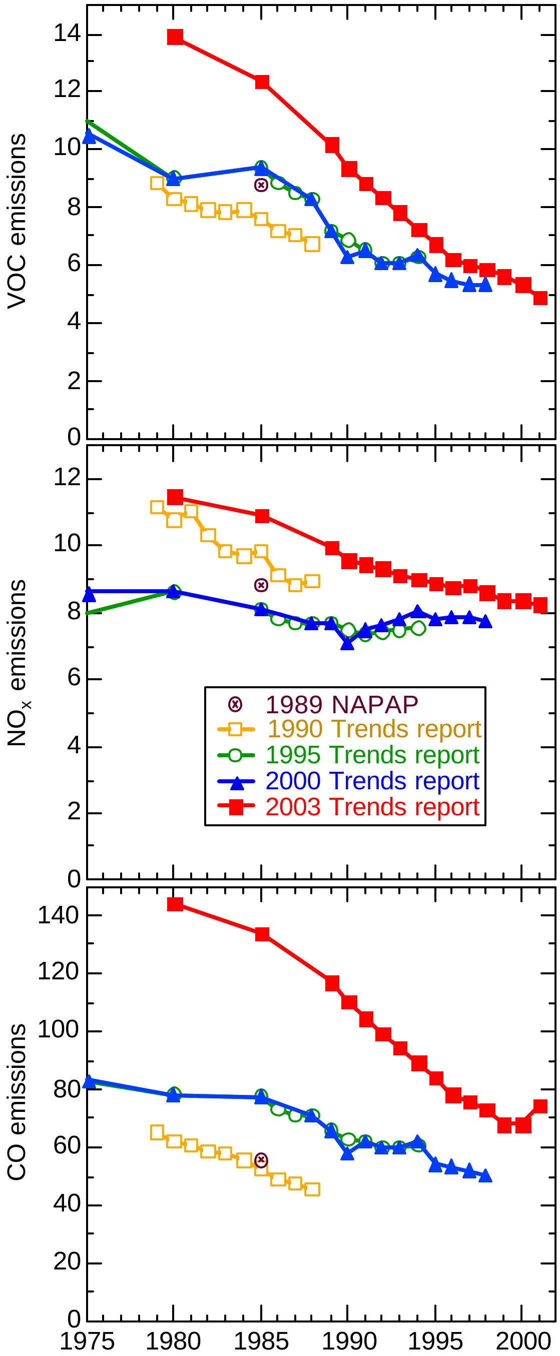


Figure 5.3. National road transport emissions from five U.S. inventories in units of 10^6 tons/yr. Road transport sources are given, except for total transport sources for NAPAP and the 1990 Trends Report, and total area sources for NAPAP CO; these exceptions are the most detailed breakdown available in the published reports. The dates indicate the year of publication of the inventory report.

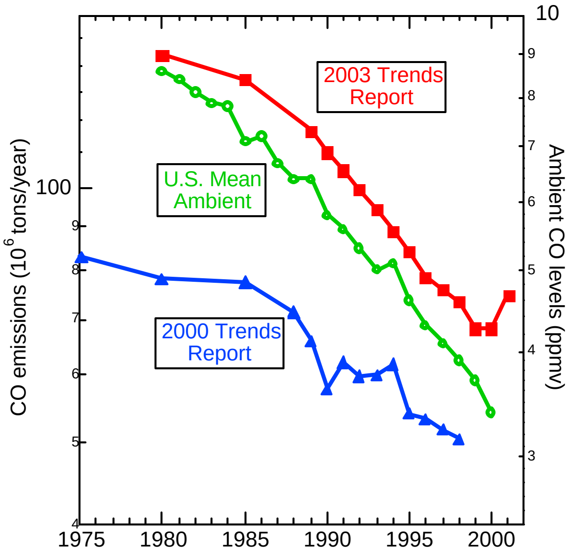


Figure 5 4. Semi-log plot of national road transport temporal emission trends. Two U.S. inventories are compared to observed urban ambient levels.

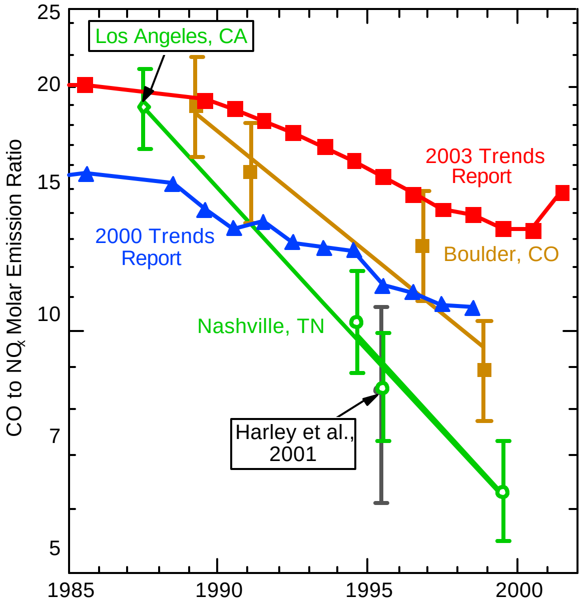


Figure 5.5. Semi-log plot of temporal trends of CO to NO_x ratio in road transport emissions. National emissions from two U.S. inventories are compared to urban ambient ratios. (Figure closely follows that of Parrish et al. [2002])

Hallock-Waters et al. [1999] note that rural U.S. CO levels have also decreased, but at a rate of only about 3%/yr. This slower rate of decrease reflects the contribution to rural CO levels from sources other than road transport, both within and outside the U.S. Thus, both urban and rural measured ambient CO concentrations are consistent with the decreasing temporal trend of road transport CO emissions presented in the 2003 Trends Report, at least before the year 2000.

5.2.1.3 Temporal trends of road transport CO/NO_x emission ratios in NEI compared to ambient measurements

In favorable situations ratios of ambient concentrations can be directly compared with ratios of the emitted species. Figure 5.5 shows the CO to NO_x emission ratios from road transport sources in the two most recent trends reports discussed in the preceding sections. Parrish et al. [2002] utilized ambient measurements of CO and NO_x made during the morning traffic peak at carefully selected urban sites to compare with the absolute values and temporal trends of CO to NO_x inventoried emission ratios. These comparisons (Figure 5.5) span 12 years in three U.S. urban areas. These emissions are shown to be representative of the national road transport emissions, and that the summer L.A.-Nashville trend likely represents the trend in the national emissions. (The Boulder ratios are higher due to the higher elevation and the winter season of those measurements.)

Comparison of the trend defined by the Nashville-Los Angeles data with the inventory trends leads to two conclusions. First, the inventory ratios are higher by as much as a factor of 2 or more, especially in the 2003 trends report and particularly in more recent years. This suggests that the CO emission estimates are higher and/or the NO_x emission estimates are lower than can be consistent with the ambient measurements. Second, the temporal trends of the inventory ratios are not nearly as steep as the trend of the measured ratio. This conclusion, combined with the good agreement found above for the temporal trends of the ambient levels and the 2003 inventory emissions for CO, suggests that NO_x emission estimates are decreasing too rapidly (or increasing too slowly) to be consistent with the ambient determinations.

5.2.1.4 Comparison of fuel-based and mileage-based road transport emission estimates

An effective comparison for the mileage-based approach to emission inventory development used by the U.S. EPA is a fuel-based approach. Harley et al. [2001] developed an inventory for Nashville, TN in 1995 by taking gasoline and diesel fuel sales as the activity factor and determining emission factors expressed as per unit of fuel burned. CO emission factors were determined from infrared remote sensing of over 34,000 vehicles at 13 sites in the urban area. VOC emission factors were estimated from these derived CO emission factors and measured VOC/CO ambient concentration ratios in central Nashville. NO_x emission factors were developed from roadway tunnel measurements made in other U.S. locations.

The CO/NO_x emission ratio from the fuel-based inventory [Harley et al., 2001] is compared to the ambient ratio in Figure 5.5. The excellent agreement gives us confidence both in the results of the fuel-based emission calculation, and in the validity of directly comparing those ambient concentration ratios with the ratio of the emissions from inventories.

Figure 5.6 compares the results of the fuel-based and EPA inventories. The EPA inventories are based on the MOBILE 5B emission factor model, which is the model upon which the 2000 Trends report is based. Thus, we will take the comparison in Figure 5.6 as a test of the 2000 Trends Report emissions. This comparison suggests three conclusions. First, there is excellent agreement in the total VOC and NO_x emissions. This comparison increases our confidence in these emission estimates from the 2000 Trends Report, and in the 2003 Trends Report as well, given the good agreement between the two trends reports for 1995 in Figure 5.3. Second, the EPA CO emissions are about 40% higher than the fuel-based estimate. Third, even though the total emissions agree well, the EPA NO_x inventory attributes a much smaller fraction (approximately a factor of 2) to diesel-powered vehicles and a larger fraction to gasoline-powered vehicles.

5.2.1.5 Reconciliation of estimated road transport emissions with ambient measurements

The three preceding sections have compared tabulated emissions to ambient measurements, and have identified some inconsistencies. These inconsistencies indicate significant errors, either in the inventories or in the ambient measurements and/or their interpretation. Here we begin a process of identifying the errors that underlie the identified inconsistencies, with the goal of guiding improvements in emission inventories as well as their evaluation through ambient measurements. This section focuses on the first step in this process, which is to suggest changes in the inventories necessary to reconcile them with the ambient measurements.

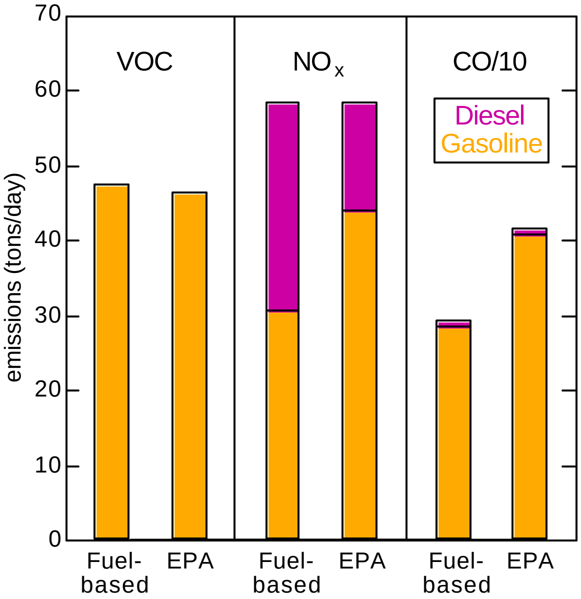


Figure 5.6. Comparison of fuel-based emission inventory for Nashville in 1995 with the EPA emission inventory for that county [Harley et al., 2001]. CO emissions are divided by 10 to include on the same ordinate.

Figure 5.7 shows inferred road transport emission estimates for NO_x and CO (black symbols) from 1990-2000 that are consistent with all of the ambient data discussed above. They are derived from three assumptions. First, consistent with the discussion in Section 5.2.1.2, CO emissions are assumed to have decreased by 5.1 %/yr, which is the temporal trend of the ambient CO levels for1990-2000. Second, consistent with the discussion in Section 5.2.2.3, the CO to NO_x emission ratio is assumed to have decreased by 8.8 %/yr, which is the temporal trend of the green line in Figure 5.3. These first two assumptions imply an increase in the NO_x emissions of

4.1 %/yr. Finally, consistent with the discussion in Section 5.2.2.4, the 1995 NO_x emissions from the 2000 Trends Report are assumed to be accurate.

This reconciliation implies errors in the road transport emission estimates. Two are particularly notable. First, CO emissions in the 2003 Trends Report are over estimated by a factor of 2 for 1990-2001. Second, NO_x emissions are increasing rather than decreasing. However, despite this divergent temporal trend, the inferred NO_x emissions are within 12% of the 2000 Trends Report values for all years and within 20% of the 2003 Trends Report values for all years after 1993. Interestingly, the inferred NO_x temporal trend closely follows the increasing trend of the first 5 years of the 1990s in the 2000 Trends Report.

No substantial inconsistencies have been identified in the VOC road transport emissions. The fuel-based and the EPA inventory consistent with the 2000 Trends Report agreed very well for 1995 in Nashville (Figure 5.5). The 2003 Trends Report estimates only 18% higher VOC road emissions than the 2000 Trends Report (Figure 5.3). The temporal trend of the VOC road emissions for 1990-2000 in the 2003 Trends Report corresponds to an average decrease of 5.7%/yr, which is in close agreement with the decrease in CO emissions of 5.1 %/yr assumed above. This close agreement between the temporal trends of CO and VOC road transport emissions is expected from on road vehicle emission studies (Parrish et al., 2002).

Future steps in this reconciliation process ideally will include feedback from inventory developers regarding the validity of the suggested inventory changes and evaluation of possible errors in the ambient measurements and/or their interpretation. With regard to this last point, the rate of increase in the inferred road transport NO_x emissions is derived from the difference between the rates of decrease of two temporal trends determined from ambient measurements. This difference between two measurement-derived quantities may be a significant source of uncertainty in the inferred emissions discussed here.

In Figure 5.7 the inferred increase in NO_x road emissions closely follows the trend in the early 1990's in the 2000 Trends Report. This increasing trend is not present in the 2003 Trends Report. It may be fruitful to investigate if the 2000 Trends Report is more accurate than the later report, and the cause of the disappearance of the increasing

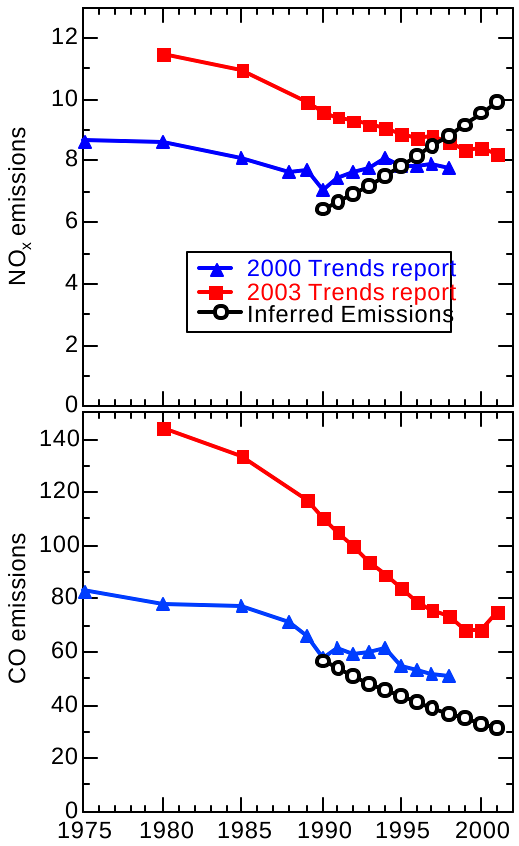


Figure 5-7. National road transport emissions from the two most recent U.S. inventories in Figure 5.2 compared to the emissions inferred from ambient measurements. Units are 10^5 tons/yr.

NO_x road emission trend between the reports. This investigation may focus on the inconsistency in the apportionment of NO_x emissions between gasoline and diesel fueled The emission factors for diesel vehicles have been stable, while diesel fuel consumption has been increasing.

Finally the inferred CO road emission trend in Figure 5.7 suggests that the road transport contribution to the total CO emissions has declined to about 40%, assuming that estimates for other CO sources are accurate. This implies that even more uncertain emission sources, such as non-road transport, are accounting for much of the inventoried CO emissions, and should be a focus for future uncertainty analyses.

5.2.1.6 Evaluation of VOC speciation

Careful evaluation of ambient VOC measurements can provide critical tests of VOC speciation in the NEI. Here we examine the example of benzene and acetylene. Both of these hydrocarbons are in the top ten in terms of ambient concentrations, are primarily from the same source (tailpipe emissions), and react slowly in the atmosphere. Fortin et al. [2004a] show that the benzene to acetylene ratio is remarkably invariant throughout the country in any given year, and exhibits long-term trends in response to VOC emission control measures (Figure 5.8). Before 1994, the ratio increased slowly due to the preferential removal of acetylene by automotive catalytic converters. Specific benzene control measures were begun in 1994 in response to the 1990 CAAA, which have reduced the ratio dramatically in recent years. These ratios and their trend can be compared to the VOC speciation in emission inventories. Benzene and acetylene emissions from three recent emission inventories are given in Table 5.1. The corresponding ratios are plotted in Figure 5.8. The National Air Quality And Emissions Trends Report, 1999 reports that the average annual ambient levels of benzene decreased by 40% from 1994-1999. It is curious that this decrease is not reflected in the benzene emission numbers.

Table 5.1. Emissions (10^5 moles/hr)[a]

Species	NAPAP 1985	NEI 1996	NEI 1999
Benzene	10.69	4.08	3.98
Acetylene	9.24	4.53	5.38
Ratio	1.157	0.901	0.740

[a] The emissions are given in units of moles/hr to ease direct comparison of inventories and the derivation of ratios. For comparison 1 mole/hr corresponds to 0.251 tons/yr of acetylene and 0.753 tons/yr of benzene. There are subtle differences in the units: 1985 are annual average hourly emissions; 1996 are hourly average for ozone season workday; and 1999 are hourly average for all summer days. These differences are likely small. The emissions exclude all fire emissions, because the ambient measurements were not significantly affected by fire emissions. The 1985 benzene emissions include halobenzenes.

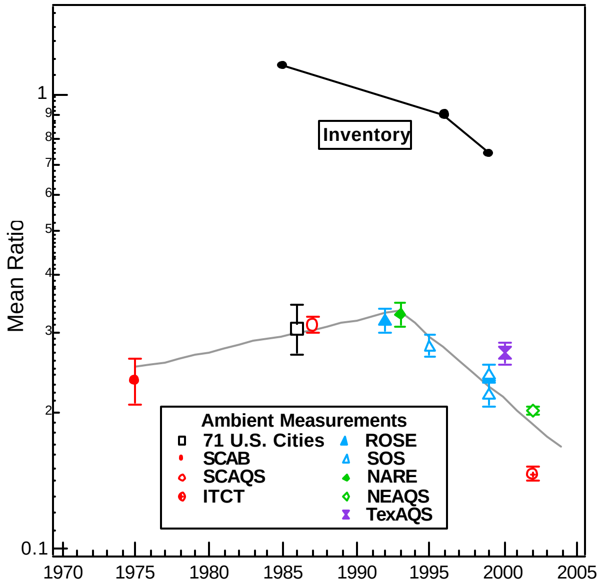


Figure 5.8. Observed trends in the mean ambient benzene to acetylene ratio from field study data as a function of year. The color of the symbols indicate geographic location: U.S. Urban (black), California (red), southeast (blue), northeast (green), and Texas (purple). The error bars indicate the 95% confidence limit of the mean. The gray lines indicate estimated ambient trends before and after 1993. The inventory ratios are from Table 5.3.

The comparison between the ambient and inventory ratios is quite poor. The inventory values are a factor of 3 to 4 higher than the ambient measurements, and the trends are not clearly in agreement. The ambient measurements must be considered to accurately reflect average emissions. The measurements are from at least seven different research groups and span most of the country. Benzene and acetylene react similarly and so slowly that average emission ratios are not altered before measurement. Disagreements must reflect biases in the inventory ratios. Although the recent trend in the inventory appears to parallel the ambient trend, it is for the wrong reasons. The ambient ratio is believed to have decreased due to reduced benzene emissions, but the inventory benzene emissions have remained nearly constant while the acetylene emissions have increased.

In conclusion, the VOC speciation in the NEI as tested by these example species are in error by factors of 3 to 4, the temporal trend in the inventory emissions is not consistent with the observations, and the NEI does not reflect trends in ambient concentrations that are discussed in the Trends Report. There is a critical need for a re-evaluation of the VOC speciation in the NEI. Correctly interpreted, reliable ambient concentration measurements must be one of the important guides for this re-evaluation. Finally the Trends Report must accurately reflect the emissions included in the NEI.

5.2.2 Evaluation of Power Plant Emissions

Power plant emissions account for a major share of NO_x, SO_2 and CO_2 emissions, and are responsible for some of the highest concentrations of these species encountered in the ambient atmosphere. In contrast to road transport emissions, there are a great many detailed, hourly emission data available, because generally these emissions are measured by Continuous Emission Monitoring systems (CEMS – see Section 6.1.3). Accurate emissions should be available simply from the integration of these CEMS data over the time period of interest. Our primary goal in this section is to test the accuracy of both the available CEMS data and their integration into annual inventories.

Transects of power plant plumes by aircraft capable of making rapid measurements of the emitted species provides a means of deriving emission fluxes from ambient measurements (see Section 6.1.4). Fortin et al. (2004b) conducted nearly 50 such plume studies on over 30 CEMS-equipped power plants during field studies in 1995, 1997, 1999, 2000, and 2002. Figure 5.9 summarizes the results from a sample of these studies. Figure 5.9a compares the flux ratios of NO_x to CO_2 and SO_2 to CO_2 derived from CEMS to those derived from aircraft transects. These flux ratios agree on average within the estimated uncertainty of the ambient determination (± 10%), although there are occasional significant discrepancies. Figure 5.9b compares the fluxes measured for NO_x, SO_2 and CO_2, with those derived from the CEMS data. Agreement is generally within the estimated uncertainty (±20% for optimum conditions) of the ambient determination, again with occasional significant discrepancies. Also, emission ratios derived from the correlation slopes are consistent with the ratios estimated from plume flux calculations. These comparisons indicate that emission fluxes from power plants derived from CEMS measurements are highly accurate.

Both the flux ratios and the absolute emission fluxes from CEMS agree, on average, to within ±10% of those derived from ambient aircraft measurements. It is notable that the absolute flux determinations (which depend on the measured total stack flow in the CEMS determinations) are as accurate on average as the determination of the ratio of fluxes (which are independent of the total stack flow.) However, these former determinations shown in Figure 5.9b do show larger scatter, but this is in part or in whole due to the reduced precision of the absolute flux determination by aircraft.

The preceding discussion concludes that the CEMS data give, in general, an accurate measure of hourly power plant emissions. The question remains if these data are accurately integrated into annual emission inventories. As a check we integrated the 1999 CEMS data for NO_x and SO_2 for seven power plants in five states. On average these integrals agreed with the values in Version 3 of the 1999 NEI to within 1%, and the largest discrepancy was 4%. These small differences simply may be due to differences in the method of handling missing data.

In contrast to the accurate CEMS derived emissions, CO emissions from power plants are generally estimated from emission factors appropriate to the burner technology and type and amount of fuel consumed. Nicks et al. (2003) have observed that power plants, particularly those fueled by lignite coal, can emit CO at rates more than a factor 10 higher than inventoried. Nevertheless, power plants still constitute only a minor fraction of total anthropogenic CO emissions.

In summary, annual average power plant emissions based upon CEMS data are highly accurate. However, the interpretation of annual average emissions must proceed with caution since the CEMS data indicate that emissions from most power plants vary on all time scales form hours to months. Consequently detailed photochemical models should include the hourly CEMS emission data.

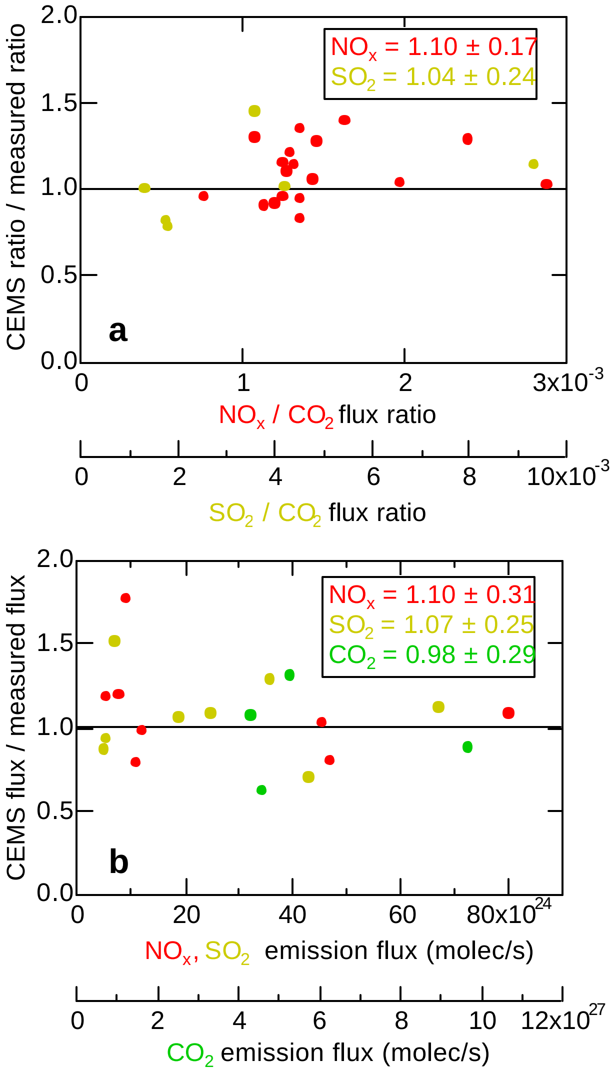


Figure 5.9. Power plant emission fluxes from CEMS data ratioed to those determined from aircraft plume transect measurements. **a)** shows the emissions of NO_x and SO_2 ratioed to those of CO_2, while **b)** shows the absolute fluxes of all three species. The annotations give the average and standard deviations for the color-coded ratios.

5.2.3 Evaluation of Emissions from Texas Petrochemical Facilities

The greater Houston, TX, metropolitan area is distinguished by the largest concentration of petrochemical industrial facilities in the U.S. Further, Houston is noted for some of the highest present-day O_3 mixing ratios routinely encountered in the continental U.S. Hourly averaged O_3 mixing ratios measured at surface sites in the area can exceed 200 ppbv during severe episodes. However, photochemical models based on existing emission inventories are not able to accurately reproduce these high O_3 levels. The TexAQS 2000 study was conducted to develop a comprehensive understanding of these extreme O_3 episodes.

During the TexAQS study aircraft measurements of emission plumes (see Section 6.1.4) from the petrochemical industrial facilities established that these emissions were responsible for the extreme O_3 episodes (Ryerson et al., 2003; Wert et al., 2003). Strongly elevated concentrations of NO_x and reactive VOCs simultaneously present are required for rapid formation of high levels of ozone. NO_x emission from a large petrochemical facility can approach that from a large electric utility power plant. These NO_x emissions are co-located with large emissions of reactive VOCs, primarily ethene and propene, released from the petrochemical processes. Thus, optimum conditions for O_3 formation are routinely found in the NO_x- and VOC-rich plumes from the petrochemical industrial facilities.

The failure of previous modeling efforts to reproduce the observed extreme levels of O_3 was traced to a very large underestimate of alkene emissions from the petrochemical facilities. Measurements established that the alkene emissions were generally as large or larger than the NO_x emissions from the petrochemical complexes. However, inventoried emissions were smaller by factors of 10 to 100. Photochemical modeling using VOC emissions scaled up to resolve this discrepancy accurately reproduced the observed concentrations of O_3. These models also accurately predicted the concentrations of other photochemical products, in particular formaldehyde, which is directly produced from the alkenes (Wert et al., 2003). Thus the mystery of the very high O_3 levels that are observed in Houston has been resolved.

Understanding the cause of the underestimate of the reactive VOC emission inventory is still lacking. One of the major goals of the planned TexAQS 2006 study is to determine the source of the very large reactive VOC emissions from within the petrochemical facilities. However one aspect of these emissions are clear; the observed discrepancy was generally consistent over all of the facilities sampled during the four-week, August-September, 2000 period of the study. On no occasion could the observed discrepancy be attributed to reported upset conditions at the investigated facility.

Allen et al. (2004) have evaluated the reactive VOC emissions from the point of view of their variability. They point out that frequently a single source within a complex can dominate that complexes emissions, and can even approach the annual average of the inventoried emissions for the entire Houston area. This variability is an important feature of these emissions that must receive due consideration in photochemical modeling. However, these workers discuss this variability in relation to the tabulated emission inventories. If the variability were compared to the emissions scaled up to match the observations discussed above, its significance would be much reduced.

5.2.4 $PM_{2.5}$ source apportionment from chemical mass balance compared to the emission inventory in Denver, CO

Receptor methods for source attribution are based on the interpretation of measured ambient concentrations of species to infer sources and to quantify the contributions of these sources to the ambient concentrations. These methods for source attribution are extensively reviewed in Chapter 7 of the NARSTO's PM assessment. These techniques can provide important evaluations of inventories.

One illustrative example presented in the NARSTO PM assessment discusses the relative contribution of $PM_{2.5}$ sources in Denver, CO derived from a chemical mass balance (CMB) analysis of ambient measurements. The CMB technique derives the contribution from secondary particulate formation as well as emission from primary sources. The relative contributions of the primary sources are compared with those included in the corresponding emission inventory. The comparison found substantial discrepancies. Compared to the CMB approach, the inventory:

- Showed nearly twice the fractional contribution from fugitive dust emissions.
- Did not include cold start gasoline vehicle exhaust, which makes a substantial contribution in the CMB analysis.
- Underrepresented high emitter (i.e., poorly-maintained) gasoline vehicles.

These last two discrepancies caused the inventory to indicate that diesel emissions were over three times those of gasoline vehicles, while the CMB analysis yielded a reversed ratio. This study again underscores the importance of assessing emission inventories through comparison with ambient measurements.

5.2.5 Inverse modeling applications

Section 6.2.2 discusses inverse modeling as one of the evolving tools that will help to improve emission inventories. This tool has already yielded useful information regarding some aspects of North American emissions. Here we will summarize one study that evaluated the U.S. emission inventory for ammonia, as an example of the application of the tool, as a test of an emission inventory that quantifies an area source, and as a good example of the feedback that must occur between emission inventory developers and top-down tests of the inventories.

Gilliland et al. (2003) used measurements of both precipitation-weighted ammonium wet deposition and gas-phase ammonia as bases for the inverse modeling to test the NEI for ammonia emissions in the eastern U.S. Both bases gave a consistent conclusion; i.e. the annual average emissions in the NEI should be about 40% lower, and should have a strong seasonal cycle that is not specified in the NEI.

An interesting feature of this study is that the model predictions for aerosol nitrate (a quantity not included in the inverse modeling optimization) were much improved. This improvement greatly increases the confidence that can be placed in the conclusions of the inverse modeling procedure.

A cautionary note for inverse modeling procedures is that they implicitly assume that the models are perfect, and any disagreements between measurements and model results are assigned to problems in emission inventories. In this example Gilliland et al. (2003) investigated where problems in the model could possibly be contributing to the disagreements; they concluded that there were two critical areas of model uncertainty: total model precipitation and the NH_3 dry deposition. This example emphasizes the necessity for the iterative process where top-down tests are applied to emission inventories to identify weaknesses in the inventories, but then the top-down tests must themselves be tested. Future developments in inverse modeling will hopefully provide many more of these top-down tests of many aspects of North American emission inventories.

5.2.6 Summary and conclusions of top down tests of emission inventories

The examples above demonstrate that top down tests do provide valuable evaluations of strengths and weaknesses of current inventories. With one exception, the evaluations suggest significant weaknesses in existing inventories. That exception is the inventory for power plant emissions of NO_x and SO_2, which are derived from direct measurements of the emissions through CEMS. The emerging lesson from these evaluations is that with current techniques it is not yet possible to develop bottom up inventories that are accurate enough for many of the scientific uses detailed in Chapter 2 without the support of direct measurements. Yet bottom up inventories are indispensable components of photochemical models and the foundation upon which our knowledge of pollutant emissions is based. The Emission Inventory Flow Diagram (Figure 2.1) shows the proposed solution to this conundrum. It illustrates a continuing process of inventory development, testing through top down evaluations and reviews, and an evaluation in turn of the top down tests. Such an iterative process is required to improve existing inventories, and to develop new ones. The evolving tools discussed in the next chapter will be essential for this process.

5.3 STRENGTHS AND WEAKNESSES OF CURRENT EMISSION INVENTORIES AND MODELS: ISSUES OF DEVELOPMENT AND IMPLEMENTATION

Numerous emission inventories and models that cover various emission source categories and pollutants have been developed (See Chapter 3) in past decades. These inventories and models provide quantitative estimates of emissions at national, state and county levels. The quantitative estimates have been used by federal, state and local agency as an aid in choosing appropriate pollution control measures and air quality management strategies (NARSTO, 2004; NRC, 2004a).

This section is intended to assess general strengths of current emission inventories and models and their general weakness in terms of inventory development and implementation. This section will first discuss the most typical strengths and weaknesses of current emission inventories and models, which are applicable to all inventories, pollutants and source categories; and then specific strengths and weaknesses associated with major emission source categories will be presented.

5.3.1 Strengths of Current Emission Inventories and Models

The main strengths of current emission inventories include:

- *Most inventories can be used, with some caveats as shown in the preceding section, to compare significance of different source categories*. For example, an analysis of the U.S. national emission inventory (NEI) shows that: (a) stationary sources contribute the largest portion of total NO_x and SO_x emissions and a considerable portion of VOC emissions, but a relatively smaller portion of total CO emissions; (b) mobile sources are the largest contributor to the total CO emissions and a considerable contributor to the total NO_x emissions; and (c) biogenic sources contribute the largest portion of total VOC emissions

(EPA,1996; Placet et al., 2000). For the most part there is a high degree of confidence in these major insights.

- *Ability to provide some insight regarding air quality trends over time and pollution control efficiency.* Current emission inventories estimate emission trends over time and give some indication of efficiency of particular control strategies and projects. For example, EPA annual emission trend reports are based upon emission inventories. Indications of the uncertainties in some of these trends are discussed in the preceding section. Emission inventories are also key inputs for air quality modeling, and can be used to evaluate the effect of different pollution strategies on the ambient air quality (Russell and Dennis, 2000). There is a high degree of confidence regarding some major changes in total emission inventories at the national level, such as reductions in SO_2 and NO_x from large point sources in the U.S. associated with acid rain provisions of the Clean Air Act Amendments of 1990.
- *Ability to help decision-makers allocate resources and develop air quality management strategies.* For example, knowledge of emissions contributed from different source categories helps decision-makers set priorities for air quality improvement in allocating limited resources to those sources with the greatest potential to reduce emissions (Frey et al., 1999; Frey and Zheng, 2002). For example, in urban areas facing ozone problems, the relative importance of NO_x versus VOC control can be assessed taking into account both urban scale and regional geographic scales, and the key source categories that should be the focus of control efforts can be broadly prioritized.

5.3.2 Weaknesses of Current Emission Inventories and Models

Current emission inventories offer the tools to answer the basic questions regarding key sources and priorities for air quality management. However, there is a critical need for improvement in response to growing needs of stakeholders and decision makers. For various reasons, current emission inventories and models have significant weaknesses, which lead to reduced confidence in insights provided for decision-makers in developing appropriate air quality strategies. The most typical weaknesses that have been identified and are applicable to all inventories, pollutants, models and emission source categories are briefly discussed here.

- *Uncertainties are rarely or not rigorously quantified, in emission inventories and models* (NRC, 2004b; NARSTO, 2004; Frey et al., 1999). For example, almost all emission estimation models, such as the widely used MOBILE, NONROAD models for mobile source emissions and BESI3 for biogenic emissions, do not contain a component that can be used to assess uncertainty in model inputs and structure. Emission inventories developed based upon these models rarely quantified uncertainty emission estimates. Although there are some examples in which uncertainties had been quantified for an emission inventory (e.g., Frey and Zheng, 2002a; Frey and Zhao, 2004; Hanna and Wilkinson, 2004), most of these examples are demonstrative case studies of quantitative characterization of emissions, or using semi-quantitative methods or AP-42 (EPA, 1995b).

- *Accuracy in emission estimates is limited due to small sample sizes of emission measurements and the potential for lack of representativeness of sample data used to* *develop emission inventories* (NRC, 1991; 2000; 2004b). Because it is often the case that there are a limited number of measurement sample data available; and the sample data used to develop inventory may not be representative of population data (NRC, 2000; 2004b), uncertainty in emission estimates are inevitably introduced and accuracy in emission estimates is limited.

- *Inconsistency of reconciling national, provincial, stage or county level inventories due to aggregation or disaggregation* (NARSTO, 2004). For example, national emission inventories are developed based upon "bottom-up" approach from state or local emission estimates. However, there are no mechanisms to ensure that the aggregation process is appropriate and consistent across the different agencies and that important sources are not overlooked. When emissions are disaggregated to local or gridded area for air quality modeling using "top-down" approach, subjective judgments have to be used during the process, and thus may lead to uncertainty for small scale inventories. For example, assumptions must be made both regarding spatial disaggregation into grid cells as well as temporal disaggregation by hour. Often, there are few if any direct measurements to support these types of allocations and "surrogate" or indirect methods are commonly used.

- *Temporal and spatial resolution in emission inventories are not appropriately addressed* (NARSTO, 2004). Emission inventories may be county, national or international, or annual and hourly, depending on the purpose of use of emission inventories. Current emission inventory practices do not appropriately define spatial and temporal resolutions of these emission inventories (NARSTO, 2000; Placet et al., 2000). For example, inventories are often developed based on the use of average data from various source categories. These data may be for a variety of averaging times. Some measurements might be made over the course of a few days or few hours at a particular point source but might be extrapolated to infer annual averages. Mobile source measurements are typically based upon test cycles of approximately 10 to 20 minutes in duration in many cases. There is a need for improved methods or procedures to better address temporal and spatial resolution.

- *Current emission inventories typically are not developed and updated in a timely manner.* For example, national emission inventories often take 2-3 years or longer to prepare. The U.S. updates the NEI every three years and in Canada the update interval for the national inventory is 5 years (NARSTO, 2004). Because there are long internals between updating and reporting of emission inventories, current emission inventory may not provide timely and updated emission information for air quality management decisions. This in turn limits the ability to accurate infer changes in emissions over time.

- *Uncertainties arising from measurement error are often ignored* Because of imperfections of measurement instruments and procedures, measurement errors inevitably appear in emission data. However, current emission inventories rarely report how measurement errors affect emission estimates. Uncertainty arising from measurement error is typically not characterized or systematically report, and yet is a key component of uncertainty especially for some types of pollutants (e.g., HAPs).

- *QA/QC (Quality Assurance/Quality control) procedures are not strictly applied in most emission model or inventory development*. Strict quality evaluation during emission inventory development helps reduce the uncertainty in emission estimates especially because of errors such as misclassification and incorrect location of sources (NARSTO, 2004). However, current emission models (e.g., MOBILE models and NONROAD models) inventories lack extensive validation and evaluations (NRC, 2000), although this situation is expected to improve in the future. QA/QC procedures for evaluating emission data sources are not strictly followed in the emission inventory development. Some of the barriers to improved QA/QC are institutional in that many different agencies and stakeholders may contribute data to an inventory.

- *Documentation for emission inventories is not adequate*. Documentation regarding emission inventory development, especially regarding key assumptions and data sources and their pedigree, is inadequate. For example, current emission inventories reports seldom clearly define emission inventory objectives, scope and the sources of emission and activity data.

- *Biogenic emission sources are poorly characteriz*ed. Compared to the analysis of non-biogenic sources, biogenic emission estimation typically receives less attention, and considerable uncertainty is associated with biogenic emission estimates (Placet et al., 2000).

- *Higher uncertainty in air toxic emission inventories*. Because there is a relative lack of measurement data for air toxics and particularly for some emission processes (e.g., fugitive emissions), emission inventories for air toxics are generally expected to have higher uncertainty compared to criteria pollutants.

5.3.3 Source Category-Based Strengths and Weaknesses

Because there are differences in emission estimate methods and emission data measurement and collection, emission inventories associated with different types of source categories have their own strengths and weaknesses. The strengths and weaknesses associated with major types of source categories are discussed.

Point Sources

Point sources are defined here as single sources (e.g., large factories and electricity-generating facilities or power plant) with stack emissions exceeding a threshold level that depends on the pollutant (NRC, 2004b). Point sources are generally inventoried individually, thus have fewer problems with spatial resolution than mobile, area, and biogenic sources. Emission inventories for point sources are typically developed based upon the direct measurements of emissions or use of emission and activity factors. For the facilities with the continuous emission monitoring systems (CEMS) systems, emissions are inventoried with the use of direct emission measurement data. For the facilities without CEMS, emissions are typically estimated using emission and activity factors, perhaps involving emission models. Thus, for sources for which

CEMS data are available, an emission inventory can be developed essentially by looking up the actual emissions for the sources and time periods of interest. The uncertainty or error in such cases is primarily based upon the precision and accuracy of the measurement methods. Section 5.2.2 demonstrates that the uncertainty is small for SO_2, NO_x and CO_2. Of course, CEMS are not available for all pollutants, and thus even for point sources for which SO_2 and NO_x emissions are monitored using CEMS, HAP emissions might have to be estimated using emission and activity factors. In contrast, for sources for which CEMS data are not available, various degrees of approximation are involved in estimating emissions. CEMS-based versus emission factor-based emission estimates have different strengths and weaknesses and thus are addressed separately here.

Point source emission inventories based upon the use of CEMS data have the following main strengths:

- Emission inventories are generally thought to be of high quality with little uncertainty, especially for SO_2, NO_x and CO_2 (Section 5.2.2) because the CEMS provide a large amount of continuous hourly emission data for the facilities.
- The emission rates, particularly for SO_2, NO_x and CO_2, from these sources are generally viewed as being among the most accurate of all known rates in the U.S (NRC, 2004b; Placet et al., 2000). For example, Emigh et al. (1997) indicate that the use of CEMS has greatly increased the accuracy of emission estimates from power plants.

The significant weaknesses for the inventories with the use of CEMS data include:

- CEMS are expensive and not available for all pollutants. For example, although about 80% of CEMS measure SO_2, NO_x and CO_2; however, less than 1% of those measure HC and air toxics (GAO, 2001), thus there is large uncertainty for these pollutants. Also, because of the expense, it is often not feasible to install CEMS at smaller point sources.
- There can be some biases in emission estimates from CEMS data. For example, when CEMS are temporally non-functional, there are missing data in monitoring database. Typically, a maximum emission estimate is used to fill in the missing data, which may lead to overestimated emissions (Placet et al., 2000; Mangus, 1997). However, at least for the sources evaluated in Section 5.2.2, this bias was never larger than a few percent.
- CEMS may be less reliable at low emission concentrations or other extreme conditions (Elliot,1994). Thus, some bias could occur because of detection limits and other manifestations of measurement sensitivity or error.
- CEMS data focus on measurements made at the stack, but do not include actual but unmeasured fugitive emissions. Thus, CEMS data are applicable only to some but possibly not all emission processes at an emission source.

Point source emission inventories for the facilities without CEMS, such as those for which emission factors are the basis of emission estimation, have the following main strengths:

- The overall inventory development cost is relatively lower compared to those with the use of CEMS data because the emissions are typically estimated by the use of emission and activity factors for the facilities (NRC, 2004b).

- Emission factors are convenient and many are available from standard reference publications, such as AP-42. The level of documentation of emission factors in documents such as AP-42 is generally improving.
- Emission factors are available for a substantial range of source categories, for many emission processes within a source category, and for a variety of pollutants.
- For some purposes, emission factors may be appropriate. For example, emission factors are typically estimated as an average based upon measurements from a few to many sources within a source category. If the goal of the inventory is to estimate total emissions or average emissions for many individual sources within a category, then the average emission factor could be reasonably accurate as long as it is based upon a representative sample of data.

The significant weaknesses for point source emission inventories that are based upon emission factors are:

- The inventories for these facilities typically have higher uncertainty compared to those based upon CEMS data because the emission factors used may not be appropriate representatives of design and operations of these facilities. For example, an emission factor is typically an average of emission data from a source category, but may not capture large emission spikes due to upsets or accidental release, which may result in increased overall emissions (TNRCC, 2003; NARSTO, 2004).
- Emission factors typically should not be used to estimate emissions for individual emission sources, since they are based upon averages from multiple sources. Because of inter-individual variability among sources, which implies that the emissions of any individual source could be much smaller or larger than the average, the use of an average emission factor applied to a particular source could be subject to a large error.
- Emission factors should not be used to estimate emission for averaging times that are substantially different than the temporal or activity basis of the measurements upon which the factors are based. For example, there is uncertainty associated with the use of emission factors based upon the average of a few days of operations when applied to estimating annual average emissions.
- Any measurement or sampling errors inherent in the data upon which emission factors are based will lead to uncertainty in the emission factor. This uncertainty can include both systematic and random components.
- The "quality" of emission factors varies depending on the source category, emission process, and pollutant. For example, emission factors for fugitive emissions of some HAPS are typically of lower quality than emission factors of key criteria pollutants at the stack. However, although data quality ratings are often reported, quantitative estimates of uncertainty are rarely, if ever, reported in emission factor reference sources.

Area Sources

Area sources include a wide variety of emission source categories. Some are point sources that have emission rates below a threshold level, which varies depending on the pollutant, such that they are not classified as major point sources (NRC, 2004b). However, area sources can also include non-point sources, such as fugitive emissions, evaporative emissions, and other types of emission processes. Typically, area sources are widely spread among a potentially large number of relatively small industrial and business facilities, as well as application and use of various materials, such as architectural coatings. In the U.S., area sources are typically inventoried and regulated collectively at the county level (Placet et al. 2000). Because of the complexity of emission sources and variety of emission estimation methods, area source emission inventories are generally thought to be of lower quality than point source emission estimates (NRC, 2004b; NARSTO, 2003; Placet et al., 2000).

The major strengths of area source inventories typically include the following:

- Estimates are developed that are intended to be comprehensive in terms of accounting for all known area sources
- Emission factors are typically used, and the strengths of area source inventories are therefore similar to those for point source inventories based upon emission factors.
- Area source inventories are allocated spatially and temporally, typically using spatial and temporal allocation profiles.

Area sources have the following weaknesses:

- Compared to other source categories, area source emission inventories have the highest uncertainty in emission rates (NARSTO, 2004). Because direct measurement of area emission sources are resource intensive, area source inventories are constructed generally through calculation procedures. In some situations, surrogates for emissions and activity factors are used for emission estimates. The quality of the estimates depends on how well the surrogate activity factor correlates with the emission rate for the source.
- Emission factors for area sources are not routinely or periodically updated in a timely manner because it is resource intensive to make measurements and inferences for the large number of diverse sources that collectively comprise area sources (Placet et al., 2000).
- The uncertainty in area source emission estimates is rarely quantified.

Mobile Sources

Mobile sources are broadly categorized into onroad and nonroad sources. Onroad sources include light-duty vehicles, light-duty trucks, heavy-duty vehicles, buses, and motorcycles. Non-road sources include all other vehicles and equipment that are mobile or capable of being transported. In the broadest sense, nonroad sources include aircraft, marine vessels, personal watercraft, railroad motive power and other mobile equipment (e.g., railroad maintenance-of-way and construction equipment), offroad recreational vehicles (including snowmobiles), construction vehicles and equipment (e.g., backhoes, dump trucks, cranes, portable generators, concrete mixers, etc.), agricultural vehicles and equipment (e.g., tractors, combines), industrial vehicles and equipment (e.g., forklifts), and lawn and garden equipment (e.g., lawn mowers, string trimmers, etc.). Because mobile sources often can operate under many conditions, including different activity patterns as well as different ambient conditions that might affect emissions, emission factors for these sources are typically estimated using models rather than look-up tables. Currently, most commonly used emission models in the U.S. are the MOBILE series models (with exception of California, where EMFAC models are used) for on-road sources and NONROAD model for non-road sources. The newest version for both models are MOBILE 6.2 and NONROAD 2002, respectively. The MOBILE model is often adapted for use in other countries, such as Mexico. There are also models for estimate air toxic and particulate matter emissions, such as MOBTOX and PART5, respectively, for onroad sources.

Mobile source emission models and inventories have the following main strengths:

- Mobile source emission inventories can be used as inputs to air quality models to simulate regional and microscale dispersion of pollutants.
- MOBILE and associated models (e.g., PART and MOBTOX) can be used to develop national, regional and urban emission inventories for criteria pollutants and air toxics
- The MOBILE models are best suited for aggregate analysis, such as national or regional applications to evaluation of regulatory strategies and state implementation plans, because it utilizes an aggregate approach for wide areas under average conditions (NRC, 2000).
- MOBILE6 includes facility-specific driving cycles under different congestion levels, as well as additional "bags" of the Federal Test Procedure intended to better characterize more aggressive accelerations than previous generations of MOBILE. Thus, the most recent MOBILE model provides some capability to explicitly account for congestion levels, roadway type, and some key factors associated with the impact of driver behavior on emissions (EPA, 2002).
- MOBILE6 separates start emissions from running emissions, intended to provide better resolution for emission factor estimates, and also provides estimates of tailpipe, running losses (evaporative emissions during operation), and evaporative emissions associated with fueling (EPA, 2002). For some types of vehicles (e.g., carbureted gasoline vehicles), "hot soak" and other emission processes may also be important and are characterized.
- The NONROAD model predicts exhaust emissions for hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur oxides (SO_x), particulate matter (PM), carbon dioxide (CO_2), as well as diurnal, and refueling hydrocarbon emissions, and the volume of fuel consumed by nonroad equipment except locomotives, aircraft, and commercial marine vessels. The level of detail from the model includes fuel type (diesel, gasoline, LPG, and CNG), individual Source Category Classification (SCC), power range, geographic area (nationwide, state, or county), and temporal (annual, seasonal, monthly, weekday/weekend) for calendar years 1970 to 2050 (Harvey et al., 2003).
- Emissions from diesel-electric locomotives can be estimated based upon throttle settings of the engine, since many locomotives are operated based upon selection of discrete settings.
- Aircraft emissions are typically estimated based upon a Landing and Take-Off (LTO) cycle that takes into account aircraft operations on the ground and in the troposphere. High altitude (stratospheric) operations are typically not accounted for since these do not have a direct impact on human exposures to pollutants in the lower troposphere.
- There are many standardized test procedures available for both onroad and nonroad emission sources. The standardized procedures provide some consistency in activity pattern that can enable comparisons of emissions under controlled conditions. For

onroad light duty vehicles, standardized tests are typically conducted on chassis dynamometers. For onroad heavy duty vehicles, standardized tests are often conducted only for the engine using an engine dynamometer. Engine dynamometers are also widely used for many nonroad emission sources. Historically, onroad emissions for light duty vehicles are reported on a mass per distance (e.g., grams per mile) basis, whereas for many other sources emissions are reported on a mass per engine output basis (e.g., grams per brake horsepower-hour).

- Activity data for many types of vehicles are developed based upon existing data sources, including data developed by other agencies. For example, in the U.S., onroad vehicle estimates require transportation data from agencies such as the Federal Highway Administration or the U.S. and state Departments of Transportation, whereas aviation emissions are estimated with the aid of data available from the Federal Aviation Administration.

Because there is a wide variety of mobile source vehicles and equipment, as well as logistical, practical, and resource availability challenges with respect to obtaining real-world emission test data, mobile source models and inventories have the following main weaknesses:

- Mobile source emission factors, both onroad and nonroad, are not subject to data quality ratings (as are point source emission factors) and uncertainties in these emission factors are rarely quantified except by independent researchers.
- There is no component in existing mobile source emission factor models that can be used to quantify uncertainty.
- Large and significant uncertainty exist in mobile source inventories for all vehicle types and classes (NARSTO, 2000; NRC 2000, 2004b; Sawyer et al., 2000 and Section 5.2.1)
- The existing in-use emission factor models, such as MOBILE, are not well suited to dealing with “mesoscale” or “microscale” emission estimates that would take into account the effect of specific transportation control measures or highly resolved (both temporally and spatially) characterization of emission hotspots, such as at intersections. As such, these models are poorly suited for analysis of the impact of specific transportation improvement projects or for conducting corridor-level analysis, thereby introducing substantial uncertainty in the assessment of future transportation improvements or controls with respect to air quality management (NRC, 2000).
- Mobile source tailpipe emissions are typically estimated based upon test procedures that are of limited duration (e.g., 10-30 minutes in many cases). Thus, there could be uncertainties associated with using such data when making estimates of emissions over a longer time period.
- For many nonroad sources, emissions are estimated based upon steady-state modal test procedures that are not based upon actual activity patterns. Thus, the mean emissions from such tests may be biased compared to real-world emissions.
- Measurements made using dynamometers, whether chassis or engine, may not adequately capture the effects of real world conditions that could substantially affect emissions.
- Treatment of the effects of emission spikes that come from variability in engine loads and the importance that such spikes have in overall emission inventories are not adequately dealt with (Barth et al., 1997; NRC, 2000; Hallmark et al., 2001).

- The allocation of mobile source emissions both temporally and spatially, such as required for gridded air quality models, involves assumptions for which data may be lacking and thus introduces additional uncertainty (Sawyer et al., 2000; NARSTO, 2000).
- Rural emissions from on-road and off-road vehicles may be underestimated (Sawyer et al., 2000) and emissions for air toxics from off-road vehicles are not adequately characterized.
- There are gaps in emissions, especially for nonroad vehicles, heavy duty diesel trucks and malfunctioning automobiles (NRC, 2004b)
- A disproportionate amount of emissions are typically attributed to a relatively small percentage of high-emitting motor vehicles (NRC, 2001); however, there is concern that high-emitters are not adequately addressed. High emitters are typically conceived to be older vehicles as well as newer vehicles that are malfunctioning in some manner.
- Non-road sources are becoming an increasingly important part of total emissions, but because of lack of data and wide use of surrogate data, nonroad models are suspected of not accurately estimating emission inventories and there is little information about the accuracy or uncertainty of such models (Bammi and Frey, 2002; NRC, 2004b)
- There is concern that Inspection and Maintenance (I/M) programs provide "much lower benefits" than those estimated by the MOBILE model (NRC, 2001). If the benefits of I/M are overestimated, this has implications for biases in emission inventories for areas with I/M programs as well as for evaluation of the efficacy of such programs (NRC, 2004b).

In brief summary, there are many strengths to the existing approaches for developing emission inventories. However, a key theme is that there is little quantification of uncertainty in emission estimates. Therefore, it is difficult to identify which source categories, emission processes, and pollutants are subject to the greatest uncertainty that affects the ability to make decisions regarding management of air pollution. The following sections explain in more detail the concepts, methods, and insights for uncertainty and sensitivity analysis that can be used to systematically characterize and target uncertainties in order to improve inventories.

5.4 UNCERTAINTY ANALYSIS

The purpose of uncertainty analysis in inventories is to provide quantitative estimates of the range and likely uncertainty of emissions. There are typically three major steps in uncertainty analysis. One is to characterize uncertainties in the inputs to a model. The second is to propagate the uncertainties through the model in order to estimate uncertainty in an output. The third is to interpret the result with respect to the objectives of the assessment. In the case of emission inventories, the model is the emission inventory itself. The inputs are typically emission and activity factors. The objectives can vary. For example, an objective might be to estimate the proportion of total emissions that are attributable to a specific source category, or to evaluate whether total emissions are within a specified emission budget. Uncertainty analysis enables quantification of the probability, confidence, or range with which a particular source category contributes to total emissions, or the probability or confidence with which a particular emission budget can be met. Of course, uncertainty analysis can be applied to assess the confidence with which many other objectives can be achieved; these are only examples. However, uncertainty analysis is currently not a required component for inventory development.

This section presents motivations for performing uncertainty analysis in emission inventory development and discusses sources of uncertainty. Approaches for characterizing uncertainty in emissions are reviewed and discussed. Current efforts of uncertainty analysis applied to emission models and inventory development are summarized. Finally, a preliminary qualitative assessment of confidence levels of source category-based emission inventories is made and an example of a quantitative estimate of uncertainty for a specific inventory is presented.

5.4.1 Motivation

As recognized by the National Research Council in1991, the quality of emission inventories is hampered by significant, yet poorly characterized uncertainties (NRC, 1991). A recent National Research Council report on *Research Priorities for Airborne Particulate Matter* (NRC, 2004a) highlights areas where substantial emission inventory enhancements are needed. A main limitation in current emission inventories is inability to quantify their uncertainty, in large part due to a cited lack of data (NRC, 2004b). However, the need for uncertainty analysis is typically greatest when data are lacking, since uncertainties are expected to be larger in such situations. Traditional emission inventories contain substantial (and largely unspecified) levels of uncertainty, typically as much as a factor of two or more, which severely limit the robustness of air quality management strategies (NARSTO, 2000, NARSTO, 2004). The identification and quantification of uncertainties in emission estimates is critical to scientific credibility as well as the policy relevance of inventories. However, the North American continent has not yet to routinely embraced uncertainty quantification in the context of local, region, national, and multinational inventories. NRC reports have specifically recommended that uncertainties in emission factors and inventories be quantified (NRC, 1991; 2000; 2001; 2004a; 2004b).

Emission factors are often used for a significant number of point sources, mobile sources and most area sources. Although emission factors for some source categories, emission processes, and pollutants are likely of good quality (e.g., coal-fired utility sources for stack emissions of SO_2 and NO_x), there is variation in the pedigree of emission factors among sources, processes, and pollutants. Furthermore, although an emission factor can be accurate when applied to estimation of emissions for many sources, the same emission factor may be subject to a larger error if applied, inappropriately, to estimate emissions for a single facility. Typical problems with available emission factor data are that they are not representative of the entire population of sources, are based upon a relatively small sample of measurements, and may be subject to considerable random and systematic measurement errors (Placet et al.. 2000; NRC, 2000; 2004b).

In a 2000 report on modeling mobile source emissions, the National Research Council discussed the following key questions that motivate the need for quantitative uncertainty analysis (NRC. 2000).

How precise do emission estimates need to be?
The required degree of precision and accuracy of an inventory will vary depending upon the intended use of the inventory. For example, if the purpose of the inventory is to serve as an input to an air quality model, then the desired precision of the inventory will be dictated by the ability

of the model to discriminate among different levels of emissions with respect to making predictions of ambient air quality. If the model is relatively insensitive to the emissions for a particular pollutant, then possibly a relative high degree of uncertainty can be tolerated. In contrast, if the assessment objective is to detect small changes in emissions from year to year as part of trends analysis, then a small amount of uncertainty in annual average emissions would be desired.

How precise are the estimates now?
Typically, there is little work to answer this question. Thus, methods and applications are required in order to answer this question. However, examples from the literature suggest that the precision of emission inventories varies depending upon the pollutant, spatial scale, and temporal scale. Examples of reported uncertainties for inventories, as described later in this chapter, range from approximately plus or minus 20 percent to a factor of two or more. However, for some source categories within an inventory, the ranges of uncertainty can be much larger than this.

What is the contribution of specific components of an emission estimate to the uncertainty in the total emissions?
Identification of the contribution of specific components of emission estimates helps to identify which source categories contribute the most to overall uncertainty. This insight can be used, in turn, to target resources to reduce uncertainties where uncertainties are largest and matter the most.

How should efforts be targeted to improve the precision of emission estimates?
Knowledge of uncertainty in emission estimates helps guide additional data collection to reduce uncertainty in order to improve the precision of emission estimates. For example, the identification of key sources of uncertainty can prioritize information gathering efforts for those inputs that matter the most to an emission inventory.

These questions emphasize the importance of uncertainty analysis as a means for assessing whether data quality objectives have been met and to help set priorities for targeting additional work in order to reduce uncertainty. The latter is done with the help of sensitivity analysis methods that are discussed in Section 5.5.

5.4.2 Sources of Uncertainty

According to Frey and Zheng (2002b) and others (e.g., Morgan and Herion, 1990; Cullen and Frey, 1999; NRC, 2000; 2004b), uncertainty in emissions is typically attributable to the factors discussed in the following paragraphs.

Precision and Accuracy in Measurement Methods. Lack of precision is attributed to random error (Cullen and Frey, 1999). This source of uncertainty is associated with imperfections in measurement techniques or with processes that are random or statistically independent of each other. Accuracy is attributed to systematic error because of bias in measurements and procedures. Such biases may originate from sources such as the imperfect calibration of equipment, simplifying or incorrect assumptions, and any other errors introduced in the selection and implementation of methodologies for collecting and utilizing data.

Variability and Sample Size. Variability in the system being modeled can be a source of uncertainty. For example, for vehicle or equipment emission factors, emissions from any one unit vary from time to time and place to place. Some portion of the variability might be explainable based upon factors such as age, design features, fuel characteristics, duty cycles, ambient conditions, and others. However, even for a specific category of vehicles or equipment, such as light duty gasoline vehicles equipped with three-way catalysts, there is intra-vehicle variability over time and inter-vehicle variability within a fleet. The variability of emissions within a category and the limited sample size of measurements give rise to random sampling error in estimation of the mean emission factor (NRC, 2000). The average emission factor, which is typically based upon the small data set when developing an emission inventory, is therefore subject to uncertainty (NRC, 2004b). If the emission inventory includes a large sample of specific units within a source category, then the uncertainty analysis should typically focus on uncertainty in the mean emission rate (e.g., Frey and Zheng, 2002b). However, if an emission inventory includes only one unit from a given source category, and if no site-specific emission data are available, then an assumption might be made that the individual unit is a random sample from the population of all similar units. In this latter situation, the distribution of inter-unit variability would be the appropriate estimate of uncertainty.

Representativeness of Data. In the development of emission inventories, data measured from a limited number of sources may not be representative of the entire population of sources (NRC, 2000; 2004b) or the study objectives. At such situations, a judgment must be made as to whether the feedstocks, processes, ambient conditions, operating conditions, maintenance history, and averaging time (e.g., such as for a process facility or combustion source) are sufficient similar between the emission sources that were tested and from which emission data are available versus the emission sources that are within the scope of a particular inventory, which will introduce uncertainty. Furthermore, emissions measured for a different duty cycle or for a different averaging time (e.g., hourly, daily, weekly, monthly, annual, etc.) may not be a reliable basis for estimation of uncertainty in a particular inventory without additional analysis or judgment.

Dependence and Correlations. When there is more than one uncertain quantity, it may be possible that the uncertainties are statistically or functionally dependent. Failure to properly model the dependence between the quantities can lead to uncertainty in the emission estimation, in terms of improper prediction of the variance of output variables. However, correlations typically matter only if they are sufficiently strong between two or more quantities each of which has a significant impact on the overall uncertainty of the inventory. Thus, it is not always the case that it is essential to properly account for correlations even though correlations may be known to exist. It is only necessary to account for correlations if they would alter the insights provided by the analysis.

Lack of Empirical Basis. This type of uncertainty cannot be treated statistically, because it requires predictions about something that has yet to be built, tested or measured. This type of uncertainty arises from data gaps or lack of knowledge of future events, and can be represented using technically-based judgments about the range and likelihood of possible outcomes. For example, when estimating uncertainty for future emission scenarios, it will typically be necessary to make use of expert judgment.

Disagreement Among Experts. Expert opinion is often used to select appropriate values or distributions for inputs into an emission inventory model. For example, experts may suggest the most appropriate emission factor for a certain pollutant, or, in a Bayesian analysis, experts may supply a subjective prior distribution. Often different experts' opinions on these data and distributions may differ. Thus, there may be disagreement regarding the most appropriate values or distributions to use. There are various methods for dealing with potentially conflicting judgments regarding uncertainties. Examples include: (1) conducting the uncertainty analysis separately with each alternative set of judgments in order to determine whether insights from the analysis differ; (2) assign weights to each judgment and perform one analysis in which the judgment is weighted; or (3) iterate on the judgment and attempt to reach a consensus among experts before proceeding with an analysis.

Aggregation and Disaggregation. When a national inventory is aggregated by adding up from local emission sources using "bottom-up" approach, or when emissions are disaggregated to gridded area from state or county level in air quality modeling using "top-down" approach, there is no mechanism to ensure whether or not the reconciliation of interstate or agency emission inventories or key assumptions of allocating emission sources, and important sources are not overlooked. Uncertainty may be introduced during the process due to the use of the "bottom-up" feature and "top-down" methodology (NRC, 2004b; NARSTO, 2004).

Model Uncertainty. Model uncertainty arises from model structures and inappropriate assumptions regarding the emission scenarios. For example, a model that is based upon standardized duty cycles for mobile sources may fail to accurately and precise estimate real-world emissions. Alternatively, structural problems could occur if emission sources are counted more than once because of ambiguity in scenario definitions. NRC (2004b) pointed out that a major contributor to the large uncertainties in current emission inventory arises from the emission model themselves to derive the inventories. Model uncertainty can be significantly high and poorly characterized (NRC, 2004b), however, it has not yet been as a routine component recognized in uncertainty analysis.

Scenario Uncertainty. A scenario is the set of assumptions regarding the structure of the inventory and scope of geographic area, temporal averaging time, source categories, emission processes, and pollutants that are included. For example, an emission scenario that fails to include all relevant emission sources and pollutants (depending on the assessment objectives) would be subject to data gaps, thereby introducing uncertainty in the emission inventory. This source of uncertainty is known as scenario uncertainty (Cullen and Frey, 1999) and typically results in a bias in emission estimates. The sources of scenario uncertainty include descriptive errors, errors in professional judgment, and incomplete specification of the scenarios (EPA, 1997).

Other possible uncertainty sources include the incorrect entry or reading of emission data, misclassification of emission source categories, and improper assumptions regarding model input distributions and model formations. All of these may lead to additional uncertainty in emission estimation. Although data entry mistakes and misclassification errors can be sources of uncertainty, these can be avoided or minimized by application of appropriate quality assurance and quality control (QA/QC) techniques. In contrast, other types of uncertainties described above exist regardless of the implementation of QA/QC.

5.4.3 Other Factors Influencing Uncertainty

Other factors influencing uncertainty in emission inventories include averaging time, spatial resolutions and level of emission analysis.

Because underlying variability in the emissions of a single unit (e.g., vehicle, power plant unit) may vary from one time period to another, the averaging time is a factor that influences the range of uncertainty of estimates of emissions. For example, uncertainty in emissions will be different for an annual emission inventory and a six-month emission inventory (Frey and Zheng, 2002b). Typically, the range of uncertainty increases as the averaging time decreases, but this can depend on autocorrelation in the emission uncertainties.

When national level emission factors are applied to estimate the county level emissions, or when national emission inventories are prepared from “bottom up” aggregation of small geopolitical units (e.g., state or county level); uncertainties associated spatial allocation due to the variation in the coverage and spatial resolution of geographic area for emission and activity factors with emission factors will arise (NARSTO, 2004).

The level of detail of an analysis level also may have some impact on the quantification of uncertainties in emission estimates. For example, the purpose of a screening analysis is to obtain rough estimates of emissions, which may be done based upon key assumptions and relatively simple model frameworks; while refined analysis requires more details in model input parameters and model structure in order to have more accurate estimates of emissions. These differences in the analysis level could lead to different estimates of uncertainty in emissions.

5.4.4 Approaches for Characterizing Uncertainty in Emission Inventory

There are various approaches available for characterizing uncertainty in emission inventories which range from simple to complex. These approaches can be categorized as: qualitative, semi-quantitative and quantitative.

Qualitative Methods

Qualitative methods used for uncertainty assessment typically involve listing and discussing sources of uncertainty. Each emission factor or activity factor is described in terms of the direction of any bias (*i.e.* whether they are judged to be over or under-estimates). An example of a qualitative method is the Data Quality Rating method in which qualitative “A” through “E” ratings are used to address the errors in the estimation of emission factors (EPA, 1995b). However, the use of these ratings is somewhat subjective and depends to an extent on the individual reviewer (Roads, 1993). An example using qualitative methods for development of an inventory was done by Steiner et al. (1994) for emissions from offshore oil production facilities.

Although qualitative methods do not require substantial resources, they have the significant drawback of not being able to produce quantitative insight regarding uncertainty. As a result, it is not possible to estimate the overall uncertainty in an inventory or to attribute uncertainty in an inventory to specific key source categories.

Semi-quantitative methods

Rather than using the purely qualitative methods, in the context of emission inventories, it is often possible to rank many individual contributors, in some cases also, to produce more meaningful information (though falling short of being fully quantitative) on the 'absolute' scores to be assigned to individual contributions to overall uncertainty of emissions. Such approaches are classified broadly as semi-quantitative methods. An example of a semi-quantitative method is the Data Attribute Rating System. DARS is a method for combining data quality scores for both emission factor and activity data to develop an overall quality score for an emission inventory. DARS provides a numerical confidence rating for emission inventories. The numerical result is called the DARS score. DARS assigns the numerical scores to the various components of the emission inventory based upon their qualities, and allows numerical manipulation of the uncertainty estimates of the system. One advantage of DARS is to provide a quick evaluation of the effect of national-level or surrogate factors and activity data relative to local source specific factors (EIIP, 1996). However, although DARS can provide useful insight regarding the quality of an inventory, it does not provide quantification of the range of uncertainty in the inventory nor regarding the key sources of uncertainty in the inventory.

Quantitative Methods

Both qualitative and semi-quantitative methods suffer from many shortcomings including: restrictive assumptions about the shape of probability distribution models; failure to deal with dependences between uncertainty estimates; failure to distinguish between variability and uncertainty estimates; inappropriate averaging times; improperly analyzed small sample data; and failure to use proper protocols in eliciting expert judgments (Frey et al., 2002)

Due to the limitations of qualitative and semi-quantitative methods, quantitative probabilistic methods for dealing variability and uncertainty in emission inventory are becoming more widely recognized and recommended. Quantitative methods for dealing with uncertainty range in emission estimates involve the characterization of uncertainty in emission factors or activity factors and propagation of uncertainty in emission factors and activity factors to total emission inventory.

The characterization of uncertainty in emission or activity factors may be based on the statistical analysis of empirical data and expert judgment. If empirical data are available and sufficient (typically, at least sample size of 3), statistical analysis with the use of bootstrap simulation is preferred for quantifying uncertainty in emission factors and activity factors. Bootstrap simulation, introduced by Efron in 1979 (Efron, 1993), is a numerical simulation techniques originally developed for the purpose of estimating confidence intervals. The advantage of bootstrap simulation can provide solutions in situations where exact analytical solutions may be unavailable and in which approximate analytical solutions are inadequate for confidence intervals of a statistic. Bootstrap simulation has been widely used in the prediction of confidence intervals, some of them with prediction of emission factors or activity factors, for a variety of statistics such as mean, distribution parameters (e.g., Frey and Zheng, 2002a; 2002b; Frey and Zhao, 2003; Zhao and Frey, 2004).

However, in some cases, empirical data are not available for model inputs in emission estimation, especially for activity factors. In such situation, expert elicitation is a good alternative to address the data gap for use in emission uncertainty analysis (EIIP, 1996). An advantage of expert elicitation is that potential bias in emission factors or activity factors can be adjusted during experts eliciting probability distributions for those factors (Zhao and Frey 2004). In general, in expert elicitation, experts are asked to estimate key parameters associated with an emission activity factors such as the qualitative lower and upper bounds of an emission estimate or the shape of a particular parameter distribution. An example of using expert elicitation in the context of emission inventory is that Dickson and Hobbs (1989) applied the method to estimate the confidence limits for a number of source categories after developing estimates of the uncertainty parameters based upon questionnaires filled out by a panel of emission inventory experts. Typically, expert judgment and statistical analysis are often used together for a large-scale emission inventory development.

Propagation methods of uncertainty from emission factors and activity factors range from analytical error propagation (e.g., Dickson and Hobbs, 1989; NRC, 1991; Balentine and Dickson, 1995) to numerical analysis methods based upon variations of Monte Carlo simulation (e.g, Frey and Zheng, 2002a, Abdel-Aziz and Frey, 2003a). Monte Carlo simulation methods have been used to estimate uncertainty in inventories, such as for criteria pollutants, hazardous air pollutants, and greenhouse gases (e.g., Winiwarter and Rypdal, 2001; Gatz, 1995).

In the United States, there is not as yet an established guideline for uncertainty analysis specifically in the context of emission inventories. However, the EPA has developed guidelines for probabilistic analysis in the context of human exposure assessment, including a 1997 Guideline on Monte Carlo Analysis, as well as guidance on probabilistic methods applied to Superfund risk assessments. Although the problem area is different, many of the methodological principles are transferable to other fields. Authors such as Morgan and Henrion (1990) and Cullen and Frey (1999) provide general principles for the application of probabilistic techniques. An emission inventory is typically constructed based upon emission and activity factors. Thus, it is possible to have a general framework to quantity uncertainty in emission inventories. The general framework includes the following main steps (Frey et al., 1999; Zheng, 2002).

- Data preparation. It includes the assessment of data needs, data collection plans, and compilation or evaluation of existing databases for the specific sources categories.
- Selection or development of emission inventory models.
- Statistical analysis of emission inventories model inputs with empirical data available. It includes visualization of data by developing empirical cumulative distribution functions for model inputs; fitting, evaluation, and selection of alternative parametric probability distribution models for representing variability in model inputs.

- Characterization of uncertainty in the distributions for variability using bootstrap simulation and using expert judgment to specify distributions representing model inputs without empirical data available .
- Propagation of uncertainty in model inputs through emission inventory models to estimate uncertainty in category-specific emissions and/or total emissions from a population of emission sources.
- Calculation of importance of uncertainty.

The Intergovernmental Panel on Climate Change (IPCC) has developed Good Practice Guidance (GPG) recommending the use of Monte Carlo methods as part of a tiered approach to uncertainty estimates for greenhouse gas emissions (IPCC, 2000). The GPG discusses the role of both statistical analysis of data as well as elicitation of expert judgment as means for quantification of uncertainty in emission and activity factors. The GPG has been used by many countries to prepare uncertainty estimates for greenhouse gas emission inventories (e.g., Winiwarter and Rypdal, 2001; El-Fadel et al., 2001; Van Amstel et al., 2000).

There is a growing literature that includes uncertainty analysis of emission factors or emission inventories. Frey and Rhodes (1998) demonstrated the use of bootstrap simulation to quantify uncertainty in mean emission factors based upon inter-unit variability in emissions and sample size for situations in which normality assumptions are not valid, based upon a case study of hazardous air pollutant emissions from coal-fired power plants. Uncertainty was propagated using Monte Carlo simulation through an emission model to yield uncertainty in emissions for any given simulated averaging period. The quantitative methods based upon the use of bootstrap for characterizing uncertainty in emission factor or inventory have been applied to various emission sources, including power plants, non-road mobile sources, natural gas-fired engines, and specific area sources (e.g., Frey et al., 1999; Frey and Zheng, 2000; Frey and Bammi, 2002; Frey and Zheng, 2002a, 2002b; Abdel-Aziz and Frey, 2003a,b, 2004; Winiwarter and Rypdal, 2001).

5.4.5 Established Methodology and Application of Uncertainty Analysis to Emission Inventories in Practice

Quantitative methods for characterizing uncertainty in emission inventories have been recommended by scientific communities (e.g., Frey et al., 1999; Byun and Kim, 2004) and the National Research Councils (NRC 2000; 2004b). There is a limited but growing track record of examples that demonstrate the application of accepted methods for quantification of uncertainty in emission inventories. Uncertainty in emission inventories have been propagated through air quality models to quantify uncertainty in the predictions of air quality. This section briefly describes these examples as well as the types of insights provided by such examples.

Quantitative Uncertainty Analysis Methods Applied to Emission Inventory Development

Quantitative methods for characterizing uncertainty range from relative simple approaches to more rigorous techniques such as Monte Carlo simulation and bootstrap simulation. There are several examples of the use of relatively simple approaches for estimation of uncertainty in emission inventories. For example, Chang et al. (1996) used fuel consumption data, actual operating schedules and AP-42 emission factors to estimate the variability in NO_x emissions from point sources in the Atlanta metropolitan region. Van Amstel et al. (2000) developed uncertainty estimates for greenhouse emission inventories in the Netherlands by assuming that uncertainty of each combined parameter was estimated to be equal to the square root of the sum of squares of the standard deviations of each input parameter. Lee et al. (1997) used a qualitative approach to estimate uncertainty in global NO_x emissions from fossil fuel combustion. NRDC et al. (2002) evaluated the variability of emission factors for the 100 largest electric generation owners. El-Fadel et al. (2001) estimated the uncertainty in a greenhouse emission inventory for Lebanon using alternative information sources. Gschwandtner (1993) used expert judgment to estimate uncertainties in VOC and NO_x inventories in the United States for the years between 1900 and 1990. Hanna and Wilkinson (2004) applied analytical approach based on Taylor series expansion to estimate uncertainty in biogenic emissions calculated by BEIS3 biogenic emission models due to uncertainties in model inputs and parameters.

There is increased use of more rigorous techniques, including Monte Carlo simulation and bootstrap simulation for quantifying variability and uncertainty in emission factors and inventories. For example, Winiwarter and Rypdal (2001) used Monte Carlo simulation to assess uncertainty in a greenhouse inventory for the year 1990 in Austria. Frey and Tran (1999) propagated uncertainties in NO_x measurement methods through a probabilistic model to estimate uncertainties in NO_x concentrations and emission rates. Frey and Zheng quantified variability and uncertainty in highway vehicle emission factors with the use of MOBILE5b (2002a) and developed probabilistic 6-month and 12-month emission inventories for utility NO_x emission inventory for the State of North Carolina (2002b), in which empirical and parametric distributions were used to quantify variability while bootstrap simulation was employed to characterize uncertainty in emissions. Similar approaches have also been used to quantify variability and uncertainty in lawn and garden engines, and for construction, farm and industrial equipment emission factors by Frey and Bammi (2002), and to characterize variability and uncertainty in NO_x and total organic carbon emissions for stationary natural gas-fueled internal combustion engines by Frey and Li (2003). Frey and Zhao (2004) characterized variability and uncertainty in urban air toxics emission inventory for Jacksonville, FL and Houston, TX. Specifically, Maximum Likelihood Estimation (MLE) was used to deal with censored (non-detected) values in emission data and bootstrap simulation in combination with MLE was used to estimate uncertainty in the mean emission factors based upon data that included non-detects. Chi et al. (2004) employed bootstrap sampling, expert elicitation and Monte Carlo techniques to characterize uncertainty of nonroad emissions for the State of Georgia based upon the use of EPA NONROAD model. Allen et al. (2004) characterizes variability in VOC emissions from industrial point sources in the Houston-Galveston area using stochastic model and techniques.

Other statistical methods to quantify uncertainty in emission estimation include the use of Analysis of Variance (ANOVA) and time series approaches. For example, Abdel-Aziz and Frey (2003a) used time series approaches to characterize uncertainty in hourly utility NO_x emissions for the Charlotte, NC air quality modeling domain. Bortnick and Stetzer (2002) applied ANOVA to a similar environmental application to emission inventories where they quantified uncertainty in ambient monitored air toxics data. They partitioned the variance of the monitored data into 4 different components namely: temporal, spatial, sample collection and laboratory analysis where it was concluded that the temporal variability contributed most to the overall uncertainty. Khalil (1992) employed a statistical approach to estimate uncertainties in total global budgets for trace gases. He assumed a uniform distribution to represent emissions of methane, carbon monoxide and carbonyl sulfide from individual source categories and found an analytical solution for the probability density function of the summation of emissions from these categories. Confidence limits for the total emissions were estimated from the probability density function. Sharma and Khare (2000) used univariate linear stochastic models to predict ambient maximum daily carbon monoxide concentration from vehicle emissions at a major traffic intersection in Delhi city, India. Gleit (1987) used autoregressive moving average models to obtain expressions for the probability of compliance of SO_2 emissions for different averaging times.

Uncertainty in Emissions and Propagation through Air Quality Models

Emission inventories are often used as inputs to air quality models to predict ambient air pollutant concentrations. Placet et al. (2000) point out that errors in emission inventories can have a significant influence on ozone predictions and that estimates of uncertainties in emission inventories can help modelers explain the difference between predictions and observations. It is generally believed that the emissions are one of the most, if not the most, uncertain inputs to air quality system (Russell and Dennis, 2000). Emission uncertainties are main sources of uncertainty in predicting air quality over urban and rural scales, as well as the impact of emission implementation control strategies (Sawyer et al., 2000; Placet et al., 2000; Guenther et al., 2000; and Russell and Dennis, 2000).

Some studies have been conducted linking the uncertainties in emission inventories to air quality models. For example, Hanna et al. (1998) used expert elicitation to estimate typical uncertainties in 109 input parameters for the Urban Air Shed Model (UAM-IV) including emissions, meteorological conditions, boundary conditions and chemical rate constants; and propagating uncertainties by using Monte Carlo simulation to quantify uncertainty in ozone predictions for the 6-8 July 1998 episode of New York City. The results indicate that the variability in anthropogenic volatile organic compounds (VOCs) emissions had most impact on the uncertainty in predicted ozone concentrations. Hanna et al. (2001) employed the same approach used by Hanna et al. (1998) but applied to the ozone transport assessment group (OTAG) domain. They addressed uncertainties in 128 input variables including emissions, initial and boundary conditions, meteorological variables and chemistry.

Moore and Londergan (2001) applied a probabilistic approach to quantify uncertainties in ozone prediction differences between a base and a control scenario in which Latin hypercube sampling was employed. They propagated uncertainties in 168 model inputs for emissions, chemistry, meteorology and boundary conditions. Lognormal and normal distributions were used based on expert judgment to describe the uncertainty in the inputs that were investigated. Bergin et al. (1999) used Monte Carlo simulation with Latin hypercube sampling to propagate uncertainties in 51 model parameters through the California/Carnegie Institute of Technology air quality model. The uncertainties in on-road carbon monoxide emissions were quantified based on remote sensing measurements. Uncertainties for other emissions were estimated based on expert judgment. The study concluded that uncertainties in motor vehicle emission contributed most to uncertainties in ozone concentrations. Abdel-Aziz and Frey (2004) propagated uncertainty of hourly utility NO_x emissions through a photochemical air quality model to estimate the uncertainty in the maximum 1-hour and 8-hour ozone concentrations for Charlotte, NC modeling domain based upon the use of Monte Carlo simulation.

Gatz (1995) used bootstrap simulation to calculate the 95% confidence interval for a weighted mean of the concentrations of nine major ions in precipitation. Moore and Sistla et al. (1996) investigated the effect of uncertainty in the specification of meteorological inputs on ozone concentration patterns. Bergin et al. (1999) quantified the uncertainties in reactivity of volatile organic compounds as a result of uncertainty in reaction rate constants.

Uncertainty Estimation and Emission Models

Uncertainty analysis is rarely incorporated into most modeling frameworks for estimating emissions (e.g., MOBILE, NONROAD, BEIS3). However, one existing and one emerging modeling framework illustrate that uncertainty analysis can be incorporated as an integral technique in combination with emission estimation. Furthermore, when uncertainty analysis is built into the modeling process from the beginning, it is substantially less resource intensive and more convenient than when uncertainty analysis is done post-hoc.

The NRC (2000) report on modeling mobile source emissions has motivated the incorporation of uncertainty analysis into the "MOVES" modeling framework. MOVES is planning to replace both the MOBILE and NONROAD model and will include a capability to quantify uncertainty. Neither MOBILE nor NONROAD models contain an uncertainty analysis component. Several studies that have focused mainly on data used to develop previous generations of the MOBILE model have identified significant ranges of uncertainty in fleet average emission estimates from the MOBILE models. For example, Guensler (1993) and Guensler and Leronard (1997) assessed uncertainty in speed correction factors (SCFs) using Monte Carlo analyses based upon SCF regression errors. Chatterjee et al. (1997) conducted statistical analysis of SCF regressions and calculated the confidence intervals of SCFs to estimate uncertainty in emissions at typical roadway types and speeds. Frey and Zheng (2002a) derived estimates of uncertainty in basic emission rates, speed correction, temperature correction and Reid vapor pressure (RVP) combined for one specific MOBILE 5b LDV technology group (port-fuel and throttle body injection vehicles). Uncertainty in emissions for these vehicles was estimated using a bootstrap technique. Uncertainty in the fleet average emission factor was as much as -90% to +280% when correction factors for alternative driving cycles, temperature, and RVP are applied. Frey and Bammi (2002) characterized both variability and uncertainty emission factors for lawn and garden (L&G) engines and for construction, farm, and industrial (CFI) equipment using parametric distributions and bootstrap simulation. The ranges of uncertainty in average emission factors were typically on the order of plus or minus 40 percent.

A main feature of the forthcoming MOVES is that it will incorporate a capability to quantify variability and uncertainty using a probabilistic approach. A conceptual basis for quantifying uncertainty in modal emission rates was demonstrated by Frey et al. (2002). Frey (2003) evaluated an error propagation approach for estimating emissions in mobile inventories as a result of uncertainties in inventory inputs. Such an approach can perform reasonably well if the ranges of uncertainty in the inputs are not too large and if the model is approximately linear. However, a Monte Carlo or similar simulation method will allow more flexibility both with respect to specification of uncertainty in inputs and propagation of uncertainty through complex models. Thus, current plans for MOVES are based upon the use of a numerical simulation approach for quantification of uncertainty.

An existing modeling framework that incorporates a probabilistic simulation capability is the Integrated Environmental Control Model (IECM) developed by Carnegie Mellon University for the U.S. Department of Energy. The IECM provides performance, emissions and cost estimates for user-specified power plant configurations using site-specific plant parameters and fuel characteristics. The IECM has the capability to explicitly quantify the uncertainty in calculated results including emission estimates. The IECM enables the user to accept default specifications of uncertainty for inputs or to provide user-specified probabilistic inputs. The IECM uses Monte Carlo simulation or Latin Hypercube sampling to propagate uncertainties through the model in order to estimate uncertainty in emission rates and other outputs.

5.4.6 Assessment of Source Categorized-Based Inventory Uncertainty

The range of uncertainty in emission inventories typically varies depending on the source category and pollutant. For example, uncertainties in emission inventories from electric utilities for SO_2 and NO_x are generally thought to be of low uncertainty because of the use of CEMS data, while emission estimates for area sources have larger uncertainty due to lack of data (NRC, 2004b). Uncertainty in emissions for air toxics generally have higher uncertainty compared to criteria pollutants since more frequent measurements are taken and more monitoring networks are available for criteria pollutants. Although it is not possible to conclude that emission estimates for one source category always have less uncertainty or a higher confidence level than other source categories due to variations in different inventory domains, a rough assessment regarding relative confidence levels based upon source categories for overall emission inventories can be made. Table 5.2 shows the source categorized-based confidence levels. The assessment was made based upon judgment from experts of emission inventory fields. The degree of confidence in the emissions for a given category and pollutant does not directly translate into significance with respect to overall uncertainty in the inventory. For example, if there is low confidence in emission estimates for a source category that makes a small contribution to total emissions of a given pollutant, it is possible that the overall emission inventory could be of high confidence if it is dominated by source categories for which emissions are known with high confidence.

Table 5.2. Estimated Relative Confidence Levels of Emission

Pollutants	Source	Estimated Confidence Levels in Overall Inventory		
		U.S.A	Canada	Mexico
SO_2[a]	Utilities	high	high	high
	Other point sources	medium	medium	low-medium
	On-road mobile	medium	medium	low
	Non-road mobile	medium	low-medium	low
	Area sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources	low	low	low
NO_x[a]	Utilities	medium-high	high	medium
	Other point sources	medium	medium	medium
	On-road mobile	high	high	medium
	Non-road mobile	medium-high	medium-high	low
	Area sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources	medium	medium	low
VOC[a]	Utilities	medium-high	medium-high	medium
	Other point sources	low-medium	low-medium	medium
	On-road mobile	medium	high	low
	Non-road mobile	medium-high	medium-high	low
	Area sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources	medium	medium	low
HAP	Utilities	medium	medium	medium
	Other point sources	low-medium	low-medium	low
	On-road mobile	medium	medium	low
	Non-road mobile	low-medium	low-medium	low
	Area sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources	low	low	low

Note: [a]NARSTO PM assessment (NARSTO, 2004)

5.4.7 An Established Uncertainty Analysis Example for Emission Inventory

An established example for developing a probabilistic emission inventory, done by Zhao and Frey (2004), is presented here to demonstrate a comprehensive methodology for quantification of uncertainty in mean emissions or activity factors as a fundamental basis for estimating uncertainty in emission inventories. The example quantified uncertainty of emission inventory for six selected urban air toxics (benzene, 1, 3-butadiene, formaldehyde, mercury, arsenic and lead) for the urban area of Jacksonville, Florida.

This example follows the general framework and steps presented in this Chapter to quantify uncertainty for Jacksonville air toxic emission inventories. The source categories considered in this example include: on-road and non-road mobile; electric utility; and area sources. Specific source categories for each pollutant considered in the example case studies vary depending on the pollutant. Surrogate uncertainty data for emission factors are used for the situation where insufficient emission sample data are available for a particular source category, but for which data are available for a similar type of emission process. This example employed Maximum Likelihood Estimation to fit parametric distributions for inter-unit variability in emissions to sample data. The MLE method can be applied also to cases in which some data are below one or more detection limits. Bootstrap simulation was used to quantify variability and uncertainty in emission factors. Figure 5.10 illustrates the results of analysis of variability and uncertainty for one of the emission factors used in the inventory for mercury. The figure shows the available sample data that represent inter-unit variability, a parametric probability distribution fit to the data, and probability ranges around the fitted distribution that were obtained from bootstrap simulation. The latter quantify uncertainty in the ability to infer the true but unknown population distribution of inter-unit variability. Furthermore, based upon the bootstrap results, uncertainty in the mean emission factor can be inferred. The advantage of the bootstrap approach over an analytical estimate of uncertainty in the mean is that the uncertainty in the mean can be positively skewed if there is a large amount of variability in the data and a small sample size. Bootstrap can capture such skewness, whereas analytical estimates of uncertainty in the mean typically are based upon a normality assumption. Skewness is an important property of a probability distribution and if inaccurately characterized can imply misleading insights.

Expert judgment was used to determine uncertainty in activity factors. Monte Carlo simulation was applied to propagate uncertainty in emission factors and activity factors to total emission inventories. Table 5.3 summarizes the relative range of uncertainty for the inventory for each of the six pollutants. The uncertainty estimates range from as little as minus 25 percent to plus 30 percent relative to the mean estimate of the inventory to more than a factor of two. A factor of two uncertainty is when the lower end of the range is one-half of the mean and the upper end of the range is twice the mean (e.g., -50 percent to plus 100 percent). Correlation coefficients were used to identify key sources of uncertainty and important source categories. Typically only one to three source categories out of a dozen or more were found to be the key sources of uncertainty for each of the six pollutants.

The results of this example indicate that the overall range of uncertainty is approximately a factor of two or greater for five of the six pollutants. The results of this example also demonstrate that random sampling error and measurement error lead to substantial quantifiable uncertainty in the emission inventories of selected urban air toxics. The positively skewed ranges of uncertainty appropriately account for the fact that emissions must be non-negative. The identification of key sources of uncertainty in the inventory serves as an aid to prioritizing resources for additional data collection or research in order to reduce uncertainty.

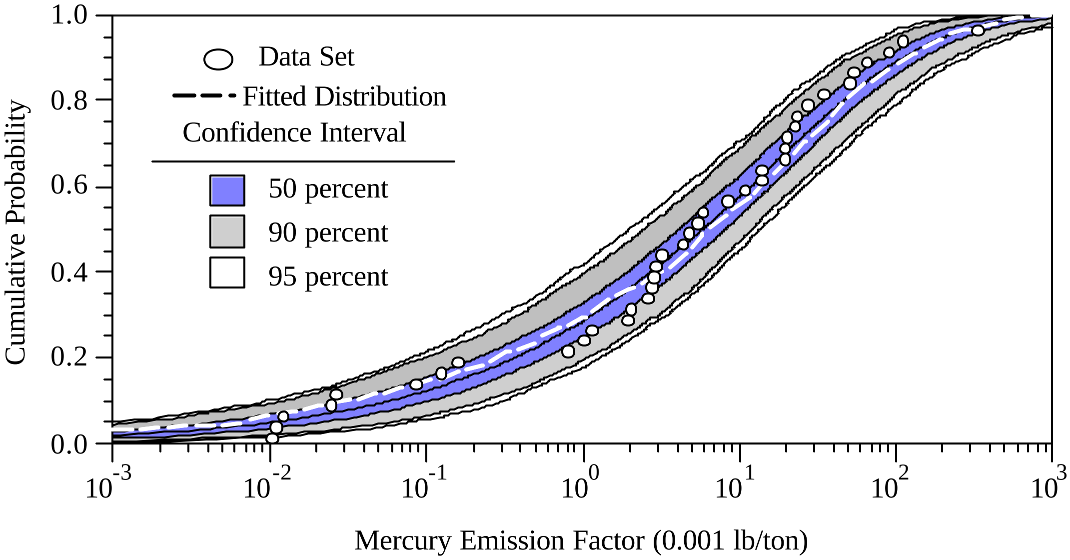


Figure 5.10. Variability and Uncertainty in Mercury Emission Factor from Pathological Waste Disposal Estimated Based Upon a Weibull Distribution (n=40; B=500).

Table 5.3. Normalized Estimates of Overall Uncertainty in Probabilistic Emission Inventories for 1, 3-butadiene, Mercury, Arsenic, Benzene, Formaldehyde and Lead: Comparative Analysis of Correlated and Uncorrelated Surrogate Emission Factor Uncertainties

Pollutant	Relative Range of Uncertainty, Plus or Minus Percent Relative to Mean Inventory Estimate
1,3-butadiene	(-46, 108)
Mercury	(-25, 30)
Arsenic	(-83, 243)
Benzene	(-54, 141)
Formaldehyde	(-42, 89)
Lead	(-52, 177)

5.5 SENSITIVITY ANALYSIS

Sensitivity analysis can help focus uncertainty analysis on a small number of key source categories and determine which model input makes the most contribution to uncertainty in a selected model output. For example, sensitivity analysis can be used to identify the key sources of uncertainty in an emission inventory so that additional research or data collection can be targeted in order to reduce uncertainty and to identify which source categories should be the target of emission controls and to help set emission limits for specific categories or groups of categories. Sensitivity analysis has been recommended for the use in mobile source emission inventories (Sawyer et al., 2000; NARSTO, 2000). NRC (2000) recommended that a comprehensive sensitivity analysis should be performed for all model inputs for MOBILE models. Thus, sensitivity analysis, as a supplement of uncertainty analysis, is an important component for emission inventory development as well as air quality management.

This section begins with the introduction to the available methods and existing guidance documents for sensitivity analysis, and then discusses the role of sensitivity analysis in emission inventory development. At last, the application of sensitivity analysis in emission inventory and air quality modeling practice is assessed.

5.5.1 Methods for Sensitivity Analysis

There are a variety of methods available to perform sensitivity analysis, and they can be classified in a variety of ways. For example, methods can be classified as screening versus refined depending upon the level of detail or sophistication. Methods can be classified as local or global depending upon whether they measure sensitivity at a specific point in the model input domain or over a large input domain when many inputs are varying simultaneously. Methods can be classified as model dependent or model independent depending upon whether a specific functional form must be assumed or existing in order for the results to be estimated or valid. Methods can also be classified as to type such as mathematical, statistical, or graphical.

Screening methods are typically used to make a preliminary identification of the most sensitive model inputs. However, such methods are often relatively simple and may not be robust to key model characteristics such as nonlinearity, thresholds, interactions, and different types of inputs (e.g., categorical, continuous). More refined methods that can adequately deal with complex model characteristics typically require greater expertise or resources to implement and interpret.

Local sensitivity analysis concentrates on the impact of changes in values of inputs with respect to a specific point in the input domain. Nominal range sensitivity analysis (NRSA) and differential sensitivity analysis (DSA) methods are examples of local sensitivity analysis methods. Global sensitivity analysis apportions the uncertainty in the output to the uncertainty in the inputs when many inputs varying simultaneously and over large ranges of variation. Global methods are applicable to situations in which model inputs are varied simultaneously over large ranges of values, typically based upon probability distributions assigned to each input.

Some methods, such as correlation coefficients regression-based techniques, require assumption or specification of a model functional form and estimation of sensitivity coefficients that depend upon the assumed form. If the assumed form of the regression model does not adequately capture the response between an input and output, then insights obtained from the analysis may be subject to error. Other methods, such as Sobol's method, Fourier Amplitude Sensitivity Test (FAST), Categorical and Regression Trees (CART, also known as Hierarchical Tree-Based Regression – HTBR) and ANOVA do not require a priori knowledge or specification of a function form and thus are typically more robust to model complexities. Such techniques are referred to as model independent. However, such methods can be more challenging to use in practice than more commonly available correlation and regression methods.

Alternatively, methods can be classified as mathematical, statistical and graphical methods. The mathematical methods include NRSA and DSA. Mathematical methods typically address the local or linear sensitivity of the output to perturbations or ranges of individually varied inputs and are helpful in eliminating unimportant inputs. However, they may not be reliable as a method for ranking and discriminating among important inputs. Furthermore, mathematical methods do not address the variance in the output due to the variance in the inputs. Statistical methods, such as correlation coefficients, regression, ANOVA, and CART, can be used to assess key sources of uncertainty when many inputs vary simultaneously. The selection of an appropriate technique will depend upon model characteristics and assessment objectives. Graphical techniques are often useful especially to help identify complexities in model responses and as an aid in selecting other sensitivity analysis methods or in interpreting results from other methods. Graphical methods can be used as complements to mathematical and statistical methods to better interpret sensitivity analysis results. More detail regarding the discussion and description of these methods can be found in Frey et al.(2003).

The most commonly used statistical methods typically are: (1) sample (Pearson) and rank (Spearman) correlation coefficients, (2) sample and rank linear regression. The sample (Pearson) correlation method can evaluate the strength of linear association between output values and values sampled from probability distribution of an input; while the rank (Spearman) correlation can account for monotonic nonlinear relationships between two random variables (Siegel and Castellan 1988). Sample regression uses a dataset for fitting a regression model including the output values from a model and sampled values from probability distributions of inputs. Sample regression can account for the linear associations between the inputs and output. Rank regression is based upon the ranks for the inputs and outputs. Rank regression is especially useful when there is high amount of variance or noise in the data or if the model is non-linear but monotonic.

In addition to the commonly used methods, there are some methods which are potentially useful for emission inventory modeling, including ANOVA and CART. ANOVA is a general statistical-based technique that can be applied to models that are linear, non-linear, monotonic, or non-monotonic. ANOVA can address both qualitative and quantitative inputs (Steel *et al*. 1997). CART is a method for partitioning data. CART produces "classification rules" that specify specific cut-off values of selected inputs that lead to statistically significantly different mean values for an output. Hence, CART can provide insight into conditions that lead to high emissions. CART is applicable to linear or non-linear models, including models with interactions and thresholds.

Selection of appropriate sensitivity analysis methods depends on objectives of performing sensitivity analysis. For example, when the objective of sensitivity analysis is to identify key sources of uncertainty and apportion variances in an output to individual inputs, the choice of methods further depends on inherent model characteristics. If a model is linear, correlation methods and regression analysis methods may be appropriate because of simplicity. If there are interactions between model inputs, ANOVA or other methods capable of dealing with interactions are better choices. When there are categorized inputs, CART may be more appropriate.

When the objective of sensitivity analysis is to identify factors contributing to high emissions in order to develop control strategies, ANOVA and CART may be appropriate since the two methods can provide insight into conditions that lead to high emissions. Except objectives of analysis and model characteristics, selection of sensitivity analysis methods also depends on other factors such as ease of implementation, responding to simultaneous variation of inputs, and being robust in practice. More information on selection of appropriate sensitivity analysis methods can be found in Frey et al. (2003).

5.5.2. Summary of existing guidance on sensitivity analysis

Although there is no guidance available specifically for the application of sensitivity analysis to emission inventory development and air quality modeling, there are guidance documents available on sensitivity analysis applied to other quantitative analysis fields such as risk assessment. For example, U.S. Department of Agriculture (USDA) sponsored the identification and evaluation of methods for sensitivity analysis (e.g., Frey and Patil 2002; Frey et al 2003) and development of a guidance document on the application of sensitivity analysis methods to food safety risk process models (Frey et al. 2003). Frey et al. (2003) discuss the various objectives for performing sensitivity analysis and identify key factors to be considered in the selection and application of sensitivity analysis methods, and in the interpretation and communication of results from sensitivity analysis.

EPA (2001b) provides guidance on how sensitivity analysis can be applied to identify important exposure or risk factors as part of risk assessment of Superfund sites. The role of sensitivity analysis in probabilistic risk assessment is discussed. Common sensitivity analysis methods such as correlation and regression methods, graphical methods such as scatter plots, and the use of these methods in the risk assessment are introduced via example case studies.
Saltelli et al. (2004) provide a guide regarding application of sensitivity analysis methods to scientific modeling. A review of the state-of-the-art in sensitivity analysis is presented and a guide regarding selection of appropriate methods for evaluating model performance and key inputs is provided with example applications.

5.5.3 Role of Sensitivity Analysis in Developing Emission Inventories

Sensitivity analysis plays important roles in the development of emission inventories. These roles include: (1) assisting in verification/evaluation of emission inventory models; (2) identifying key sources of variability and uncertainty; (3) evaluating the importance of key assumptions.

Emission inventory model verification is a process of making sure that the model properly calculates emissions from various emission sources and activity factors. If a model responds in an unacceptable way to changes in one or more inputs, then troubleshooting efforts can be focused to identify the source of the problem. For example, if a significant increase in activity factor does not lead to appropriate increase in the emission inventory, efforts need to be focused on fixing problems with the emission inventory model structure. Model validation ideally involves comparison of model results to independent observations from the system being modeled. Generally, in most emission inventory development, complete validation is not possible because of lack of sufficient observational data. Cullen and Frey (1999) discuss partial validation of a model when observational data are available for only a part of the modeling domain. Sensitivity analysis can be used to help develop a "comfort level" with a particular model. If the model response is reasonable from an intuitive or theoretical perspective, then the model users may have some comfort with the qualitative behavior of the model even if the quantitative precision or accuracy is unknown. Saltelli (2002b) discusses the role of sensitivity analysis in model evaluation and how to make use of sensitivity analysis to verify or validate a model. Russell and Dennis (2000) discuss the application of sensitivity analysis to air quality model evaluation and verification.

Sensitivity analysis methods, in combination with probabilistic analysis techniques, can support the identification of key sources of variability and uncertainty. Even though an emission inventory may involve many inputs that are subject to uncertainty, it is often the case that only a few inputs contribute substantially to total uncertainty. Therefore, as a means for conserving resources devoted to an analysis, sensitivity analysis can be used concurrent with the process of developing input assumptions to continually refine the identification of key sources of uncertainty and to prioritize information gathering efforts for those inputs that matter the most to an emission inventory. Similarly, the results of sensitivity analysis, appropriately conveyed to a decision maker, can help the decision maker focus questions regarding pedigree of information or regarding research needs, to specific parts of the emission inventory thereby saving time and cost. For example, even though there may be a large relative degree of uncertainty in a particular source category, if the particular category does not contribute substantially to uncertainty in the overall inventory, there would not be a large benefit associated with improving the characterization of uncertainty for that particular source category. In such a case, it would also not be worthwhile to devote substantial resources to additional data collection or research in order to reduce uncertainty.

Sensitivity analysis can be used to evaluate whether key assumptions in a model are acceptable. For example, independence among model inputs is a commonly employed assumption. Using sensitivity analysis, it is possible to evaluate whether the assumption is reasonable. For example, bounding analyses can be performed in which the inputs of interest are assumed to be independent versus assumed to be completely correlated. If the results and insights from the analysis do not change irrespective of which assumption is made, then the issue of correlation is unimportant. Frey and Zhao (2003) demonstrated that correlation between uncertain emission factors for hazardous air pollutants was typically unimportant for several inventories. Furthermore, sensitivity analysis can be used to determine whether simplifying assumptions or judgments in the absence of empirical data have a significant influence on results. Frey and

Zhao (2003) demonstrated, for example, that assumptions regarding weighting factors for emissions of different processes within a source category were unimportant to an overall assessment of urban-scale emissions because the source categories were also unimportant to the overall uncertainty estimate.

5.5.4. Assessment of Sensitivity Analysis Application in Practice

Sensitivity analysis has been applied to assist the verification/validation of emission models, to identify key sources of uncertainty and source categories in emission inventory development, and to identify key model inputs in air quality modeling.

Sensitivity analysis has been used to evaluate emission models. For example, Kear et al. (2002) evaluated the sensitivity of exhaust emission rates to vehicle population and mileage accrual data for the California Air Resources Board's (CARB) mobile source emission model, EMFAC 200x V2.08. Sensitivity analyses have been also done to evaluate how important model inputs in MOBILE models such as average speed, ambient temperature, fuel property and I/M parameters. Heiken et al. (1994) assessed the sensitivity of model outputs to alternative fuel formulations for exhaust emission rate, evaporative system pressure and evaporative basic emission rates. Fox (1996) evaluated the contributions of key model inputs (e.g., temperature, fuel RVP, average speed) to emission factor estimates for Mobile 5. Chatterjee et al. (1997) analyzed key travel-related inputs (e.g., speed, VMT, vehicle classification, operating-model fraction) and assessed the sensitivity of model outputs to these variables.

Sensitivity analysis has been applied to the development of emission inventories to identify key sources of variability and uncertainty. For example, Frey and Zheng (2002a and 2002b) used sensitivity study to identify key sources of variability and uncertainty in developing a probabilistic emission inventory for utility NO_x emissions, and key contributors (e.g., speed correction factor, temperature correction factor, base emission rate and Reid vapor correction factor) to the uncertainty in highway vehicle emission factors. Frey and Zhao (2003) performed sensitivity studies to identify key source of uncertainty in developing probabilistic air toxics emission inventory for Houston, TX and Jacksonville, FL. Sax (2003) used sensitivity analysis to determine the importance of different roadway classifications, speed, emission factor and other sources contributing to uncertainty of on-road emission estimates. In most of these example applications, sample or rank correlations and regression were the most commonly used methods to identify key contributors to uncertainty in the emission estimates.

Sensitivity analysis has also been used in air quality modeling to investigate how emission control strategies affect atmospheric air quality and to quantify the sensitivity of air quality model results to uncertainty in emission input or other input parameters (e.g., chemical reaction rates). For example, Morris et al. (2004) investigate how ozone concentration is sensitive to emission reductions scenarios for controlling anthropogenic VOC versus NO_x emissions. Odman et al. (2002) calculated sensitivities of air quality concentrations and deposition fluxes to various emissions. Bullock et al. (1998) used scatter plots to analyze model sensitivity to uncertainty in mercury air emission. Bergin et al. (1999) evaluated the effects of uncertainty in air parcel trajectory, emissions, rate constants, deposition affinities, mixing height, and atmospheric stability on the predictions from a photochemical air pollution model by using regression analysis, with the help of scatter plots to determine the relationship (linear or nonlinear) between the model output variables and uncertain inputs. Mendoza-Dominguez and Russell (2000) linked sensitivity analysis of air quality models with an inverse modeling technique to help identify improvements in emission strengths, pattern, and composition of various source categories. Chock et al. (1995) investigated the sensitivity of urban airshed model (UAM) results for test fuels to uncertainty in light-duty vehicle and biogenic emissions and alternative chemical mechanisms. Jiang et al. (1997) evaluated the sensitivity of ozone concentrations to VOC and NO_x emissions in Canadian Lower Frasier Valley. Other examples include the analysis of sensitivity of predicted ozone and other secondary pollutants to uncertainty in rate parameters and product yields of chemical mechanisms (e.g., Gao, 1996; Yang, 1996), and sensitivity analysis of key model inputs, particularly emissions and meteorology, to the ambient concentrations (e.g., Kumar and Russell, 1996; Kuklin and Seinfeld, 1995; Seinfeld, 1988).

5.6 SUMMARY OF KEY FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

Emission inventories are an essential component of air quality modeling and management. Air quality management strategies typically have substantial economic and health implications. Thus, it is important to have reliable inventories. There is growing recognition that emission inventories are subject to substantial (and typically unspecified) levels of uncertainty, which undermine the confidence that can be placed in the resulting air quality management strategies. Other factors also motivate increased scrutiny of inventories. For example, the fractional contribution of what used to be relatively small source categories tends to increase with time. This, in turn, leads to the need to accurately and precisely estimate emissions in situations where measurement methods have previously been unavailable, inadequately sensitive or costly. This section summarizes the key findings based upon the assessment of current emission inventories and models and presents conclusions and recommendations based upon these findings.

5.6.1 Key Findings

Key findings regarding the strengths of current emission inventories and models include:

- Most current inventories or models can provide quantitative estimates of emissions at national, state and county levels, which can be used, with some caveats as shown in Section 5.2, to compare the significance of different source categories.
- Emission estimates from current inventories and models can provide some insights regarding air quality trends over time and pollution control efficiency and help decision-makers develop air quality management strategies. However, uncertainties in these estimates limit the confidence that can be placed in these insights.
- In situ analysis of plumes from point sources such as electric utilities are of high quality with little uncertainty because of the use of CEMS, especially for SO_2, NO_x and CO_2; while emission inventories for area sources are of lower quality and have higher uncertainty.

Key findings regarding the weaknesses include:

- Top-down tests suggest significant weaknesses in existing inventories derived from emission and activity factors.
- There are long intervals between updating and reporting of emission inventories; thus, current emission inventories may not provide timely and updated emission information for air quality management decisions.
- Accuracy in emission estimates is limited in many cases because of small numbers of samples and potential lack of representativeness of sample data used to develop emission inventories. Uncertainty in emission estimates arises due to limited samples and non-representativeness of these sample data
- Inconsistency exists in reconciling national, provincial, stage or county level inventories. There are not mechanisms to ensure that the aggregation or disaggregation process is appropriate and consistent across different agencies.
- Temporal and spatial resolutions of emission inventories are often not appropriately addressed.
- QA/QC procedures are not strictly applied in most emission models or inventory development.
- Documentation regarding emission inventory development, especially regarding key assumptions and data sources, is inadequate
- Compared to the analysis of non-biogenic sources, biogenic emission estimation receives relatively less attention. However, considerable uncertainty in total emission may be associated with biogenic emission estimates.
- Compared to criteria pollutants, there is higher uncertainty in air toxic emission inventories because of lack of measurement data in air toxics.

Other key findings associated with uncertainty and sensitivity analysis activities in emission inventories include:

- Decision making is more robust when uncertainties are acknowledged and taken into account.
- Scientific good practice includes quantification of uncertainty for any numerical estimates, i.e. the degree of confidence that should be placed in numbers can be inferred from a quantitative estimate of uncertainty associated with the number.
- There are many methods for quantification of uncertainty, and an appropriate method can be selected based upon the assessment objectives, information availability, and resource availability.
- Uncertainties in emission inventories may range from relative small (e.g., plus or minus 10 percent) to relatively large (e.g., a factor of three or more) depending on the pollutant, averaging time, and geographic scope. Uncertainties tend to be largest for source categories or inventories for which available emission factor data are limited in sample size. Random sampling error and measurement errors are typically key sources of uncertainty.
- Judgments regarding what constitutes an "acceptable" level of uncertainty are context-specific and depend on the assessment objective, i.e., the required degree of precision and accuracy of an inventory will vary depending upon the intended use of the inventory.

- There is need to identify key sources of uncertainty since such information is helpful to explain the factors contributing to uncertainty in the inventory and to focus discussions on those source categories that most influence the uncertainty estimate.
- There is a need to target resources to reduce key sources of uncertainty, such as via additional data collection since an increase in the sample size will typically tend to reduce uncertainty in the mean.
- There is a need for practical guidance on how to quantify uncertainty.
- There is a need for systematic reporting of information that can be used to support uncertainty analysis.
- Uncertainty analysis is less resource intensive when it is incorporated into emission inventory development, rather than conducted post hoc.

5.6.2 Conclusions

The key conclusions regarding the strengths and weaknesses of emission inventories based upon these findings are as follows:

- Current emission inventories have many strengths that are relevant to assessment of air quality trends and development of air quality management strategies.
- The precision and accuracy of emission data used for inventories varies depending on the source category, emission process, pollutant, geographic area, and averaging time.
- Although there are many strengths to current inventories, there are also many critical weaknesses. For example, the typically long intervals between updates of national inventories may not provide adequately updated information for trends analysis nor for many air quality management decisions.
- Uncertainties, including precision and accuracy, are rarely quantified for emission factors and are not quantified in practice for emission inventories.
- There is a need for consistency in reconciling emission inventories at overlapping temporal and geographic scales, such as national, provincial, state, and county-level inventories. There is a need for mechanisms to ensure that the aggregation or disaggregation process is appropriate and consistent across different agencies.
- There is a critical need for improved documentation regarding emission inventories, especially regarding the objectives, scope, key assumptions and data sources.

The key conclusions regarding uncertainty and sensitivity are:

- Quantification of uncertainty in emission inventories is scientific good practice and improves the quality of decision making regarding air quality management.
- Practitioners can appropriately choose from among many methods for quantifying uncertainty and would be assisted by guidance to help with respect to methodological choice and interpretation of results.
- Quantified uncertainties in emission inventories can be evaluated in terms of assessment objectives to determine if the range of uncertainty is acceptable and, if not, to identify and prioritize key sources of uncertainty in order to target efforts to reduce uncertainty.

- The quantification of uncertainty is significantly less resource intensive when conducted as an integral part of inventory development and when information regarding uncertainty is routinely reported and readily available.

Overall, the main conclusions from the assessment of current practice and methods for uncertainty and sensitivity analysis are that decision making based upon inventories would be better informed if uncertainties are quantified, and that knowledge of uncertainty can be used to prioritize resources toward improving the inventory. To assist practitioners, it is important to develop practical guidance on how to conduct uncertainty and sensitivity analysis and to facilitate such analyses with more systematic reporting of uncertainties.

5.6.3 RECOMMENDATIONS

This section presents recommendations that are based upon the findings and the conclusions. The key recommendations are presented briefly.

(1) More effort should be made to reduce uncertainty in total emissions, such as for area and biogenic emission sources
(2) Air toxics emission inventories should be improved
(3) Emission inventories should be reported and updated in a timely manner.
(4) Temporal and spatial resolution should be adequately addressed.
(5) Evaluation of inventories, including validation and verification, should be given greater priority than currently is the case.
(6) Complete and clear documentation should be provided for emission inventories
(7) Uncertainty analysis should be incorporated into emission inventory development
(8) Quantitative methods should be given priority for characterizing uncertainties in emission inventories
(9) Uncertainty and sensitivity analysis should be integrated into emission inventory development.
(10) The results of uncertainty analyses should be systematically reported.
(11) A guidance document and other training resources should be developed to assist practitioners regarding choice, application, and interpretation of methods for quantification of uncertainty and sensitivity.

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CHAPTER 6. FUTURE PERSPECTIVES: EVOLVING MEASUREMENT TECHNOLOGY, INTERPRETIVE METHODS, AND SCIENTIFIC ISSUES

6.0 INTRODUCTION AND OVERVIEW

As noted in Chapter 1, scientific programs during recent years suggest that several evolving methodologies are potentially applicable as advanced techniques of emission-inventory development and/or verification, and that these potential approaches should be considered for future application. This chapter provides a brief overview of several of these methodologies.

At the outset it is important to note three general aspects of these techniques. First many, if not all, of the methods discussed here are not really “new”; indeed, most have been in existence in one form or another for a number of years. Earth satellite remote sensing and receptor modeling, for example, have been evolving for some time. Other techniques which are relatively new to air-pollution analysis, such as inverse modeling, have experienced extensive application in other fields. Key points to note in this respect are that these methodologies are indeed *evolving*, leading to potentially new approaches to emission-inventory analysis, and that workers in the field should monitor these developments as they progress.

The second noteworthy aspect is the fact that the potential for innovative application often lies more in a *combination or integration* of two or more of these technologies, rather than in isolated deployment of a single technique. Creative combinations of aircraft remote-sensing measurements and ambient concentration data from a well designed field campaign with an inverse-modeling analysis, for example, might be expected to reveal substantial information regarding specific emission sources.

Finally, it is important to note that many of the technologies discussed in this chapter were not developed with particularly strong foci (if any) on emission-inventory development, but rather have led to potential applicability mainly because of fortuity. The emission-inventory community badly needs a procedure that is more direct and focused than this largely happenstance approach. Accordingly, it will be important to establish an active, two-way dialog between emission-inventory developers and scientists involved in creating future measurement and interpretive methodologies. Inventory developers need to maintain an awareness of technological developments related to their field; but more importantly, they also must think creatively about their future needs and communicate these requirements to their counterparts so that future development occurs less by chance and more by intentional design. A dialog between emission-inventory scientists and those developing sensors for future satellites is a prime example of such an interaction. The sections of this chapter discuss these evolving methodologies, and are intended to provide a starting point for this process.

6.1 OBSERVATION AND MEASUREMENT METHODS

The purpose of this section is to describe selected evolving observational and measurement techniques having potential emission-inventory applications, and to summarize them in sufficient detail to give the reader a basic idea of their measurement principles, their future potential, and their limitations. As is readily apparent in the following sections, some of these methods are much more complex than others, and require more extensive descriptive detail to convey their basic features. This is reflected by the selected lengths of the individual descriptions presented below, which are arranged in general order of complexity and attendant descriptive detail.

6.1.1 Remote Sensing

Remote-sensing techniques fall into a number of classes depending on the type of sensing signal applied (e.g., electromagnetic or sonic), electromagnetic wavelength range (ultraviolet, visible, infrared, or microwave),[1] whether the method in question observes spectrally disperse or broadband radiation, whether it has ranging capabilities, and the type of signal detected (e.g., absorption, Mie-scattering, fluorescence, . . .). Several systems within these categories have been deployed to determine emissions from both stationary and mobile sources, using surface, aircraft-based, and satellite-mounted sensors.

A noteworthy aspect of existing remote-sensing measurements is the fact that, in general, they provide measurements of path-integrated loadings only, or at best (in the case of ranging measurements) concentrations. Deriving actual emission rates from these data requires a direct or indirect indication of flow velocity, such as actual effluent flow-rate measurement or the use of index species (such as CO_2) in conjunction with process-stoichiometric calculations. Although these deficiencies may be resolved during future years by application of advanced techniques such as tomography for path-measurement reconstruction and laser, microwave, and/or sonic anemometry for flow measurement, they should be borne in mind as significant issues in the present context.

Electromagnetic radiation remote-sensing applications fall into several categories, the most important of which are summarized as follows:

Absorption Spectroscopy. Open path, absorption-spectroscopy techniques produce path-integrated measurements, and monitor attenuation of a light beam as it transects the sampled atmosphere. As such they require a sensor viewing a remotely located radiation source, or else a source co-located with its sensor, viewing a remote reflector.

Variants of absorption spectroscopy include non-dispersive infrared (NDIR) techniques, which measure the attenuation of a broad-band radiation source by the sampled medium. This

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[1] Light absorption and emission by molecules and atoms occurs as a consequence of energy transitions between quantum states, and thus individual pollutants have characteristic spectroscopic signatures, which can be used for their identification and measurement. Individual “signatures” often dictate which portion of the electromagnetic spectrum is most appropriate for measuring a specific pollutant. Because of its comparatively high photon energy, the ultraviolet/visible portion of the spectrum is associated mainly with transitions between electronic energy levels. Lower-energy infrared radiation is associated with energy transitions between various molecular vibrational and rotational energy states; microwave radiation, which has even lower photon energy, interacts mainly with rotational transitions. These features usually dictate the choice of one technique versus another for observation of a specific pollutant. One should note that besides these molecular-level interactions, radiation can be scattered physically through interactions with atmospheric density fluctuations, airborne particles and precipitation elements.

approach is applicable to pollutants such as CO, whose broad-band absorption spectrum dominates those of other gases in specific spectral regions. Dispersive techniques, in contrast, typically deploy a continuous light source and a detector incorporating a diffraction grating to disperse the incoming radiation according to wavelength, or else a laser light-source which may be tunable over a limited wavelength range. Variants of these methods include Fourier transform infrared (FTIR) methods, which use an interferometric sensing approach to generate a Fourier transform of the spectral signal, and thus can monitor the entire spectral range essentially simultaneously. Because of its spectrally resolved approach FTIR can measure emissions of a large variety of compounds. Yokelson et al. (19976), for example, applied FTIR to measure formaldehyde, ethanol, acetic acid, ethene, propane, propanol, HCN, CO, CO_2, CH_4, and NH_3 emissions from combustion processes. Another technique, differential optical absorption spectroscopy (DOAS), applies a broadband light source, disperses the incoming signal into a resolved spectrum, and applies an interpolation process to estimate the spectral background, which is subtracted from the total spectral signal to obtain the pollutant-induced component. Both FTIR and DOAS can operate in passive mode, using natural light sources such as the sun or moon. Positioning requirements, however, generally dictate the use of active techniques in the case of pollutant-emission analysis.

Tunable diode laser spectroscopy (TDLS) is another absorption spectroscopic technique with a high application potential for emission assessment. As its name implies, this technique employs an (infrared) laser light source, whose frequency output is adjustable over a specific wavelength range. TDLS offers the advantage of very highly resolved spectral resolution but has the disadvantage, compared to FTIR, of limited wavelength ranges attainable by the tunable sources.

Fluorescence Spectroscopy and Raman Spectroscopy. Fluorescence-based methods transmit a light beam through the sampled atmosphere to induce electronic excitation of pollutant molecules, which emit radiation when transitioning back to their ground states. The emitted radiation is monitored by a sensing device, providing a measure of pollutant concentration or pathway loading. Excitation of specific molecules, as well as their resulting fluorescence, is wavelength specific; thus single- or dual-wavelength lasers, selected for the specific pollutant of interest, are applied most often for this purpose. In their simplest form open-path fluorescence-based methods produce path-integrated results, but can incorporate ranging when applied in conjunction with lidar systems (see below). Raman spectroscopy operates in a manner somewhat similar to standard fluorescence spectroscopy. Here, however, the frequency of the incident light beam is shifted to a (usually) lower value (by extraction of a portion of the photon energy through interaction with the sampled medium) prior to excitation of the target molecules.

Light detection and ranging (lidar). Lidar is based on projection of a coherent light beam through the sampled air volume and monitoring the return signal, which results from light scattering by the target pollutant material. In contrast to the methods described above, lidar has a range-gating capability, which allows generation of pollutant-profile information at relatively fine intervals (down to about 3 m). Single-wavelength lidars have been applied since the 1960s to remotely sense PM concentrations, and more elaborate, multi-wavelength lidars (e.g., differential absorption lidar, DIAL) have been applied increasingly to measure spatial distributions of trace gases. A Raman spectroscopy lidar variant also has been applied during recent years.

All of the techniques described above must address issues of sensitivity and specificity, which are highly species- and technique-dependent but of some concern in practically all cases. The associated equipment tends to be expensive and in many cases requires highly experienced operators. Moreover, it is important to recognize the point, noted above, that these detection methods generally depend on ancillary flow measurements or on inferred flows based on stoichiometric ratioing techniques to determine actual emission rates. The following sections, which discuss remote sensing from satellite-, aircraft-, and surface-based platforms, provide some examples of these issues and their resolution.

6.1.1.1 Satellite Remote-Sensing Applications

Measurement and Interpretive Bases

Although satellite applications for determining trace-gas and particulate-matter (PM) emissions must deal with numerous technical challenges, their ability to cover large, typically global, spatial domains provides a major advantage not shared by other approaches. This global coverage encourages the application of European, as well as North American satellite observations for emission evaluations over the NARSTO domain, and thus it is important to discuss efforts by both communities in this overview.[2] The European research community is making considerable progress in this field (Borrell et al., 2004), and indeed data from European satellites are being applied currently for interpretation of North American emissions (e.g., Palmer et al., 2003).

Satellite observations of trace gases and PM in the troposphere to date have been confined largely to passive, downward-looking, spectrally resolved techniques, which observe energy emanating from the planet or the atmosphere and derive concentrations and/or column densities from the amplitudes of spectral lines at specific wavelengths associated with the pollutant molecules of interest. Currently operational (and most planned) measurements are made from low Earth orbit, providing a swath of data during each orbit with individual measurements on spatial scales of tens to hundreds of kilometers.

Many of these observations are based on ultraviolet or visible light reflected or backscattered from the surface or from clouds, and derive vertical-location estimates from the spectral-line widths, which result largely from pressure broadening. These techniques are available only during daylight hours and provide no information at night. Other passive techniques operate in the infrared portion of the spectrum, which is available continuously throughout the day and night. Usually, vertical location is derived from infrared measurements based on variation of radiative properties with atmospheric temperature; thus vertical temperature structure is an important data-processing consideration. Satellite PM observations have been demonstrated using lidar, an active technique which can provide detailed vertical information under most conditions. Lidars produce sparser horizontal data sets than passive systems because greater

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[2] More comprehensive information on North American and European satellite programs is available on the NASA and European Space Agency (ESA) Web sites, www.earth.nasa.gov/ese_missions/satellites.html and envisat.esa.int.

instrument energy is required. Satellite-based lidars have been deployed to date mainly for PM measurements.

Typically the inference of emission rates from satellite measurements occurs in two general steps: 1. "retrieval" of lower-atmosphere pollution concentrations from the raw satellite data and 2. estimation of emissions on the basis of this near-surface information, usually in conjunction with ancillary data and interpretive calculations. Substantial processing is required in the retrieval stage to convert raw satellite data into useful products, such as concentration patterns, column densities, and optical depths, and the "retrieval algorithms" applied for this purpose tend to be complex. Estimation of emission rates from retrieved satellite products also requires substantial processing and interpretive effort. The following subsection gives several examples of different approaches in this general area.

Satellite-based measurement of tropospheric pollutants presents several technical challenges, which include compensating for variations in the air-chemistry matrix, aerosol loading, cloud cover, surface albedo, and temperature, as well as dealing with masking effects of the stratospheric overburden, which can be dominant. Satellite measurements beneath cloud cover are virtually impossible with present technology. Moreover - with the exception of lidar – attempts to resolve measurements vertically typically depend on interpretation of secondary effects such as pressure broadening and temperature influences, thus limiting the resolution of vertical structure. In fact, current trace-gas measurements have not yet resolved even two separate layers in the troposphere. Further, satellite instrument sensitivity is often a strong function of altitude. Thus, each instrument has its own characteristic "averaging kernel" for each species, which defines altitude dependence of its sensitivity. As a result, retrieval of integrated concentration profiles requires a priori information regarding the species' vertical distribution, and leaves a significant uncertainty regarding the derived quantities. These features combine to result in highly species-specific retrieval algorithms, and limit the number of tropospheric pollutants that can be observed reliably; however, this limited set includes important pollutants such as PM, and a number of key secondary-pollutant precursors.

Table 6.1 summarizes existing, planned, and feasible satellite-based tropospheric trace-gas and PM measurements by NASA and the European Space Agency (ESA). Future measurement systems that are feasible with current sensor technology include geostationary trace-gas measurements, which can provide essentially continuous coverage (many observations per day over the same location) at high horizontal resolution. As indicated by Table 6.1, satellites currently in use revisit portions of the globe only periodically, usually at the same time of day, and thus provide less temporal coverage than is usually desired. This issue may be resolved during future years for both North America and Europe by the deployment of sensors on geostationary satellites, providing almost continuous temporal coverage (see Geo-TRACE and Geo-SCIAMACHY in Table 6.1). Finally, satellite observations typically report data in terms of average concentrations, column densities, or derived quantities such as optical depth; thus any inference of emissions from such products necessarily depends on the application of inverse modeling, or some other interpretive technique.

Table 6.1. Selected past, current, and future remote sensing instruments used to determine amount and distribution of constituents in the troposphere.

Instrument	Name	Vertical extent of measurement	Horizontal resolution, domain	Temporal revisit	Target Constituent/ Property for Air Quality	Platform
Current and past instruments						
GOME	Global Ozone Monitoring Experiment	TR and ST	40 x 40 km^2, 40 x 320 km^2 swath	Once every 3 days	Tropospheric columns for O_3, NO_2, BrO, SO_2, HCHO, clouds and aerosols	ESA-ERS-2 (1995-present)
MODIS	Moderate Resolution Imaging Spectroradiometer	Surface to space	0.25 - 1 km , 2330 km wide swath	Once 1-2 days	Aerosol column optical thickness, aerosol type (sulfate, biomass burning) over land	NASA Terra (1999) NASA Aqua (2002)
MISR	Multi-angle Imaging SpectroRadiometer	Surface to space	0.275 -1.1 km, 141 x 563 km^2 swath	Once every 9 days	Aerosol properties (angular radiance dependence)	NASA Terra (1999)
MOPITT	Measurement of Pollution in the Troposphere	TR columns, layers	22 x 22 km^2, 22 x 640 km^2 swath	Once every 3 days	Total column of CO, CH_4 ; CO layers	NASA Terra (1999)
SBUV-2	Solar Backscatter Ultraviolet Ozone Experiment 2	ST profiles	200 x 160 km^2	Daily	Stratospheric O_3	NOAA-9 (1985-1998) NOAA -11 (1989-94, 1998-present) NOAA-14 (1996-present) NOAA-16 (2000-present)
SCIAMACHY	SCanning Imaging Absorption spectrometer for Atmospheric ChartograpHY	TR columns	30 x 30 km 960 km swath	Once every 3 days	Tropospheric columns for O_3, NO_2, N_2O, CO, CH_4, SO_2, HCHO, clouds and aerosols	ESA Envisat (2002)
OMI	Ozone Monitoring Instrument	ST profiles, TR columns	48 x 48 km^2	Once per day	Tropospheric columns for O_3, $S0_2$, HCHO, $N0_2$, and aerosol	EOS Aura (2004)
TES	Total Emission Spectrometer	ST profiles, TR layers	26 x 42 km^2	~ once every 2 days	Tropospheric columns for 0_3, NO_y, CO, SO_2, CH_4	EOS-Aura (2004)
Future instruments scheduled to be launched						
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	ST profiles, TR profiles	0.3 x 0.3 km^2	Not operated continuously	Aerosol density and radiative properties	NASA CALIPSO (2005)

Table 6.1. Concluded.

Anticipated Future Instruments						
GeoTRACE	GEostationary Observatory for TRopospheric Air ChEmistry	TR layers	4 x 4 km^2, 8000 x 4000 km^2 (entire North American continent)	Once per hour	Tropospheric columns for O_3, NO_2, SO_2, HCHO, CH_4, , clouds and aerosols: tropospheric columns and layers for CO	Potential future NASA Earth probe
Geo-SCIAMACHY	Geostationary SCanning Imaging Absorption spectrometer for Atmospheric ChartograpHY	TR layers	25 x 25 km^2, entire Earth disk, European view	Twice per hour	Tropospheric columns for O_3, NO_2, H_2O, SO_2, HCHO, CH_4, CO, clouds and aerosols	Potential future ESA mission

Example Applications

The objective of this section is to provide the reader with an initial appreciation of satellite products available as a result of retrieval processing, and to demonstrate these products' potential applicability for emission assessment. Figure 6.1 provides a simple example for an initial approach to this objective. Here observation swaths from ESA's SCanning Imaging Absorption spectrometer for Atmospheric ChartograpHY (SCIAMACHY) (Richter, 2003), show tropospheric NO_2 column densities observed in the vicinities of some Middle Eastern cities. Because of these cities' isolation from confounding sources, this image immediately suggests that local NO_x emission rates could be inferred from these data in conjunction with observed winds and chemical-transport model analysis, using a relatively straightforward approach.

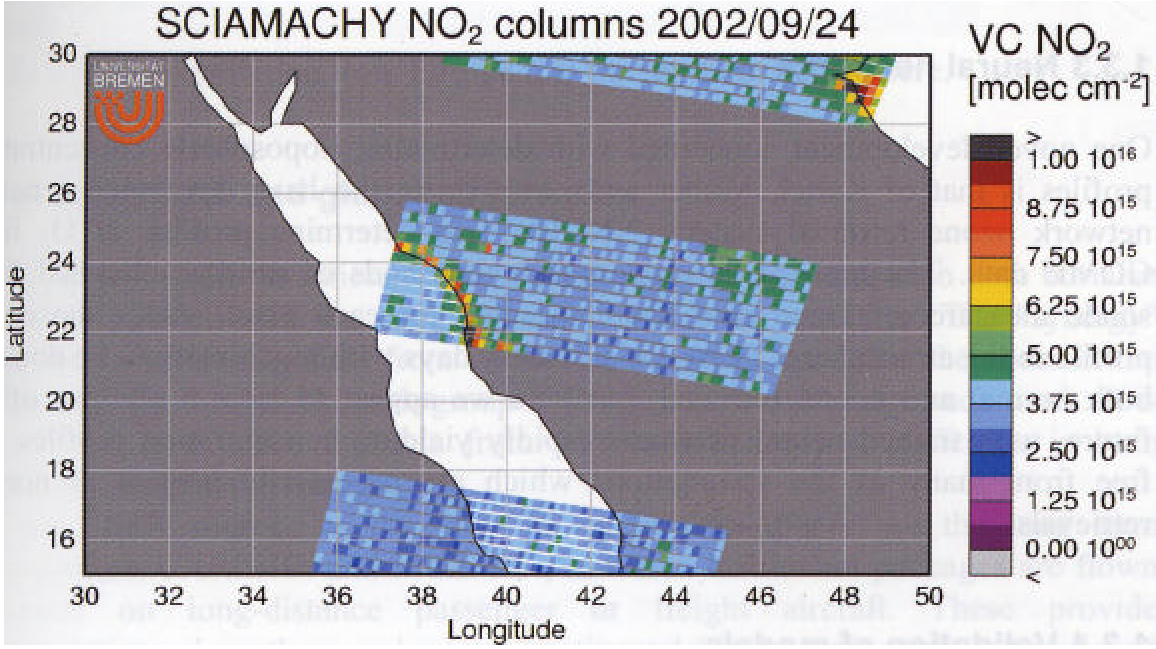

Figure 6.1. Tropospheric NO_2 column densities in the Red Sea/Arabian Gulf area derived from SCIAMACHYdata for September 2002 (Richter 2003). Emissions from isolated, individual cities such as Jeddah, Mecca, Medina, and Kuwait City are easily identified.

Figure 6.2, which shows tropospheric column densities of selected pollutants obtained from a variety of North American satellite sensors (Neil, Fishman, and Szykman, 2003), provides a more complicated (but also more typical) example. These plots indicate the potential complexity of inferring emission rates from continental data, which reflect long-range transport and multitudes of individual sources. The following paragraphs present some examples of studies where inroads are being made in this area.

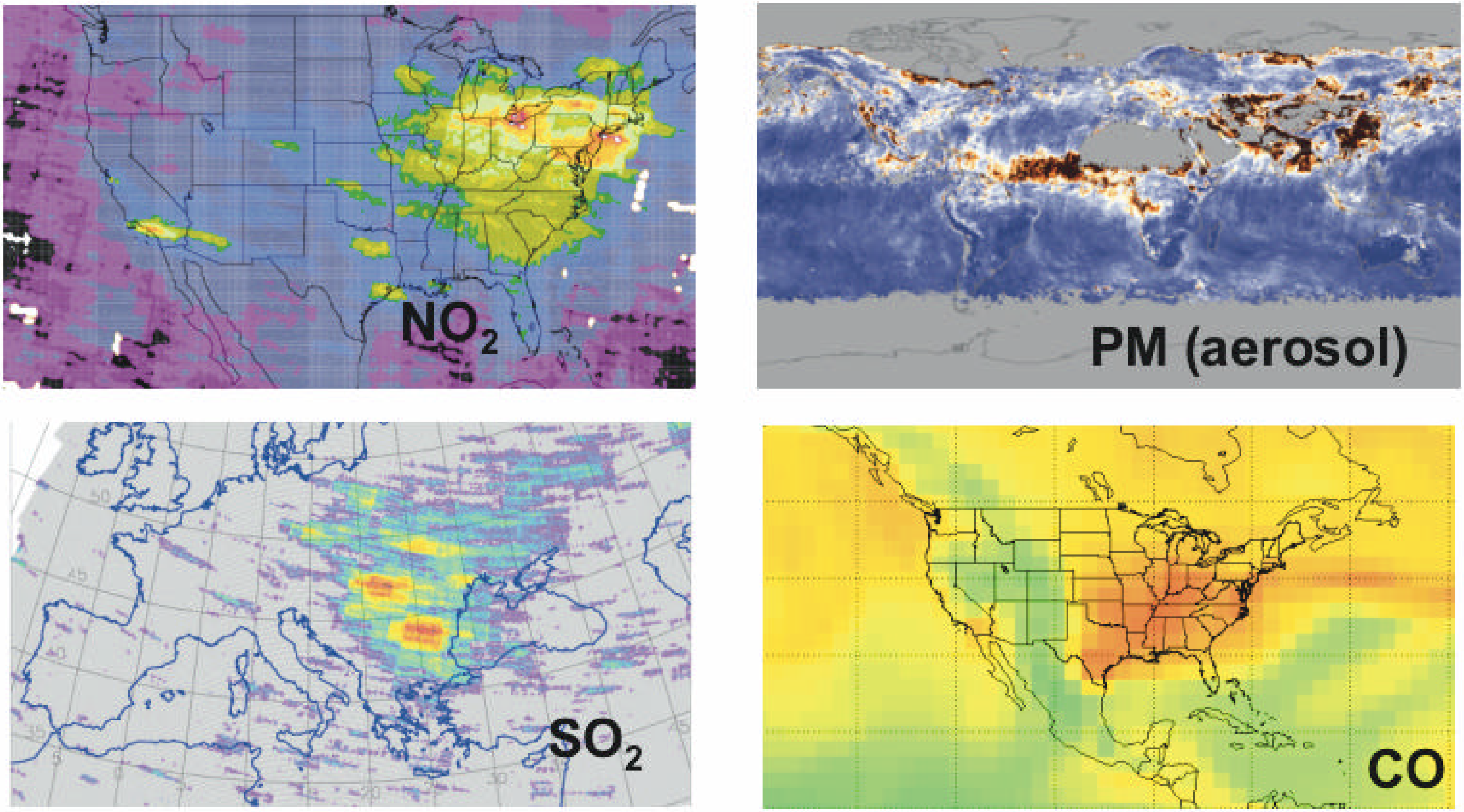

Figure 6.2. Typical satellite-derived tropospheric column densities of selected pollutants. Raw data obtained from a variety of satellite sensors (Neil, Fishman and Szykman 2003).

Given the measurement challenges noted above, emission assessments using satellite-derived products are currently at a relatively nascent, but evolving, state. Interpretive work to date has consisted largely of studies wherein satellite-based column densities of a pollutant or its reaction product are observed, and compared with model-derived column densities based on an assumed emission inventory. Subsequently the model is executed repeatedly, adjusting the emission inventory until a match between the model- and satellite-derived values is achieved. For cases involving multiple sources this can be viewed as a rather broad-brush approach, providing gross estimates of overall emission magnitudes; nevertheless much of this work has been highly innovative and has produced useful and enlightening results in a number of cases where large spatial scale data are of interest.

Examples of this approach include the work of Petron et al. (2004), who applied Measurement of Pollution in the Troposphere (MOPITT) CO data in conjunction with the NCAR Model for OZone And Related chemical Tracers (MOZART) to infer CO emissions from Western US wildfires occurring during August, 2000. Similarly, Palmer, et al. (2003) applied formaldehyde column data derived from Global Ozone Monitoring Experiment (GOME) measurements to infer North American emissions of the biogenic formaldehyde precursor, isoprene, using the GEOS CHEM chemical-transport model as an interpretive tool. As can be noted in Figure 6.3. comparison of the of GOME data with GEOS CHEM simulations based on two existing isoprene emission inventories indicated significant biases in these inventories.

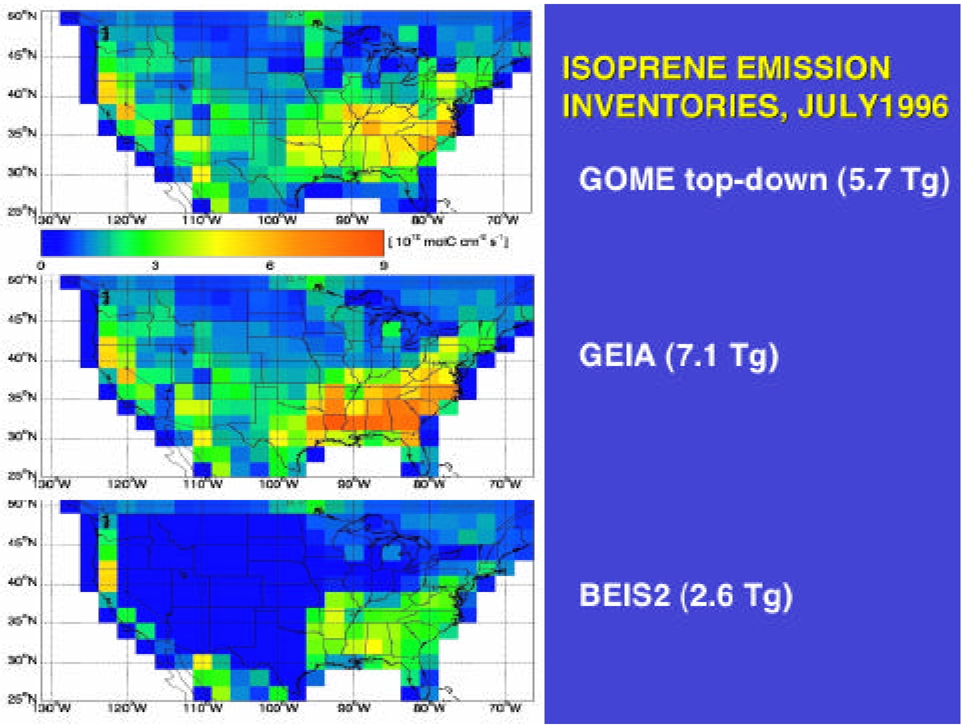

Figure 6.3. Comparison of North American isoprene emissions derived from GOME formaldehyde data for July 1996, with those predicted by the GEIA and BEIS2 inventories. From Palmer et al. (2003).

A third example of this approach is the work of Martin et al. (2003), who applied GOME-derived NO$_2$ column data to reduce errors in the global NO$_x$ emission inventory. In some respects model applications of this type can be considered as zero-order inverse-modeling applications. More formal inverse-modeling approaches described in Section 6.3.2 involve a substantially more detailed mathematical treatment, but offer the possibility of increased resolution of individual pollution sources. To date this more formal approach has been limited to a few special applications, such as global CO_2 emissions (e.g., Kasibhatla et al., 2003), but can expect extended application in the future.

In conclusion to this overview of satellite applications for emission assessment it may be noted that these methodologies are currently in an evolutionary state, and future developments should be expected in at least three general areas. The first of these involves the realization of more highly specific measurements with regard to chemical species, vertical and horizontal resolution, and temporal coverage, which will be provided by platforms and sensors currently planned or envisioned. Progressively higher-quality satellite-based measurements of O_3, NO_2, SO_2, HCHO, CO and PM will be available over the next five years from the recently deployed ESA SCIAMACHY and NASA's EOS Aura (http://eos-chem.gsfc.nasa.gov/project). Moreover the geostationary platforms noted in Table 6.1, if deployed, will substantially improve spatial/temporal coverage of the North American and European continents.

The second of these general areas has a somewhat longer time horizon, and depends strongly on the ability of scientists working in the emission inventory field to envision new satellite-derived products desired for their specific purposes, and to communicate these ideas to their counterpart scientists in the satellite community.

Finally, and as demonstrated by the example applications described above, considerable development can be expected in inverse-modeling applications and other innovative interpretive techniques, often using satellite measurements in conjunction with surface-based measurements. With developments in these three specific areas, satellite applications can be expected to attain significantly greater source-resolving power, and have a major future impact on large spatial scale emission inventory development.

6.1.1.2 Aircraft Remote-Sensing Applications

Both surface- and aircraft-based remote-sensing applications to evaluate pollutant emissions have relied almost totally on open-path optical techniques, and share considerable commonality with sensors currently deployed on satellite platforms. In contrast to most satellite-based approaches, a majority of surface and aircraft-based sensors deployed for emission assessment observe radiation emitted by the measurement device, and thus are classified in the "active" category.

Aircraft remote sensing provides a useful complement to in-situ emission measurements from aircraft, which are described in Section 6.1.4. As with their in-situ counterparts, aircraft remote sensing is usually applied for determining pollutant fluxes through vertical planes encompassing the plumes being observed.[3] Typically, such measurements are made by differential optical absorption spectroscopy (DOAS) (Melamed et al., 2002 and references therein), infrared spectroscopy (Stearns et al., 1986) and, potentially, by lidar techniques.

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[3] See Section 6.1.4 Aircraft Plume Measurements for a more detailed discussion.

Remote sensing has several advantages in aircraft applications. Most importantly, these methods provide a measure of the vertical column of the concentration through the plume, thereby directly evaluating an integral of pollutant concentration over the vertical dimension. The evaluation of integrated plume concentration is then reduced to integrating the column measurement across the plume. The plume flux can be determined knowing the average wind speed (See equation 6.1 in Section 6.1.4 below). A second advantage is that the column measurement is insensitive to variations in the height of the planetary boundary layer (PBL) and vertical inhomogeneities of concentrations. Finally, the required cross-sectional measurement is accomplished in a single aircraft transect that can be carried out above the PBL. It is thus more suitable for determining plume-wide fluxes from extended sources, such as urban areas. One disadvantage of the technique is that the species that can be measured are presently limited; plume fluxes have been reported only for DOAS measurements of NO_2 (which allows the calculation of the corresponding NO_x fluxes) and for SO_2. The reported precisions for these measurements are near ±30%. In intense biomass burning emission plumes, molar ratios of a variety of species have been determined (Worden et al., 1997).

Current aircraft deployed, remote-sensing instrumentation is limited to DOAS determinations of NO_x and SO_2 fluxes and infrared spectroscopy determinations of emission factors for species released in biomass burning. DOAS techniques could potentially be extended to some VOC species including formaldehyde, alkenes and aromatics. There is also potential for lidar instrumentation to be applied to ozone and PM. It is possible to remotely measure wind speeds using Doppler lidar techniques; application of this instrumentation would be a useful advance. The limiting factor in these possible projections will be the ultimate signal-to-noise ratios that can be achieved.

6.1.1.3 Surface-Based Remote-Sensing Applications

Stationary Sources

For discussion purposes it is convenient to subdivide surface-based remote sensing of emissions into two categories, depending on whether the source in question is mobile or stationary. Remote-sensing evaluations of stationary-source emissions have applied several of the optical methods summarized in the introduction to this section. Often used more for pollutant-concentration studies not directly related to emission-inventory evaluation, these techniques are currently at a less developed state for emission analysis than their mobile-source counterparts. North American application, for large point sources at least, has been inhibited by the heavy reliance on standard reference methods and continuous emission monitoring systems, which often provide a much more straightforward and direct approach to emission measurement. On the other hand, remote sensing is often highly attractive in situations (such, for example, as petroleum refineries) involving complex source configurations and/or fugitive emissions. The availability of commercial, off-the-shelf equipment for this purpose is limited, although a few organizations – particularly in Europe – offer services applying remote sensing for emissions from sources such as refineries and feedlots (e.g., www.spectrasyne.ltd.uk/; www.kassay.com/kfshome.htm; www.erg.com/services/environ_meas_source.htm).

Numerous examples of successful application of remote-sensing technology for stationary-source emission assessment can be cited. Apart from the previously cited application of FTIR by Yokelson et al. (1996) to determine combustion-process emissions, examples include the work of Schröter et al. (2003) who applied lidar measurements of a power-plant plume to remotely sense SO_2 concentrations, and processed the results with co-located sound detection and ranging (sodar) flow measurements to estimate SO_2 emissions. Schäffer et al. (2004) applied simultaneous upwind and downwind DOAS measurements to measure emissions from automobile service stations and from tanker filling operations, using a small-scale dispersion model to back-calculate emissions. Galle et al. (2001) applied active FTIR to monitor methane emissions from landfills and NH_3 emissions from agricultural manuring applications. They also applied passive FTIR (using the sun as a radiation source) to determine emissions from petroleum-processing complexes and harbor operations. Haus et al. (1998) applied FTIR analysis of radiation by CH_4, CO_2, CO, NO, and water to determine emission rates by natural-gas flares.

A survey of this subject indicates that remote-sensing technology has large future potential for evaluation of emissions from complex sources, such as refineries or chemical plants, which are not amenable to standard single stack treatment. Reflecting this future potential, the US EPA is currently supporting research and demonstration programs applying remote sensing to a variety of fugitive emission sources (www.epa.gov/ORD/NRMRL/scienceforum/thoma_e.htm), and a number of innovative techniques – such as the application of tomography to FTIR path measurements to determining spatial distributions (Hashmonay and Yost, 1999; Hashmonay et al., 1999) – are currently in a developing stage. Although it has received little application to date, remote-sensing of velocity fields in conjunction with pollutant measurements has a large potential for emission quantification, and can be expected to be expanded considerably during future years.

Mobile Sources

As noted in the previous subsection, mobile-source remote sensing has received significantly more application for emission analysis than its stationary-source counterpart, and several commercial applications are currently in operation. The most important of these is cross-road optical sensing, which performs a series of light-absorption measurements intercepting exhaust plumes behind moving vehicles. The initial implementation of this technology involved NDIR measurements, initially for CO and CO_2, with CO_2 serving as the internal plume tracer. Stoichiometric ratios of excess (above background) plume CO/excess plume CO_2 can be used to compute the fraction of CO in the exhaust at the vehicle's tailpipe (Bishop et al., 1989; Stedman, 1989). The measured excess target pollutant/excess CO_2 ratio also can be used along with a combustion equation to provide a target pollutant emission index (g pollutant emitted/kg fuel consumed). This system was soon extended to measure hydrocarbon (HC) and NO_x emissions using NDIR absorption, and later, with greater selectivity and sensitivity, using ultraviolet spectroscopy (Guenther et al., 1995; Bishop and Stedman, 1996; Popp et al., 1999). Similar NDIR cross road instruments were also successfully developed by General Motors Research Laboratories to monitor CO and HC exhaust emissions (Stephens and Cadle, 1991; Cadle and Stephens, 1994). Commercial Instruments based on this technology and exploiting advances in software and computer hardware for improved instrument control and signal processing are currently produced by Environmental Systems Products, Inc. (ESP, 2003a).

Advanced cross-road remote sensing systems based on tunable infrared laser differential absorption spectroscopy (TILDAS) have been developed and deployed by Zahniser and co-workers (Nelson et al., 1998; Jiménez et al., 1999; Jiménez et al., 2000 a,b). These systems have the advantage of longer measurement path lengths, more easily manipulated light paths, and greater sensitivity for a range of individual exhaust species, allowing more pollutants to be quantified more specifically. TILDAS measurements of exhaust NO, NO_2, N_2O, and NH_3 have been reported and calculations show measurements of other species such as CO, H_2CO, CH_3OH, C_2H_4 and $CH_2=CH-CH=CH_2$ are feasible.

Dispersive infrared spectroscopy also can be used to quantify exhaust emissions from moving vehicles, although cross-road path lengths and vehicle speeds may be restricted, especially compared to the TILDAS systems. Baum et al. (2000) have demonstrated a prototype on-road vehicle emission-measurement system combining infrared and ultraviolet spectrometers. This system can quantify exhaust CO, NO, NO_2, N_2O, HONO, NH_3 and as well as some light aldehydes, aromatics, and aliphatic hydrocarbons, and has been used to measure NH_3 emission distributions on a Los Angeles freeway on-ramp (Baum et al., 2001). Finally, instruments to measure exhaust PM are currently being developed and demonstrated (Moosmüller et al., 2003; ESP, 2003b). ESP's latest commercial remote-sensing technology includes a UV spectral measurement to generate a smoke index (g particles emitted/kg fuel consumed).

Cross-road remote-sensing studies have been extremely valuable in characterizing on-road emissions for light duty gasoline powered vehicles. A critical finding from these fleet-emission measurements indicates that a small fraction of the vehicles emit a large fraction of a given pollutant; typically 10% of the vehicles measured account for 50% or more of a given pollutant detected. This highly skewed distribution was recognized by Zhang et al. (1994) for CO and HC emissions, and is also reported for CO and HC by Stephens (1994). The same distribution also been shown to characterize NO (Jiménez et al., 1999) and N_2O emissions (Jiménez et al., 2000a). This fact has a large impact on the sample size of light-duty vehicles whose emissions must be evaluated to determine statistically valid inputs for mobile emission models.

Relatively long time-series of remotely sensed emissions for light-duty vehicles are now available for a number of North American and European cities, allowing a determination of how well new cars meet regulatory standards and assessments of emissions change with vehicle age (Pokharel et al., 2003; Sjödin and Andréasson, 2000). Comparable data are available from enough cities around the world that the impacts of variations in maintenance practices can be recognized (Zhang et al., 1995). Data on vehicle emissions from several Mexican cities have been compared and contrasted with similar data from U.S. cities (Bishop et al., 1997). Studies like these are important to inform mobile-source emission models about expected temporal and geographic variations of mobile-source emissions from evolving light-duty vehicle fleets. However, ongoing studies will need to be maintained to keep such projections valid as new vehicle technology is introduced and older vehicles age.

It also should be noted that while the great bulk of remote-sensing data available is for light-duty vehicles, emissions from heavy-duty diesel (HDD) vehicles have been characterized, even though many North American HDDs have elevated exhaust emissions that are not well sensed by normal low level cross-road optical technology. Both traditional non-dispersive systems (Bishop et al., 2001a) and TILDAS systems (Jiménez et al., 2001b) have been deployed to reliably characterize on-road HDD trucks. It is interesting to note that these vehicles have emission distributions that are much closer to normal than the γ-distributions found for light-duty emission distributions. The same technology also has been used to characterize significant off-road mobile sources, such as snowmobiles (Bishop et al., 2001b). Measurements on a wide variety of off-road vehicles are underway and will help inform off-road mobile emission models.

It is possible to construct light-duty vehicle emission inventories directly from cross-road remote sensing data. Singer and Harley (2000) have used remote-sensing data to construct a fuel-based inventory for mobile emissions in Los Angeles, CA and Stedman and co-workers have recently published one such inventory for the Denver, CO metropolitan area (Pokarel et al., 2002). If more continuous and comprehensive remote-sensing data sets become available, the derivation of mobile emission inventories directly from these data may become widespread. However, because remote sensing measurements typically sample each vehicle for less than a second, thus sampling a very small segment of each vehicle's operating range, Wenzel et al. (2000) caution that it is necessary to sample a very large number of vehicles to estimate valid mobile-source emission inventories.

Remote-sensing measurement data have demonstrated utility for evaluating the effectiveness of air-quality control programs. One of the earliest uses of remote-sensing data was to assess the impact of using oxygenated fuels to reduce mobile CO emissions (Bishop and Stedman, 1990). Systematic analyses of multi-year data sets have been used also to evaluate the effectiveness of Inspection/Maintenance (I/M) programs (Stedman et al., 1997). A recent extensive roadside pullover study that stopped vehicles which remote sensing instruments had identified as high emitters and subjected them to conventional tailpipe emission inspections has confirmed that remote sensing does generally correctly recognize vehicles with excessive emissions (BAR, 2001). A recent report by the National Research Council concluded that remote-sensing measurements are an excellent source of on-road CO and HC emission data, that they can also be a useful screening tool to identify vehicles likely to pass or fail conventional I/M program tests, and that remote sensing is underutilized in current I&M programs (NRC, 2001). Since the impacts of control strategies must be factored into mobile-source emission inventories, remote sensing data can play a key role in updating current EIs and projecting future emissions.

From a mobile source standpoint, remote-sensing technology is now sufficiently developed that routine operational deployment as part of state or provincial Inspection/Maintenance (I/M) programs is feasible. The potential adoption of operational "clean screen" and/or "gross emitter" on-road Inspection/Maintenance programs may provide nearly continuous and real-time remote-sensing data sets, which can be incorporated to keep mobile emission inventories much more current and provide better spatial resolution. Several large studies of commercial cross-road remote-sensing technology of ongoing I/M and other clean-air initiatives have been concluded recently (McClintock, 2002; ESP, 2003a; McClintock, 2004), opening up the prospect of more widely distributed and more continuous data sets gathered on a daily basis. For instance, a recent program sponsored by the State of Missouri to test a clean-screen component for the I/M program for the St. Louis metropolitan area operated 20 to 26 days per month, collecting 300,000-500,000 vehicle-emission records per month for a total of nearly 5 million over the course of a year (McClintock, 2002). Future extensions of mobile remote-sensing applications include applications to trucks and buses, motorcycles, and off-road vehicles.

Traditionally focused on VOCs, NO_x, and CO, future mobile-source sensing technology can be expected to address additional chemical species during future years. There is an increasing concern about mobile sources of airborne toxic species, with particular emphasis on possible carcinogens including formaldehyde, acetaldehyde, benzene, acrolein, and 1,3 butadiene, as well as the organic portion of exhaust fine PM. Advanced remote sensing systems employing dispersive spectrometers (Baum et al., 2000) or tunable lasers (Nelson et al., 1998) have the capability to quantify some exhaust air toxics directly and may well be able to quantify related indicator compounds for others. Advanced remote sensing systems also have the capability to quantify mobile emissions of greenhouse gases beyond CO_2, including N_2O and CH_4 (Baum et al., 2000; Jiménez et al., 2000a). Both types of advanced systems have also demonstrated the ability to quantify the production of NH_3, an important PM precursor, on overactive NO reduction catalysts (Baum et al., 2000; McManus et al., 2002).

6.1.2 Additional Methods for Mobile-Source Characterization

Mobile source emission categories represent one of the more vexing aspects of emission-rate estimation. Typical mobile-source emission models are idealized, in the sense that they assume standard driving cycles and fleets having uniform characteristics (e.g., Sawyer et al., 2000), and thus give rise to serious concerns regarding their "real-world" applicability. These models have received ad hoc adjustments for urban/rural situations as well as for Mexican and Canadian driving conditions, but remain relatively coarsely evaluated. In recent years, testing under real-world driving conditions has increased, using different creative approaches, which attempt to avoid limitations embedded in the existing emission models. One such approach – remote sensing – was discussed in Section 6.1.1. Several additional approaches are summarized in the following subsections.

6.1.2.1 Roadway Tunnel Studies

One means of testing motor vehicle emission models has employed measurements of various pollutants in a roadway tunnel instrumented for pollutants and for traffic number and type. The first of this kind of experiment was reported in the 1970s (e.g., Pierson et al., 1983). More recently a number of these studies have been reported in Los Angeles, Baltimore and Vancouver (e.g., Gertler et al., 1997; Pierson et al., 1995; Sawyer et al., 2000; Graham et al., 2003). The methods adopted for tunnel studies, include the gas and particle sampling from tunnel entrance and exhaust air using conventional instruments, documentation of driving conditions during sampling, documentation of the types of vehicles passing through the tunnel, and estimation of emission-rate distributions expected from the fleet observed in terms of speed (or speed variation) and distance traveled through the tunnel.

Tunnel studies have been useful in providing data with which to check the reliability of models such as MOBILE and EMFAC for calculating traffic aggregate emissions of CO, VOC, NO_x and

PM under near on-road conditions. These studies, raised serious questions regarding the performance of emission models as early as the 1980s. While the tunnel studies have limitations in themselves, they nevertheless proved to be valuable in identifying ambiguities in model calculations, and resulted in improved model estimates of gaseous emissions.

The tunnel studies have been criticized for not being representative of open-air on-road driving conditions, for having ambiguities in vehicle operating conditions, and for having only limited representation of traffic mixes. The method also gives ambiguous results for evaporative emissions under tunnel conditions. Critics also have questioned whether or not the pollutant mixtures are characteristic of open-air conditions, given the constrained air circulation present in tunnels.

Despite these limitations, the tunnel studies have been instrumental in providing cross-checks for mobile emission models (e.g. Sawyer et al., 2000). Taken in conjunction with roadside remote-sensing, chase-vehicle observations, and on-board sensing, considerable improvement can be made in data evaluating the model performance for vehicle exhaust under a range of conditions.

6.1.2.2 Mobile Laboratories and Chase Vehicles

The development of robust, fast-response sensors for many gaseous pollutants, as well as PM physical and/or chemical properties, has allowed the deployment of useful instrument suites in a variety of on-road vehicles. This combination enables truly “mobile laboratories” capable of real-time measurements while in motion. In general, modern mobile laboratories can be used to characterize on-road, mobile source emissions in two distinct ways, termed vehicle-fleet and chase-measurement modes.

In the fleet mode, mobile laboratories characterize on-road pollutant emissions in two ways. The most accurate and informative method is by intercepting individual on-road vehicle exhaust plumes and correlating target pollutant enhancements with above background CO_2 levels. Less quantitatively, elevated on-road pollutant concentrations can be measured and correlated with traffic volume or average elevated on-road CO_2, or CO as an emission marker without resolving individual vehicle plumes. These “fleet” methods can be thought of as tunnel studies without the tunnel. Like tunnel studies, they yield fleet-averaged emission indices for individual pollutants. The individual plume-intercept method has the advantage of also yielding a full distribution of emission indices for the target pollutants, since an individual emission index is obtained for each exhaust plume intercept. Since plume excess CO_2 readily can be related to the fuel consumption rate through the combustion equation, measurements of emission ratios (plume excess pollutant/plume excess CO_2) can be directly converted to emission indices (g pollutant emitted/kg fuel consumed).

In the chase mode, mobile laboratories are designed to repeatedly sample the exhaust plumes of specific target vehicles. This mode can be used to characterize the emissions of either cooperative or non-cooperating “wild” vehicles over a range of operating parameters. The major requirements are that the chase laboratory be able to shadow the target vehicle and that it contain fast response (~1s) sensors, typically measuring CO_2 and the target pollution of interest. Data from fast-response sensors for the target pollutants are correlated with the CO_2 data to yield emission ratios and derive emission indices for the target vehicle as a function of its operating condition. The target vehicle's speed and acceleration can be obtained from on-board sensors (for cooperative vehicles) or from the speed and acceleration values of the chase vehicle, plus range finder measurements providing the instantaneous distance between the chase and target vehicles. Chase-vehicle measurements are similar to on-road dynamometer measurements, but may typically sample a wider range of operating conditions

Fleet emission ratios for nitrous oxide emissions from U.S. vehicles have been reported by Jiménez et al. (2000) and formaldehyde emission ratios for vehicles in Mexico City and Boston by Kolb et al. (2004). Jiménez et al. (2000) demonstrated that the distribution of U.S. fleet N_2O emission ratios measured using on-road via mobile laboratory plume sampling was very similar to that obtained by cross-road remote sensing, using tunable infrared laser differential spectroscopy sensors in both cases. A variety of mobile laboratories have been developed recently and deployed to characterize on-road pollutant levels and mobile emissions in Europe and North America (Seakins et al., 2002; Bukowieki et al., 2002; Kittelson et al., 2004; Weijers et al., 2004; Gouriou et al., 2004; Kolb et al., 2004), although only the latter group has published fleet-emission ratios and indices based on ensembles of individual exhaust-plume emission ratios (Jiménez et al., 2000; Kolb et al., 2004). A number of groups have focused on characterizing on-road exhaust emissions of fine particles, with some placing particular emphasis on ultrafine or "nanoparticle" concentrations and properties (Kittelson et al., 2004, Gouriou et al., 2004; Weijers et al., 2004).

Kittelson et al. (2000) have deployed a cargo container-mounted "mobile emission laboratory" that has been mounted on a truck chase vehicle to characterize on-road diesel emissions from cooperative heavy-duty diesels. Vogt et al. (2003) have instrumented a chase van to characterize emissions from cooperative light-duty diesel vehicles on a test track. Kolb and co-workers have utilized a large van-based mobile laboratory to quantify a range of gaseous and PM emissions from a range of heavy-duty diesel and heavy- to light-duty gasoline vehicles in Mexico City and several U.S. cities (Shorter et al., 2001; Cangaratna et al., 2004; Kolb et al., 2004). Initial analyses of these measurements indicate that the data are comparable to cross-road remote-sensing data, giving the advantages that individual vehicles can be sampled for a larger range of operating conditions and a much wider range of gaseous exhaust species and fine particle properties can be specified. For instance, the mobile laboratory described in Kolb et al. (2004) is equipped to quantify exhaust emissions of gaseous CO, NO, NO_2, HONO, NH_3, H_2CO, CH_3CHO, CH_3OH, benzene, toluene, C_2-substututed benzenes, and SO_2, as well as a range of PM properties, including number density, size distribution, and mass loadings of sulfate, nitrate, ammonium, organic carbon species, and PAHs.

6.1.2.3 Portable Emission Measurement Systems (PEMS)

As their name implies, portable emission measurement systems (PEMS) consist of analytical equipment that is sufficiently compact and field-operable to allow deployment on vehicles under actual operating conditions. This is particularly important for some mobile sources – such as construction and farm equipment – which are difficult and expensive to subject to standardized testing. PEMS provides a way of testing such equipment without having to either remove the machine from service or modify it in any way.

Portable emission measurement systems have been under development for about a decade. EPA, for example, recently patented the Real-Time On-Road Vehicle Exhaust Gas Modular Flowmeter and Emissions Reporting System, better known as ROVER (U.S. EPA, 2003). As the first generation of PEMS devices, ROVER established a method for measuring mass flow from engines.

EPA workers have continued PEMS development and introduced the Simple Portable Onboard Test (SPOT) in 2001. SPOT was designed specifically for non-road applications. Building on the ROVER system, the SPOT system consists of a rugged, compact package and provides further advances in mass-flow measurement and activity data capture. The technology has been licensed to equipment manufacturers and a competitive market has emerged to design and manufacture PEMS that meet stakeholder needs.

Current PEMS-related goals are to encourage and support private industry in equipment development and refinement. EPA is also working on developing and demonstrating PM mass measurement. Prototype equipment is under evaluation in EPA and contractor laboratories to establish correlation between reference methods and prototypes. Development and field adoption of this capability is ongoing, and similar work will pursued for measuring toxics in the future.

Currently PEMS are being deployed in a number of ways such, for example, as checking compliance of in-use heavy-duty vehicles. EPA is also undertaking an extensive program in Kansas City in 2004/2000 (Baldauf et al., 2004) to evaluate PM emissions from light-duty vehicles. About 500 cars will be tested on a portable dynamometer and most of those will also be equipped with PEMS and returned to their owner for real world emission measurement. This will constitute the first large database of real-world, in-use emission measurements ever assembled. In addition, EPA plans to launch a test program involving 150 non-road engines. Plans are also in progress to test heavy-duty trucks.

PEMS enable the testing of motor vehicles in any location, and the cost of testing per vehicle is believed to be a fraction of that of laboratory testing – by an order of magnitude or two in the case of non-road engines and heavy-duty trucks. These two advantages will allow testing of statistically significant national samples of vehicles. PEMS are sufficiently inexpensive that state governments can afford to acquire and deploy them to generate local emission and activity data for use in refined local- and mesoscale modeling. This will improve the quality of data input for emission models and inventory projections in the future.

6.1.2.4 Onboard Sensors

A complement to other mobile-source measurements has been developed using the monitoring of onboard engine diagnostic (OBD) sensors in contemporary vehicles, such as exhaust-gas oxygen and temperature sensors, and engine-load and fuel-consumption monitors. By using an engine performance model in conjunction with a wireless device to communicate, these sensors can provide an essentially real-time, indirect estimate of CO, NOx and VOC emissions from equipped vehicles. Tests in California on a fleet of 1000 taxicabs, for example, have provided useful data on a large number of vehicles for comparison with the federal OBD II I/M emissions test (e.g., Banet, 2003). Using these data, non-performing vehicles can be identified, and returned for maintenance to correct failing emission-control equipment. The data have not been used extensively as yet for comparison with other on-road measurements. Further investigation of their application to emission estimation should yield at least qualitative performance data to check limited sampling data acquired from PEMS and roadside monitoring.

Further into the future, new micro-sensors are under development that can withstand the conditions present in high temperature, hostile post combustion environments (e.g., http://www.es.anl.gov/html/sensor.html). At the Argonne National Laboratory, for example, prototype "smart" voltammetric/electrocatalytic microsensors combining cermet materials, voltammetry and neural network signal processing. Tests have been conducted on these prototypes for CO2 detection, but the sensors also can be "trained' to detect other chemicals, including VOCs. With these sensors, one can foresee opportunities for on-board emission sensing by vehicle far in advance of current practices. Such sensors also would have important applications as CEMs in a range of industrial applications.

6.1.2.5 Sampling and Dilution Tunnels for Reactive Emissions

Although applicable for evaluation of both stationary and mobile sources, sampling and dilution tunnels are of particular interest in the context of transient emissions from diesel-powered roadway vehicles, and thus are discussed here. Determining emission rates from sources whose pollutants transform quickly once emitted to the atmosphere has received increasing attention during recent years, primarily as a consequence of heightened importance placed on ultrafine particles and associated health impacts, as well as the evolution of specific combustion-technology categories (e.g., advanced diesel engines), which emit large numbers of particles in this size range. Characterizing fine-particle emissions from combustion systems is difficult because of the high temperatures and moisture content of exhaust gases, as well as the strong coagulative tendency of ultrafine particles. Upon exiting the stack the combustion products cool rapidly and dilute with ambient air, during which time physicochemical reaction processes such as coagulation, condensation, and nucleation change PM size-distribution and composition. Measurement of PM in hot exhaust is further complicated by the presence of semivolatile material, which may either undergo homogeneous nucleation or condense on existing particles, thus changing chemical composition and size distribution. Because particle count is dominated by the small particles, particle-number distributions are especially sensitive to sampling and dilution conditions. Measured particle-number concentrations can be changed many orders of magnitude by varying sampling conditions.

The most obvious approach to this issue is to utilize fast-response instruments to continuously measure flow rates and the concentrations of species of interest. Frequently, this is not possible because of sample temperature, relative humidity, and the lack of suitable instrumentation. Dilution sampling (Lipsky et al., 2002) represents an alternative technique for this purpose. Depending on their design, dilution samplers either quench the physicochemical reactions by rapid dilution and cooling, or else they provide for quantitative examination of these processes by mixing with specified amounts of conditioned air.

Some sampling systems have added residence chambers to increase the time between exhaust dilution and sampling the diluted exhaust. This is done to allow additional time for equilibration between the semi-volatiles and the PM as well as time for coagulation of some of the fine PM.

Additional dilution of the sample immediately before the residence chamber can be done to better simulate atmospheric conditions. While dilution tunnels are designed to minimize particle losses, surface interactions between the gases and particles remain problematic. Care has to be taken in the sampling system to determine losses of trace reactive gases. Semivolatile materials tend to slowly adsorb and desorb from tunnel walls, resulting in a variable background contribution from the tunnel itself. Hence, care must be taken in conditioning the tunnel if it is used on sources of greatly varying magnitude.

Fast-response sensors, fast-response mass flow controllers, and improved electronics are likely to result in more accurate and reliable dilution samplers in the near term. The impact of semivolatile material on PM measurement, however, will not be solved by improved sampling methods. Standardization of measurement procedures should greatly increase precision of the measurement, but will not resolve the problem of applicability to different atmospheric conditions (i.e., ambient temperature, humidity, dilution, and background PM). Relating sources of rapidly reactive emissions to ambient concentrations will require improved modeling of atmospheric processes and more comprehensive source measurements of the appropriate parameters as input to models.

6.1.3 Continuous Emission Monitoring Systems

Continuous emission monitoring systems (CEMS) were described in some detail in Chapter 5, and are mentioned again here mainly to note that these systems, and their application, can be expected to evolve substantially as newer sensors are developed (e.g., Jahnke, 2000). As noted in Chapter 5, CEMS for SO_2, NO_x, CO_2, O_2, opacity, and flow have been deployed on large electric utility boilers in the U.S. since the early 1990s to comply with the allowance trading requirements established by the Acid Rain Program (ARP) under Title IV of the U.S. 1990 CAAA. Hourly emission data from CEMS are reported quarterly to the ARP's Electronic Data Reporting System (ETS). These data form the basis for the annual emission data included in the US National Emission Inventory for electrical generating units and also serve as highly accurate inputs to modeling inventories The variation in emissions recorded by the CEMS reflect changing boiler and combustion-turbine operating conditions, fuel compositions, meteorological conditions, startups, and shutdowns. Additional continuous NO_x monitors will be installed on other sources in the East in the next several years to comply with allowance trading that is integral to the NO_x budget program. In addition, opacity monitors are commonly installed on incinerator stacks

CEMS for gas-phase constituents typically use optical sensors, based on absorption, emission, or fluorescence, depending upon the species being detected. Pollutant emission rates are calculated by multiplying pollutant concentrations by stack volumetric flow. Table 6.2 contains a representative list of mature and developing CEMS technologies indicating the physical measurement basis for each pollutant species.

There are many challenges associated with demonstrating the accuracy, precision, and reliability of CEMS. Substantial effort will be needed to develop protocols and experience to insure that their operation provide credible data. For example, interferences, such as that associated with UV absorbance bands of SO_2 and Hg, must be minimized. Precision and accuracy at low emission levels, such as single-digit ppm NO_x levels from state-of-the-art combustion turbines must be demonstrated. CEMS must be maintained and carefully calibrated in a hostile thermal and corrosive atmosphere of the hot effluent gas. Validation and management of a large body of continuous data from thousands of sources presents a formidable task for the operators and for EPA and States as the archivers of these data. In spite of these difficulties, Section 5.2.2 demonstrates that CEMS systems on power plants have yielded highly accurate flux measurements for NO_x, SO_2 and CO_2.

CEMS for other pollutants are being developed in the United States and Europe for regulatory compliance, for process-control needs, and to support future allowance trading programs. Pollutants for which CEMS are currently under development include NH_3, black carbon, mercury (total and speciated), PM, and VOCs. Most of the development is being conducted by instrument manufacturers with the expectation of growing markets for this technology.

Table 6.2. Representative CEMS Technologies

Pollutant	Measurement Principle	Status
SO_2	UV Absorption	Mature technology
NO_x	Chemiluminescence	Mature technology
CO_2	NDIR[a]	Mature technology
CO	NDIR	Mature technology
Flow	Various	Mature technology
Hg total	Carbon tubes/CVAFS[b]	Under development
Hg, total, speciated	Aqueous/AF[c]	Under development
NH_3	UV Absorption	Under development
Carbon Black	Multi-angle absorption	Under development

[a] NDIR = non-dispersive infrared absorption spectrometer
[b] CVAFS = cold vapor atomic fluorescence spectrometer
[c] AF = atomic fluorescence spectrometer

6.1.4 Aircraft Plume Measurements

An important alternative to remote sensing of stationary sources is the use of aircraft, helicopters and even blimps to sample plumes, and characterize their near stack chemical reactions with distance downwind. Plume tracing has been used to characterize at least qualitatively gas and particulate emissions from large power plants, industrial sources and urban areas since the 1970s (e.g., Newman et al., 1975; Easter et al., 1980; Cher et al., 1984).

In the past, emission-rate has been difficult using aircraft sampling because of large uncertainties in identifying the plume location, and the flux of pollutants moving through a plume cross section. A part of these problems derives from the lack of fast-response instruments compatible with aircraft speeds. Another arises form the imprecise sampling and measurement from an aircraft flying at different altitudes. Yet another is the lack of complete, simultaneous measurement that provide for estimating a material balance for reactants and products. Recently, plume measurements have become more quantitative with the use of fast response instrumentation and carefully planned, systematic sampling across plumes, the location of which has been identified in-flight.

In principle, the absolute flux of a species emitted from a source can be directly determined from aircraft measurements of its concentration in the downwind plume. The flux is equal to the wind speed at the time of emission multiplied by the integral of the species concentration over the cross section of the plume perpendicular to that wind direction. These concentration data can be collected during aircraft transects of the plume. In practice, collection of data of adequate spatial resolution and coverage to allow accurate integration over the plume cross section is daunting. Generally the plume flux determinations are carried out under favorable conditions that allow significant simplifications (see Ryerson et al., 1998, and references therein).

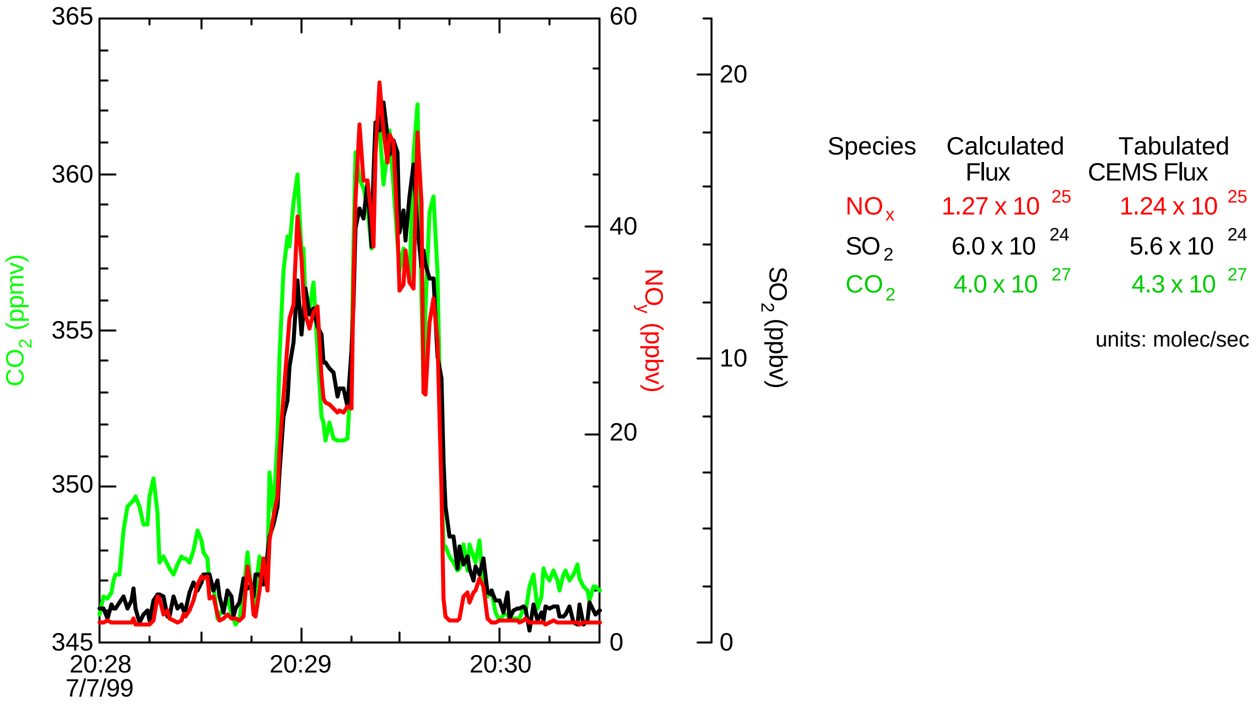
The favorable conditions for aircraft plume flux determinations are those where three approximations can be made: 1) the plume is confined to the planetary boundary layer (PBL), 2) the plume is well-mixed over the depth of the PBL, and 3) the wind speed and direction in the PBL are constant from time of emission to measurement. Under these conditions the flux of species m can be calculated from wind and concentration measurements collected in a single plume transect:

$$flux_m = v \bullet \cos a \int_0^{Z_0} n(z)dz \int_{-y}^{+y} X_m(y)dy\,. \qquad (6.1)$$

Here v is the wind speed and a is the deviation of the aircraft transect from perpendicular to the wind direction, $n(z)$ is the number density of air as a function of z, the height above ground, z_0 is the PBL height, and $X_m(y)$ is the mixing ratio enhancement above background of species m as a function of y, the cross plume distance. Under optimal conditions the uncertainty in this calculation can be as low as ±20%. Figure 6.4 shows data collected under such favorable conditions in the plume from the Thomas Hill coal-fired power plant in Randolph County, MO during the 1999 SOS study. The fluxes derived from Eq (1) for NO_x, SO_2 and CO_2 agree very well with tabulated CEMS data. (The NO_y measurements plotted represent the sum of all oxidized nitrogen species, which includes not only the emitted NO_x that remains in the plume, but also any species, such as HNO_3 and PAN, that are produced by photochemical oxidation of NO_x between emission and measurement.)

Under conditions where one or more of the above approximations fail, it is still possible to determine at least the ratio of the fluxes of two emitted species, even from only a partial transect of the emission plume. The slope of the correlation between the concentrations of two species is equal to the ratio of their fluxes. For example, for the data of Figure 6.4 the slope of NO_y versus CO_2 is 3.3×10^{-3} with an r^2 of 0.93; the corresponding slope for SO_2 versus CO_2 is 1.14×10^{-3} with an r^2 of 0.89. These slopes agree well with the ratios of the CEMS emissions: 3.3×10^{-3} and 1.30×10^{-3}, for NO_x/CO_2 and SO_2/CO_2, respectively. These derived slopes are not affected by failure of any of the three approximations listed above. Using this technique, several studies have evaluated emission factors for many species in biomass burning emissions (see Sinha et al., 2003, and references therein.)

A major challenge in these measurements is developing and deploying instruments that can perform fast response (~1 second resolution) measurements of the ambient concentrations of the emitted species with sufficient accuracy and precision. In addition, the wind speed and direction at the time of emission are required to derive a flux from the concentration measurements. Finally, conservation of the emitted species in the plume from emission to measurement is required to determine absolute emission flux. This conservation implies negligible loss by any mechanism, such as in situ chemical removal, surface deposition or venting of the plume out of the PBL. The determination of flux ratios is not sensitive to boundary layer venting, but is affected by different rates of removal of the two species by either chemical removal or surface deposition.



Species	Calculated Flux	Tabulated CEMS Flux
NO_x	1.27×10^{25}	1.24×10^{25}
SO_2	6.0×10^{24}	5.6×10^{24}
CO_2	4.0×10^{27}	4.3×10^{27}

units: molec/sec

Figure . 6.4. One-second average data collected during a 2.5 minute transect of the Thomas Hill coal-fired power plant in Randolph County, MO during the 1999 SOS study. This transect was conducted 20 km downwind of the plant, approximately 1.5 hours after emission. The fluxes of the three emitted species calculated from Eq. (6.1) are compared to those reported from CEMS measurements.

Section 5.2.2 discusses an extensive set of plume flux determinations that are used to evaluate the inventoried power plant emissions. In general quite good agreement is found between the aircraft flux measurements and the tabulated fluxes from CEMS data. Attempts to quantify emissions from urban areas are given by Trainer et al. (1995), Klemm and Ziomas (1998), and Plummer et al. (2001).

Current instrumentation is adequate for fast response measurements of CO, NO_x, SO_2 and CO_2. Biomass burning emissions have been determined by Fourier transform infrared spectrometry and other techniques that often have considerably slower response times. In this case various integrating procedures are utilized (Sinha et al., 2003). However much of this current instrumentation is heavy and requires a good deal of electrical power and experienced operators. It could be more extensively applied if lighter, lower powered and more routinely operated instruments are developed. There is an important need to develop instrumentation for determination of speciated VOC emissions from intense sources such as petrochemical industrial facilities. Such emissions have been identified as critically important to some outstanding air quality issues (see Section 5.2.3).

6.1.5 Direct Flux Measurements

In the context of the present section "flux measurements" pertain to direct or indirect determinations of pollution fluxes (amount of pollution issuing from a unit area of the Earth's surface per unit time). Measurements of this type typically apply to emissions from sources having relatively uniform spatial distributions (e.g., isoprene emissions from a forest canopy, ammonia emissions from pasture land, DMS emissions from an ocean surface) or aggregated sources which can be approximated as uniform in a spatially-averaged context (e.g., urban and suburban areas under specialized conditions). Because pollution fluxes can be either positive (emission) or negative (deposition), measurement technology for emission-flux measurements closely parallels that for dry-deposition assessment.

Although several inferential techniques have been applied to estimate pollution fluxes (Hicks et al., 1987), most direct emission-flux measurements fall into two basic classes: *profile measurements* and *covariance methods*.[4] As their name implies, profile measurements depend on observations of vertical pollutant-profiles in conjunction with appropriate meteorological measurements. Typically fluxes are calculated on the basis of these observations using an equation of the form

$$\mathrm{flux} = -K_z \frac{dc}{dz} \qquad (6.2)$$

where $\frac{dc}{dz}$ is the vertical gradient of pollutant concentration c, and K_z is a transport coefficient inferred from meteorological observations.

Covariance methods (Rinne et al., 2001) measure fluctuations in local concentrations and wind-velocities, and calculate fluxes on the basis of fundamental turbulence theory using the form

$$flux = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} w'c'\,dt \qquad (6.3)$$

---

[4] *Enclosure methods*, wherein an emitting area is enclosed in a monitored chamber, constitute another class of flux measurements (cf. Baldocchi, et al., 1996). This class is of more limited applicability in the context of criteria pollutants and their precursors, and will not be considered further here.

where w’ and c’ respectively are the fluctuating components of the vertical wind-velocity and concentration, and $t_2 - t_1$ is some appropriate time-smoothing interval. Measurement approaches that observe w’ and c’ directly and compute fluxes by subsequent integration often are referred to as *eddy-correlation* techniques.

Eddy-correlation instrumentation must be sufficiently responsive to monitor all important components of the turbulence spectrum, typically of the order of 0.1 Hz and higher; and while modern wind-velocity instrumentation can satisfy this requirement easily, current pollution-monitoring equipment often cannot. *Eddy-accumulation* methods, wherein the w’ sensing device operates a fast-response valving system feeding two air-sampling reservoirs at rates directly proportional to w’, represents one method of overcoming this difficulty. Subsequent concentration measurements of the two chambers leads to evaluation of the integral in equation (6.3). Additional attempts to overcome the time-response issue have led to various “relaxed” or “disjunct” covariance approaches, wherein the required sampling frequency is degraded in one form or another. Such approaches typically involve additional approximations or limiting assumptions regarding turbulence behavior.

In addition to the obvious challenges posed to measurement instrumentation, both profile and covariance techniques depend strongly on measurement location, meteorology, and pollutant behavior. Equations (6.2) and (6.3) both are single, one-dimensional components of the general relationship describing three-dimensional, transient behavior in the real atmosphere, and their valid application for flux measurement generally requires that the local environment approximate a one-dimensional steady state. This in turn implies a uniform source distribution and a uniform wind fetch. Informed meteorological guidance is essential for determining the presence of these conditions. Moreover while equation (6.3) can be considered a fundamental, first-principles relationship, equation (6.2) is more inferential in the sense that the transport coefficient, K_z, is quasi-empirical in nature and is an estimated entity. This renders profile measurements somewhat more subject to uncertainty - in principle, at least - than their covariance counterparts.

Finally, equations (6.2) and (6.3) both imply that turbulent transport dominates the total flux term, a situation that will be violated if other mechanisms, such as gravitational sedimentation, are significant. In addition chemical reaction of the observed component, if sufficiently rapid, can confound both profile and covariance observations.

Direct flux-measurement techniques have been applied for both monitoring and special-purpose measurements. Table 6.3 provides several examples of such observations. As noted above, both profile and covariance methods are limited by applicable source and meteorological conditions. Covariance methods tend to be less demanding in this respect, and this combined with their stronger theoretical basis suggests their preferential use during future years.

The currently rapid development of sensitive, fast-response chemical instrumentation (e.g., mass spectroscopy) will encourage extensive future covariance-method application, both on stationary and aircraft platforms. While the bulk of these applications will focus on relatively ideal boundary-layer situations, some encouraging developments are taking place in less ideal settings, such as urban and mixed suburban areas (Lamb, 2003; Fowler et al., 1997). Future results will determine practical applicability and the extent of future use under such situation.

Table 6.3. Examples of Direct-Flux Emission Measurements

Pollutants	Technique	Source/Location	Platform	Reference
Isoprene, CO_2	disjunct eddy covariance	deciduous forest Michigan	tower	Westburg et al. (2001)
Biogenic organic compounds	disjunct eddy covariance	Forests, mown croplands	tower	Karl et al. (2001, 2002)
Ethane	disjunct eddy covariance	urban area Mexico City	rooftop tower	*(pending Science article) Lamb, et al. (2004)*
CO_2	eddy covariance	Various locations throughout the world.	tower	http://public.ornl.gov/ameriflux/ http://daac.ornl.gov/FLUXNET/ Baldocchi (2003)
Suspended dust flux	eddy covariance	Prototype testing in western U.S.	tower	Gillies et al. (2003)

6. 2. MODELING AND INTERPRETIVE METHODS

Over the last 25 years, air-quality models establishing the relationship between sources and ambient concentrations or receptor exposure have improved dramatically for both non-reactive and reactive pollutants. In principle, the models can be used to estimate ambient conditions for periods of less than a day to multiple years, provided the input emissions and meteorological data are available. Sufficient testing and evaluation of models has been accomplished over the years that workers have identified emission estimation as one (if not the principal one) of the major uncertainties in the model results (e.g.., NARSTO, 2000, 2004).

Modeling has offered an important opportunity for checking the reliability of the emission models on which they depend. The methods use two different kinds of models that are readily available. These are: (a) receptor oriented modeling, and (b) source based modeling. These modes of approach have been used extensively in the past two decades, but recent advances increase the potential for both techniques. The following describe recent results which improve the reliability of emission evaluation from air-quality models.

6.2.1 Receptor Modeling

"Receptor modeling" is a term describing a variety of (largely) statistically based techniques for inferring source categories and/or magnitudes on the basis of ambient-concentration measurements. Differences among these various techniques are based on the types of statistical approaches employed and the types of observational patterns (e.g., temporal differences, spatial differences, ratios among specific compounds) considered, as well as whether the specific technique depends on source-profile information in addition to ambient measurements (e.g., NARSTO, 2004). Although most receptor models are totally statistical in nature, some variants employ limited deterministic information as well. Table 6.4 summarizes a variety of receptor-model types and their data requirements.

As with inverse modeling, receptor modeling is generally considered more as a verification tool, as well as a means for generating semi-quantitative insights regarding questionable or unknown emission sources. The success of receptor modeling depends heavily on the selection and quality of associated input measurements. Moreover, receptor-model results can be strongly prone to misinterpretation unless treated with appropriate caution: The experience and capability of the practitioner is of supreme importance in this regard.

Receptor modeling is most applicable to situations where differential attrition of the observed species, by deposition or by reaction, is minimal, although techniques to deal with such issues have been incorporated into some receptor models by adding quasi-deterministic components to account for these effects. Receptor modeling should be applied with special caution when such conditions are suspected. Brook, Vega, and Watson (2004) describe a variety of past receptor-model applications for source apportionment and source verification, as well as a detailed description of the techniques described in Table 6.4. The interested reader is referred to their work for additional details.

Receptor-model applications for atmospheric pollution-source analysis are presently at a relatively mature state. Although such models can expect to experience further development during future years they can be considered to be stable cadre of useful tools for emission verification and analysis, which should see continuing and extensive future application.

Table 6.4. Summary of receptor model source apportionment models (Adapted from Brook, Vega, and Watson 2004)

Receptor Model	Data Requirements	Strengths	Weaknesses
Chemical Mass Balance	-Source and receptor measurements of stable pollutant properties that can distinguish source types. -Source profiles (mass abundances of physical and chemical properties) that represent emissions pertinent to the study location and time. -Uncertainties that reflect measurement error in ambient concentrations and profile variability in source emissions. -Sampling periods and locations that represent the effect (e.g., high concentrations, poor visibility) and different spatial scales (e.g., source dominated, local, regional).	-Simple to use, software available. -Quantifies major primary source contributions with element, ion, and carbon measurements. -Quantifies contributions from source sub-types with single particle and organic compound measurements. -Provides quantitative uncertainties on source contribution estimates based on input data. uncertainties and co-linearity of source profiles. -Has potential to quantify secondary pollutant contributions from single sources with gas and particle profiles when profiles can be "aged" by chemical transformation models.	-Completely compatible source and receptor measurements are not commonly available. -Assumes all observed mass is due to the sources selected in advance, which involves some subjectivity. -Does not directly identify the presence of new or unknown sources. - Typically does not apportion secondary particle constituents to sources. Must be combined with profile aging model to estimate secondary aerosol. -Much co-linearity among source contributions without more specific markers than elements, ions, and carbon.
Injected Marker Chemical Mass Balance Tracer Solution	-Non-reactive marker(s) added to a single source or set of sources in a well-characterized quantity in relative to other emissions. Sulfur hexafluoride, perfluorocarbons, and rare earth elements have been used.	-Simple, no software needed. -Definitively identifies presence or absence of material from release source(s). -Quantifies primary emission contributions from release source(s).	-Highly sensitive to ratio of marker to PM in source profile; this ratio can have high uncertainty. -Marker does not change with secondary aerosol formation—needs profile aging model to fully account for mass due to "spiked" source. -Apportions only sources with injected marker. -Costly and logistically challenging.

Table 6.2.1.1. Continued

Receptor Model	Data Requirements	Strengths	Weaknesses
Enrichment Factor	-Inorganic or organic components or elemental ratios in a reference source (e.g., fugitive dust, sea salt, primary carbon). -Ambient measurements of same species.	-Simple, no software needed. -Indicates presence or absence of emitters. -Inexpensive. -Provides evidence of secondary aerosol formation and changes in source profiles between source and receptor.	-Semi-quantitative. More useful for source/process identification than for quantification.
Multiple Linear Regression	-100 or more samples with marker species measurements at a receptor. -Minimal covariation among marker species due to common dispersion and transport.	-Operates without source profiles. -Abundance of marker species in source is determined by inverse of regression coefficient. -Apportions secondary aerosol to primary emitters when primary markers are independent variables and secondary component (e.g. SO_4) is dependent variable -Implemented by many statistical software packages.	-Marker species must be from only the sources or source types examined. -Abundance of marker species in emissions is assumed constant with no variability -Limited to sources or source areas with markers. -Requires a large number of measurements.
Eigenvector Analysis [a]	-50 to 100 samples in space or time with source marker species measurements. -Knowledge of which species relate to which sources or source types. -Minimal covariation among marker species due to common dispersion and transport. -Some samples with and without contributing sources.	-Intends to derive source profiles from ambient measurements and as they would appear at the receptor. -Intends to relate secondary components to source via correlations with primary emissions in profiles. -Sensitive to the influence of unknown and/or minor sources.	-Most are based on statistical associations rather than a derivation from physical and chemical principles. -Many subjective rather than objective decisions and interpretations -Vectors or components are usually related to broad source types as opposed to specific categories or sources.

Table 6.2.1.1. Concluded

Receptor Model	Data Requirements	Strengths	Weaknesses
Aerosol Evolution	-Emission locations and rates. -Meteorological transport times and directions. -Meteorological conditions (e.g., wet, dry) along transport pathways.	-Can be used parametrically to generate several profiles for typical transport/meteorological situations that can be used in a Chemical Mass Balance formulation.	-Very data intensive. Input measurements are often unavailable. -Derives relative, rather than absolute, concentrations. -Level of complexity may not adequately represent profile transformations.
Aerosol Equilibrium	-Total (gas plus particle) SO_4, NO_3, NH_4 and possibly other alkaline or acidic species over periods with low temperature and relative humidity variability. -Temperature and relative humidity.	-Estimates partitioning between gas and particle phases for ammonia, nitric acid, and ammonium nitrate. -Allows evaluation of effects of precursor gas reductions on ammonium nitrate levels.	-Highly sensitive to T and RH. Short duration samples are not usually available. -Gas-phase equilibrium depends on particle size, which is not usually known in great detail. -Sensitivity to aerosol mixing state not understood/quantified.
Time Series	-Sequential measurements of one or more chemical markers. -100s to 1000s of individual measurements.	-Shows spikes related to nearby source contributions. -Can be associated with highly variable wind directions. -Depending on sample duration, shows diurnal, day-to day, seasonal, and inter-annual changes in the presence of a source.	-Does not quantify source contributions. -Requires continuous monitors. Filter methods are impractical.

6.2.2 Inverse Modeling

The term "inverse modeling" is typically applied to data-analysis procedures that employ a deterministic source-receptor model to derive information on sources (usually considered as independent model variables), based on sampled values of observable, dependent variables such as ambient pollutant concentrations. In a somewhat simplistic sense, conventional atmospheric source-receptor models adhere to the general form

$$c_i(x,y,z,t) = f(Q_1,Q_2,Q_3,...v_1,v_2,v_3,...), \qquad (6.2.2.1)$$

where the dependent variable c_i represents concentration of pollutant i at some point x,y,z and time t, the Q's denote strengths of associated emission sources, and the v's the remaining ensemble of independent model variables such as winds, solar insolation, and deposition rates. Inverse modeling for source evaluation involves a reformulation of the modeling equations to express the Q variables (usually implicitly) in terms of the observed concentrations, combined with the remaining independent variables. This essentially involves "running the model backwards," hence the term "inverse modeling."

The mathematical details associated with inverse modeling are described in a number of texts (e.g., Bennett, 2002). To date inverse-model applications have been much more extensive in non-atmospheric areas such as ground-water contaminant transport and seismic analysis (e.g., Parker, 1994; Zheng and Bennett, 2002), although significant recent advances have occurred in the atmospheric field (Bennett, 2002; Enting, 2002; Kalnay, 2003).

Although inverse modeling is currently considered a potentially useful "top-down" verification of existing, "bottom-up" emission inventories, it is not generally viewed as a direct tool for quantifying specific emission sources. There are two major reasons for this. First, the source-receptor models applied for inverse analysis are subject to substantial overall (i.e., "global") uncertainty, owing to stochastic considerations as well as to uncertainties in model characterizations of individual contributing phenomena. Emissions calculated from inverse models on the basis of sampled concentration values are typically highly sensitive to this global uncertainty. Second, the sampled concentration data applied for inverse-model analysis must be chosen judiciously, and one must be careful to collect a sufficient number of samples to provide a well-specified mathematical system. Information redundancies between data samples – which are usually difficult to evaluate in a direct manner – add to the complexity of this specification problem. It is apparent that future model improvements combined accumulated application experience will render inverse-modeling applications more quantitative during future years.

To date inverse-model applications for atmospheric source analysis have been confined mainly to large-scale phenomena and disperse sources, such as global CO_2 emissions (Gurney et al., 2002), global CO emissions (Pétron et al., 2002; Palmer et al., 2003;, Kasibhatla et al., 2003), and continental NH_3 and carbonaceous PM emissions (Gilliland et al., 2003; Park et al., 2002).

As noted above atmospheric inverse-modeling techniques have lagged those in the other geological sciences. Improvements in atmospheric models combined with more general appreciation of the technique's potential for emission analysis, however, will undoubtedly result in significantly increased application during future years. It can be anticipated that future intensive field studies will be designed with direct inverse-model applications in mind, resulting in collection of data specifically intended for this purpose.

6.2.3 Specialized Experimental Design

The use of models to evaluate emissions, and the application of specialized measurements are optimized by a careful design for field experiments. Experience in developing appropriate designs for verifying emissions from different sources has expanded dramatically in the last decade or so. Field experiments have become increasingly expensive to achieve their goals with the sophistication in approach now desired for credibility. Yet there are significant opportunities to conduct meaningful experiments with relatively simple and inexpensive approaches. Perhaps the simplest situation concerns the emissions from a single source. Complexity increases substantially when there are multiple sources present, such as in a city, with similar species emissions.

Ideally a source verification design should include:

- At least qualitative specification of the chemical constituents emitted by the source, and identification of similar sources in the surroundings that may confound the emission estimation.

- Specification of the time duration for estimating the emission rate; determination directly or indirectly the expected material input (e.g. fuel and its composition), and process variables, and notation of the availability of source test data from the source or a similar source.

- Identification of appropriate sampling and instrumentation, including response times, specificity of composition, etc. to determine or estimate the emissions for the period of interest.

- Consideration for ancillary tracer measurements to assist in tracking the plume a posteriori.

- Consideration for the chemical reactions that may take place between the exit point and downstream tens of meters.

Few source oriented experiments aimed at establishing emissions have taken all these requirements into consideration. However, there have been a number of experiments in recent years that have been designed to account some of the element listed above. Notable among the design of source oriented experiments recently are hybrid-source receptor studies including the investigation of the Mohave power plant in southern Nevada (e.g., Eatough et al., 2000), the Hayden and Craig power plants in west-central Colorado (Watson et al., 1996), the Nashville urban and power plant studies (e.g., Ryerson et al., 1998), the BRAVO experiment (Pitchford et al., 2004) and TexAQ2000 (2003). These experiments were not designed to obtain emission rates, per se, but emission rates were a necessary element for the studies to examine dispersal of the plume and its impact on surrounding areas, including human exposure, and visibility degradation.

6. 3 IMPROVING THE EMISSION RATE ALGORITHM

For the foreseeable future, there appears to be no new format or algorithm for organizing emission inventories (e.g., Mobley and Cadle, 2004). Thus it is expected that the form of the emission rate equation (Equation 2.1) will continue to specify rates in terms of an emission factor, an activity factor, and an emission control adjustment. The basic format for estimating these factors will continue to be listed by source and discussed in reports like the AP-42 reference (EPA, 2004).

The key problem in continued use of the conventional emission rate algorithm is the utilization of data from newer measurement technique in the listing of factors, and relating such data to conventional reference test methods. This is a part of the challenge for integrators of knowledge faced today. Improvements in the emission rate factors are in process, now, and continue to be evaluated and revised or updated for each national need. The following is a summary of the revision process for some sources.

6.2.1 Emission Factors

An extensive evaluation of the emission factor programs is undertaken by three nations; the U.S. program has been in place since the mid-1960s. The purpose of the review is to make the program increasingly responsive to emission factor users, quantify uncertainties where possible, broaden the sources of data used to develop factors, and improve the cost-effectiveness of the program. Many of the existing emission factors in versions of EPA's AP-42 report (e.g. U.S.EPA, 2001) are old and outdated, and not always used appropriately. In addition, the current emission factor development program is both expensive and cumbersome, in terms of measurements assimilated from the literature from source testing, taking account quality assurance measures. The evaluation includes the following steps:

- Developing options and methodologies for assessing, documenting, and assigning quality ratings to source test data. The objective is to review the existing qualitative four-level source test rating criteria presented in the EPA's Factors Procedures Document 5and review the specific processes that were used to evaluate the quality of source tests for several recently revised AP-42 sections.

- Developing quantifiable uncertainties for emission factors to replace the existing subjective ratings. The current A-E ratings described in the EPA Factors Procedures Document,[5] for example, are subjective and provide limited information regarding the precision, accuracy, and within-source variability of the emission factors.

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[5] Procedures for Preparing Emission Factor Documents. http://www.epa.gov/ttn/chief/ap42/index.html

- Investigating ways to automate the emission factor development and dissemination process. Mechanisms are being explored for using data identification and assimilation techniques to access source test reports from national and regional agencies to expand the universe of available data for emission factor development. An option for improved data dissemination is the development of an interactive website that would consolidate emission factors information and allow users to look up factors and download background information.

- Identifying and prioritizing source categories for emission testing to establish or improve emission factors. Priorities would be placed on source categories by national emissions contribution and uncertainty in the existing factors. . This may be completed by analyzing the National Emission Inventory (NEI). Emissions of hazardous air pollutants would also be emphasized.

Particular attention is being given to key sources, including diffuse ones; e.g., for NH_3, and carbonaceous compounds, which challenge the current measurement capabilities.

6.2.2 Activity Factors

The recent emission inventories show that non-point, mobile, and natural sources are an important fraction of criteria pollutant emissions – this is particularly true for VOC – and that only limited progress has been made in improving the activity estimates used in North American emission inventories during the past 20 years. EIIP guidance has suggested that national and regional or local agencies conduct surveys in their jurisdictions to better quantify pollution generating activity for certain non-point source categories. While some RPOs in the U.S. have sponsored research to improve activity estimates for certain non-point categories like open burning and residential wood burning, there is limited evidence that S/L/T agencies have performed surveys to improve activity estimates for non-point source categories. These agencies likely will not invest the funds necessary to perform such surveys unless it is demonstrated that there is payoff to them in terms of reduced uncertainty in the emission estimates for certain source types, or added confidence in their ability to develop effective future control strategies for these categories.

For many of the non-point source solvent categories (consumer products, painting, auto body refinishing), emission factors are applied to surrogate activity indicators, such as population or industry employment to estimate emissions. These techniques rely on solvent usage patterns being consistent with time and there being a correspondence between product sales and usage. Pollution levels/fluxes from households are low enough that remote measurements are not likely to be effective in capturing hourly/daily activity patterns (and resulting emissions).

For highway vehicles, there continues to be a significant amount of research on improving emission factor models (MOBILE and EMFAC – USEPA, 2004) as well as estimating vehicle miles traveled (VMT) or VKT. The U.S. EPA is proposing to update these tools with the Multi-Scale Motor Vehicle and Equipment Emission System (MOVES), which is intended to include and improve upon current capabilities and, eventually, to replace them with a single, comprehensive modeling system. In MOVES, how activity is defined will depend on the emission process being modeled. For most processes, EPA plans to characterize total activity by *source time* (source hours operating or source hours parked). Source time is an attractive way of characterizing activity, because it is common to all emission processes and operating modes. However, while source time is an important new metric in MOVES, its use does not preclude areas using VMT to express activity of on-highway vehicles, since source hours operating and VMT are easily inter-changeable if average vehicle speed is known. In addition, some vehicle emission processes activity is non-time based, so the activity indicator can be the number of vehicle starts, hours parked, engine-on hours, or gallons of fuel used.

Intelligent Transportation System (ITS) data are now collected by roadway surveillance equipment that monitors traffic, namely volumes, speeds, and lane occupancies. The most prevalent measurement technology is loop detectors embedded in the roadway. However, transportation agencies are increasingly turning to non-intrusive technologies, such as radar and video image processing. Video image processing offers the potential of providing length-based vehicle classifications, but this capability is still emerging. From an emission indicators improvement perspective, there are opportunities for better utilizing the more sophisticated traffic data collection devices available today to track travel demands on roadways and how these vary by time-of-day.

Roadway network usage is measured for many purposes, one of which is to provide estimates of vehicle travel activity for making air pollution emission estimates. Traditionally, measurements have been made using ground-based sensors. The sensors provide a temporally rich data set, but an individual sensor lacks spatial coverage, limiting their use and application. High-resolution imagery remotely sensed from satellite or airborne platforms is an attractive alternative that can potentially supplement and enhance the existing traffic monitoring programs with a spatially detailed data set. With the progress in image processing technologies, roads and vehicles can be identified from imagery automatically with a high level of accuracy.

During the last ten years, tools/models have been developed by EPA and to allow users to perform more sophisticated assessments of non-road vehicle/engine emissions. While default activity profiles are available in these models, these defaults may not provide acceptable information on actual activity for modeling specific areas of interest. Improvements can be had via surveys of off-road equipment usage, and stakeholders have been performing such surveys. Another research focus is on developing and using portable activity monitoring systems, either alone, or in conjunction with portable emission monitoring systems, to track how often equipment is used for the purpose of better quantifying activity by equipment type.

6.2.3 Emission Control Adjustments.

An increasingly important element in the emission rate expression is the adjustment for emission controls. In many source categories, emission controls are now required as part facility permitting. In versions of the AP-42 catalog, many of the emissions reported do not include the emission control adjustment. Such data must now be added by state and local staff while updating and upgrading their inputs into the NEI. Addition of this data is a non-trivial exercise because one needs to know the control device added, and the emission reduction efficiency of the unit under normal operating conditions. The latter is basically the adjustment factor, and can range from less than 50% emission reduction to greater than 99% reduction depending on the species emitted.

The verification of performance of emission controls will require supplemental source testing on example source classes, and will involve conventional methods as well innovative techniques noted in this chapter. This issue is suspected to be of particular importance for fugitive emissions in petrochemical facilities in the Houston area. The emission control factor is often as low as 0.02 (i.e., 98% control). An overestimate in this degree of control, may account, at least partially, for the very large underestimate of the emissions of very reactive VOCs in the Houston area (See Section 5.2.3).

6.4 ADVANCED DATA-BASE MANAGEMENT

In Chapter 2, a vision for a direction towards improved data base management was described, perhaps learning from innovative methods evolving from areas outside of pollution engineering technology, for example, the human genome community. While this ideal should certainly be targeted as a long term goal, there a number of opportunities within a more conventional approach that are being considered today. This section summarizes this progress.

Emission inventories like the NEI contain very large data collections. The NEI alone, for example, has a collection of more than 60 million items. Access to the inventories now involves complex manipulations of data, which remain user “unfriendly.” A major challenge for managers of emission data, along with producing quantitative uncertainty estimates, is the development of a means for access that uses contemporary management techniques, accommodates a variety of different data sources, and ensures data quality. This challenge is compounded by the need for efficient access of large amounts of spatially and temporally resolved data for air quality modeling. Access to these collections depends not only on efficiency of entering the tabulations for specific locations and times, but also on the ability to summarize emissions in terms of sources and emission density graphically, or by other visual means.

Most current emission databases are not seamlessly integrated with other the information sources needed to design emission-control strategies. For example, the task of de-trending air quality data to isolate the effect of meteorological fluctuations and year-to-year emission changes is made extremely cumbersome by the data architectures currently used by regulatory agencies. The problem is further compounded by the fact that the emission data bases are typically not integrated with geographically encoded land-use and urban-planning information systems. There has been an explosion in the use of Geographical Information Systems (GIS) by urban planning agencies; but these advances have not as yet migrated into the systems used by air pollution agencies.

When designing the data architectures and reporting systems it must be recognized that inventories serve multiple purposes. One of the reasons why there are no real incentives to improve the quality of the existing data is that the local agencies charged with the permitting process do not derive any real benefits from the current systems that are used to aggregate emissions for air quality modeling studies. Once the local data is aggregated to the state and regional levels there is no feedback to the permitting officers. Open access to local emission information would provide an incentive for both the public and industry to ensure that the information is correct.

In the future, it is expected that a North American emission inventory will be universally available to all who want to access its information. This facility should be capable of handling information that has high temporal and spatial resolution, is source and facility specific, is comprehensive with respect to pollutants and sources, is well documented, and is based on comparable methodologies and factors. Advances in information technology and the pursuit of collaboration among emission-inventory organizations are paving the way to an inventory that meets these goals.

6.4.1 Distributed Emission Inventory Network

The guiding principles of an integrated emission inventory follow those of distributed databases and distributed computing. The design objectives are to create a network of relevant data, as well as visualization and analysis tools, which is characterized by the following attributes.

Distributed. Data are shared but remain distributed and maintained by their original inventory organizations. The data are dynamically accessed from multiple sources through the internet rather than collecting all emission data in a single repository. Responsibility for data quality and availability remains with the data providers; however, data users can also make their collated and refined data sets available to other users via this distributed system.

Non-intrusive. The technologies needed to bring inventory nodes together in a distributed network need not be intrusive in the sense of requiring substantial modifications by the emission inventory organizations in order to participate. However, there will be needs for some harmonization of existing inventory data and structure and to assign certain functions to maintain a fluid system.

Transparent. From the emission inventory user's perspective, the distributed data should appear to originate from a single database to the end user. One stop shopping and one interface to multiple data sets are desired without required special software or download on the user's computer.

Flexible/Extendable. An emission network should be designed with the ability to easily incorporate new data and tools from new providers joining the network so that they can be integrated with existing data and tools.

Figure 6.5 depicts an envisioned end state of a distributed emission inventory. Distributed data sources (emission estimates, activity data, surrogates, etc) in a variety of formats (relational database-management systems, text files, etc.) are available through the Internet and registered in one or more data catalogs. These data can be uniformly accessed with the aid of data wrappers (translators) and connected with web tools and services to support a variety of end applications. Mediators are used to find and combine the appropriate mix of data and services to fulfill a user's task.

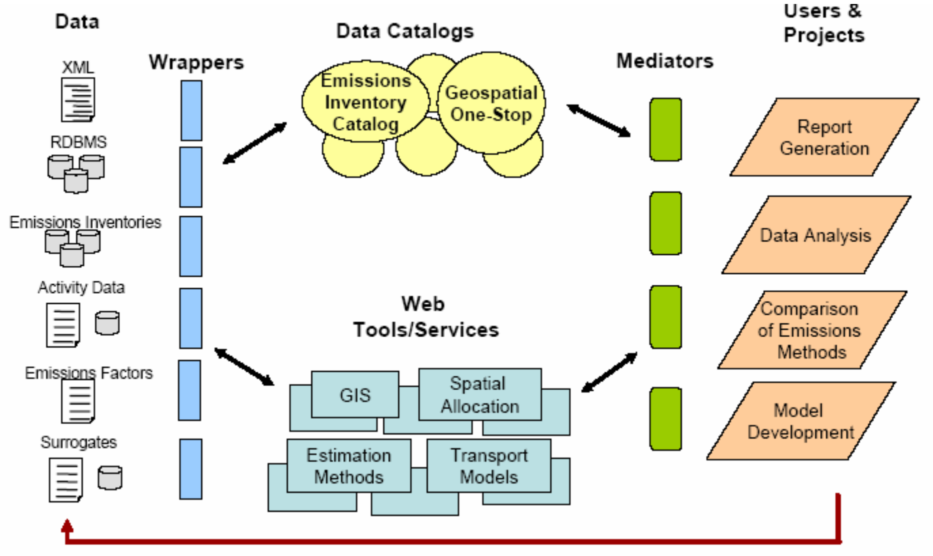

Figure 6.5. Conceptual Diagram of a Distributed Emission Inventory

Information technologies available to develop a distributed emission inventories include web services and related interoperability standards, such as the OpenGIS Consortium Web Map Server and Web Feature Server specifications. An important aspect of many of these technologies is that they can be implemented without requiring substantial modifications of the existing emission inventory databases and data dissemination systems.

6.4.2 Data Sharing and Web Services

Many emission databases are already accessible through Internet-based methods either through direct data file download or through web query tools. The query systems allow users to filter and access data at multiple levels of detail. These systems were designed to meet the needs of individual end users who log-in to the online system, manually complete forms for defining their query, and then viewing the results in tables/graphics or downloading the data. While these systems serve the individual user, they are not easily integrated into a distributed emission inventory framework where automated computer-to-computer, rather than human-to-computer access is needed. However, supplementing existing systems with distributed data capabilities is feasible.

Approaches to developing distributed emission-inventory databases can be grouped into two general categories, those that make data files available for external access and those that implement innovative information technologies and standards to make their data dynamically accessible.

For smaller inventories the solution can be straightforward – provide a ftp or http address where MS Access, MS Excel, or ASCII text files are stored, a description of the data format, and a consistent file naming convention. For example, if emission inventory A has point emission data for each year since 2000 and each year is stored in a separate file, they might use a naming convention such as NAME_Type_Year so that the files stores would be InventoryA_Point_2000.dat, InventoryA_Point_2001.dat, and so forth. An external user can then automatically access these data using a ‘get data’ request based on that inventory’s file naming convention. When new data become available in the inventory, the ‘get data’ request can automatically retrieve the new data.

For larger, more complex inventories, alternative methods are in order. Certainly, a larger inventory could provide subsets of its inventory in separate files through ftp or http addresses. A more attractive scenario is where the forms that allow users to query the inventory are “filled out” by the computer rather than by hand. This would allow dynamic access to the data and opens possibilities for “middleware” to provide value-added processes (filtering, aggregation, and integration) to the data. Middleware may make the data available in a specialized format, in different graphical views, or through tools that allow the data to be combined with other data. For example, a middleware application may provide a tool that could access multiple distributed inventories through a single query form thereby avoiding the need for a single user to access each inventory individually. The use of standardized naming conventions and adhering to national and international standards provided by the National Institute of Standards and Technology (NIST) and the International Organization for Standardization (ISO) greatly simplifies the task of providing data to the users.

An emission network using middleware would allow automated access to each emission node on the network after each data server implemented a web interface method of dynamically accessing its data. A new category of information technologies called web services offers one method for creating nodes on the distributed network. Web services are self-contained software that use Extensible Markup Language (XML)-based standards for describing themselves and communicating with other web resources. These characteristics allow web services to be reused in a variety of independent applications.

In the web services network approach, mediators serve the role of brokers, providing users with the interfaces for finding available data, dynamically retrieving it, and integrating it with other distributed data sources. These network users can function on an independent level, each addressing local issues of importance. These individual components can then be integrated or modified to handle differing data types dynamically on demand.

Web service technology is still evolving and does not currently provide a complete off-the shelf software solution. However, many required components are considered standards in web programming applications and therefore make it possible to create an operational data web service network. These components allow computer-to-computer communication in a platform- and programming language independent manner. Additionally, web service technology provides existing software applications with service interfaces without changing the original applications, allowing them to fully operate in the user's existing environment.

Distributed data network principles are being studied and implemented by a variety of emission relevant projects and programs. The CEC commissioned a study examining available data and technology for a distributed North American emission inventory (http://capita.wustl.edu/NamEN), EPA is initiating a program for Networked Emission Inventories for Global Emission Inventories (http://www.neisgei.org), a NASA and NSF funded project is pursuing web services for aerosol data and tools (http://www.datafed.net), EPA is developing a network for exchanging data between states and the agency (http://exchangenetwork.net), and a federal effort aims to provide single point access to interoperable data sources (http://www.geo-one-stop.gov).

Other examples of internet based systems include the California Air Resources Board which has recently developed a internet based graphical way to look the amounts and spatial distribution of emissions in California. The prototype system is called CHAPIS, Community Health Air Pollution Information System, and provides a mapping tool to analyze the spatial distribution of emissions from point, area, and mobile sources of various criteria and toxic air pollutants. In addition, the Great Lakes Commission has begun development of a internet based system to provide emission data, including charting and mapping tools designed to me client needs. The system is called CAROL, Centralized Air emission Repository On-Line and is designed to provide easy access to the Great Lakes Air Toxins Emission Inventory.

6.5. SUMMARY AND CONCLUSIONS

There are limitations inherent in the traditional process of developing emission inventories embodied in the historical approaches described in Chapters 3 and 4. Many of these are concern with the practicality of obtaining emission rates from generic emission and activity factors representative of the spatial and temporal resolution required for many regulatory analyses. Searching for methods to evaluate and verify emission rates, a variety of techniques have evolved over the past 20 years that complement historical practices. This chapter goes beyond Chapter 5 in describing a variety of evolving measurement methods that will enhance the ability to estimate emission rates and their uncertainty, especially for variable and intermittent sources, including transportation, urban area sources, wildfires, biogenic vapors and particles, and dusts rising from the surface. These methods are reinforced with new modeling techniques for analysis and comparison of air quality models and analysis of ambient data in the light of source contributions. Completing this tool box, is an important focus on "enabling" data management for emission access that for the user.

The discussion of important measurement techniques focuses in part on the improvements in remote sensing both from ground instrumentation and aircraft/satellite observations. Satellite observations offer the potential for tracking global scale emissions of NO_x, formaldehyde, and particles. There appear to no other practical means for continuous monitoring on this spatial scale. Another major component involving evolving measurement methods is the observations of operational on-road and off-road mobile sources. A third important area for improved observations is in the area of surface flux determinations using fast response instrumentation, which are the key to estimating fugitive sources, including blowing dust and biogenic components.

Complementing the increasing use of new measurement methods, are the modeling techniques that progressively have revealed ambiguities in emission estimates. These include (a) the maturing of receptor modeling, in combination with air mass trajectory modeling, and diffusion modeling using output from fast response instruments, and (b) the application of inverse source based modeling for estimation of emissions by comparing modeling results and ambient concentration observations.

Last but not least is the increasing attention to the application of major Internet based improvements in data management practices that will permit flexible, user-friendly access to distributed emission data and processors such that the emission data and their origins are transparent to the user.

The combination of these elements, measurements, analysis and modeling and data management offer major opportunities for enhanced confidence in timely, spatially and temporally resolved emission reporting (with specified uncertainty) for the range of stakeholder applications foreseen in the next decade or more.

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CHAPTER 7. RECOMMENDATIONS AND CONCLUSIONS

The key findings of this Assessment are summarized in this Chapter; these findings support recommendations to enable inventories in North America to advance toward the vision set forth in Chapter 2: to provide all emissions from all sources for all time periods in all areas and to make them accessible to all in a timely manner. The findings and recommendations in this Chapter are intended to apply to Canada, the United States, and Mexico, although the priorities may change based on different needs in each country.

An overarching recommendation that is not explicitly directed at inventories, but is implied by the development of this document, is the need to maintain and enhance the interactions and collaborations among and across Canada, Mexico, and the United States. These cross-border interactions and collaborations have been consistent and robust, but as the achievement and maintenance of air quality becomes more complex and more interdependent, the need will grow to ensure that these partnerships are continued and strengthened.

The order of the findings and recommendations below reflects what NARSTO believes should be the priorities for resource expenditures over the next decade. While these recommendations are intertwined and while it may be most appropriate for resources to be applied toward multiple activities simultaneously, it is generally recommended that a comfort level be achieved with the first recommendation before proceeding to the next recommendation and so forth.

7.1 FINDINGS AND RECOMMENDATIONS

7.1.1 Focus Inventory Improvements

Finding: **Comparisons of inventories with ambient measurements and other independent measures indicate that emission inventories for certain source categories and pollutants, particularly gaseous emissions from electric utilities, are well characterized and reported. Inventories for other source categories and pollutants, especially area sources including fugitive classes and transportation, as well as sources of organic compounds and carbonaceous PM, are much more uncertain. Estimates are also believed to be poor for ammonia and hazardous air pollutants.**

Many new and emerging technologies and approaches are now, or will shortly be, available that can address these and other areas of uncertainty. Identifying and reducing these uncertainties can lead to more robust and effective air-quality management decisions.

Recommendation**: Apply sensitivity and uncertainty analyses to identify priority measurement and research needs and address them using new and updated tools.**

There is a need to target resources to reduce key sources of uncertainty, including non-representative emission factors and missing or incomplete emission and activity data. Identifying key sources of uncertainty is helpful in explaining the factors contributing to uncertainties in inventories and applications that use those data such as air-quality models. After the key uncertainties are identified, the wide range of tools and approaches now becoming available should be applied in a targeted manner to reduce the overall inventory uncertainties and improve the information available to air-quality managers.

Discussion

Several recent independent reports [NRC (2004a,b), NARSTO (2004)] have identified the need to ensure that emission inventories adequately describe actual emissions to enable informed decision-making. In previous chapters, this Assessment has recognized the recommendations from these reports and the need to allocate resources to reduce uncertainties in key areas. In an era of limited resources, priorities must be set, and the application of uncertainty and sensitivity analyses can provide quantitative measures of where the greatest sources of uncertainty lie. Particularly for air-quality issues that will require significant actions on the part of the regulated communities, it is crucial to identify the sources that are most effectively controlled to achieve the air-quality management goals.

For instance, the greatest uncertainties in existing inventories of precursors of airborne fine particulate matter are in the sources of organic and elemental carbon and ammonia. Although improved speciation will help to improve our understanding of carbonaceous PM emissions, it is equally important to understand how critical specific source types are to local and regional air quality. This understanding can be reached by evaluating the uncertainties in PM inventories and the sensitivities of air-quality models to changes in carbonaceous PM emissions from specific source categories. Priority for improved data should then be placed where uncertainties are greatest.

Once the key uncertainties have been identified, new and updated tools and approaches, such as those discussed in Chapter 6, can be applied to reduce those uncertainties. In some cases, existing approaches and technologies may be appropriate, but may need to be applied more broadly. For instance, emissions from marine or offroad sources are becoming more important as these categories grow or as other sources reduce emissions. Application of existing measurement methods may be appropriate for characterizing these sources, but greater emphasis may need to be placed on such categories if they are shown to be one of the areas of key uncertainty.

For some applications, such as air-quality modeling for ozone and secondary PM, key contributors to uncertainty in the modeling results may be inadequate temporal and spatial resolution from human-made and biogenic sources. In such cases, significant changes to emissions processors may be required before uncertainties are reduced to acceptable levels. In a similar vein, irregularly spaced or timed impacts on inventories, such as fires, fugitive emissions, or traffic jams may need to be represented differently than is currently possible with existing emission processors. In these cases, new approaches may need to be developed and evaluated.

In general, however, it is more likely that the new and emerging tools described in previous chapters will address the majority of key inventory uncertainties. The inventory user and development communities have made substantial progress in understanding where the greatest differences exist between inventoried and actual emissions. The tools described previously have been developed to address those differences; more formal analyses are needed to identify where these tools are most effectively applied to achieve air quality management goals, given the limited availability of resources.

Priorities for improving emissions estimates by pollutants and source category are dependent on the use of each inventory, the quantity of the emissions, the relative contribution of individual source categories, and the degree of confidence in reported, calculated or estimated emissions. While there is no established procedure to quantitatively rank pollutants and sources, there are key areas that have been consistently identified in this and other reports as being sources of significant uncertainty in emission inventories. These key areas are noted below:

- Size-segregated, speciated emissions of fine particles and their precursors, including black and organic carbon emissions
- Emissions from onroad 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
- 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
- Paved and unpaved road dust.

7.1.2 Improve Inventory Estimation Methodology

Finding: **Contemporary air-quality issues such as PM and ozone nonattainment and air toxics hot spots are all characterized by a need for information about the detailed species being emitted from sources.**

For example, the need for speciated emission estimates is especially important for PM, where source apportionment methods require some understanding of particle composition and there is strong interest in improving the ability to link emissions from specific source types to adverse health effects. In the future, increased reliance on reported speciated emissions estimates will be sought by stakeholders as air-quality, exposure, and health modeling become more sophisticated. Likewise the need for improved and updated emission factors, especially for PM2.5, is critical for making informed air-quality management decisions.

Recommendation: **Develop and/or improve source profiles and emission factors plus the related activity data to estimate emissions for particulate matter, volatile organic compounds, ammonia, and air toxics.**

A high priority commitment should be made to develop through measurements or other means speciated source profiles, emission factors and activity data for important source categories for particulate matter (especially carbon compounds), volatile organic compounds (including a separation between high- and low-molecular-weight material), ammonia, and airborne toxins.

Critical to this effort is the need to develop temporally and spatially resolved and compound-specific emissions from biogenic sources. There has been progress in this area over the last several years, but further effort is needed to develop more complete knowledge of the chemical constituents emitted from sources. Canada is also contributing to the improvement of these profiles and requires Canadian industries to report speciated volatile organic compound emissions annually.

Discussion

Current air-quality management issues are going well beyond the management of easily measured pollutants. As more is learned about the relationships between air pollution and adverse health effects, more detailed information is needed about the types and amounts of material being emitted into the ambient atmosphere. Improved air-quality models require increased levels of detail regarding the chemical species that participate in the atmospheric reactions that create ozone and secondary particulate matter. Increasingly accurate source apportionment models provide greater insight concerning the sources of pollutants measured in the ambient air. In each case, substantially more detail is needed about the chemical composition of source emissions.

The most pressing speciation needs are for organic compounds from human-made and biogenic sources, which are often the most difficult and expensive to quantify. Reactive VOCs that play a key role in ozone and/or secondary PM formation need to be measured with greater accuracy, even though they are often present in the atmosphere at very low concentrations. Although some hazardous air pollutants can be emitted in relatively high concentration streams, the temporal and spatial variability of those emissions is often enormous. In addition, heavier-weight organic compounds that condense to form primary PM are not consistently measured using many of the techniques now in use.

The ability to estimate the basic mass emissions of PM, especially $PM_{2.5}$, and gaseous mass emissions of VOCs, is hampered by poor quality (or in too many cases, nonexistent) emission factors. The characterization of mass emission estimates is also dependent on reliable source activity data, which are critical if emission estimates are to be improved.

Numerous new technologies and approaches are being evaluated for improving the measurements of source emissions. Open source, laser-based technologies, CEMs for pollutants previously considered to be “trace” elements, and satellite-based measurements are among the techniques that have shown considerable promise in providing more accurate source measurements. Improvements in ambient measurement methods, including satellite-based sensors, have also shown promise as means to check the correlation between emission estimates and environmental concentrations of pollutants.

In some cases, the advances in technology are minor, but the implications for inventory improvement are significant. One of the most visible is the need for dilution sampling systems for measuring fine PM emissions. Because a significant fraction of primary organic PM can be in the vapor phase at exhaust temperatures, it is necessary to dilute and cool the exhaust to ambient temperatures, thereby forcing these vapors to condense and yielding a more accurate measurement of fine PM emissions. In addition, the need to understand the chemical composition of these emissions in order to better understand the link between emissions and adverse health effects, dilution sampling systems coupled with detailed organic speciation methods are needed to develop a more comprehensive emission inventory of potential biologically active emissions.

In other cases, the advances in technology are substantial, such as the use of satellites for identifying sources of wildfires or dust, or for measuring ambient levels of pollutants across a broad area, providing additional information about times and locations of emissions. Although satellite-based measurements will clearly not be led by regional, state, or local air-quality management agencies, the data from these measurements can be used to refine and, in some cases, determine emission levels, events, and activities that are of importance to these agencies.

In general, the application of new technologies is driven or impeded by two key questions. First, is the technology necessary to meet regulatory requirements? If it is, then it is much more likely that the needed resource investments will be allocated than if the same measurements can be made with existing technologies, even if the existing technologies provide less reliable data or are more expensive to maintain over the long term. Second, is the technology something that requires an extensive and costly infrastructure to operate? Obviously, satellite systems represent one extreme in terms of infrastructure. But the need to hire even a single expert chemist to operate a measurement system, for instance, can significantly reduce the likelihood that agencies will have the resources to invest in that method.

The application of appropriate technologies and approaches for estimating speciated emissions and incorporating them into inventories is likely to require more resources than the other recommendations.

7.1.3 Improve Timeliness

Finding: **Timely and historically consistent emission inventories are crucial elements for stakeholders to assess current conditions and estimate progress in improving air quality.**

The current inventory cycle is not short enough to capture changes in emissions caused by increasingly rapid economic and technical changes. As cycle times shorten, inventory estimates are more accurate in describing actual conditions. Shorter times between inventory updates also make it easier to identify trends that provide feedback about the effectiveness of air quality management strategies. Long inventory cycle times have inhibited the ability of all three nations to link emissions changes with trends in ambient air quality.

Recommendation: **Create and support a process for preparing and reporting national emission inventory data to reduce the inventory cycle to no more than one year.**

Special efforts are needed to accelerate the preparation and reporting of national emission inventories on an annual cycle, with self-consistent estimates. If historical estimates need to be changed for method improvements or other technical reasons, updated historical inventories also must be reported in a timely way to ensure that such changes are clearly communicated to users.

It may be necessary to create “draft” and “final” inventories that are differentiated by their level of quality review so that new data can be incorporated into inventories as rapidly as possible.

Discussion

With some exceptions, inventories are currently revised on a cycle that can take three or more years to complete. Because of rapid changes in population, economic activity, industrial output, and technologies, these data can only partially represent current emission patterns. Inventories that are capable of quickly incorporating and reporting new information without significant increases in uncertainty will provide a more up-to-date picture of the current situation and will therefore be of much greater value to policy development efforts.

Several inventories have demonstrated approaches that significantly reduce the length of the inventory update cycle. In Canada and California, for instance, inventory cycles are being shortened to as little as one year. A number of program changes to improve the timeliness of the Canadian emission inventories have been recently initiated, including a process to compile annual emission inventories for the criteria air pollutants. Such examples can serve as guides to help improve timeliness of other North American inventories.

The use of historical inventories for quantifying emission trends is an important application for evaluating the effectiveness of air-quality management strategies. As inventory methods change, such trends analyses can be misleading if those changes are not communicated clearly and in a timely manner. Inventories are products of a complex and dynamic process, and historic consistency may be difficult, if not impossible, to achieve in certain instances (such as for mobile source emissions). Even so, updating and reporting changes to methodologies and their impacts on comparability to historical inventories will provide more accurate tools for air-quality decision makers.

It must be recognized that there are limits to improving inventory timeliness. In many cases data collection and reporting follows a multi-step process from a source to a local agency to a state agency, and then to a national inventory. Each step involves complex quality control and certification steps and procedures. There will remain a tension between quality and responsiveness, and the balance between the two will be defined by the needs of the inventory user communities.

7.1.4 Increase Inventory Compatibility

Finding: **There have been substantial improvements in reporting national inventories in a mutually consistent way by categories, estimation methods, and chemical constituents.**

Canada’s inventories and Mexico’s evolving inventories use techniques similar to those in the United States, reflecting the longer inventory history in the United States. Nevertheless, coordination among nations and among different governmental levels is still needed to improve the comparability among inventories.

***Recommendation:* Develop mutually acceptable formats for reporting emissions in Canada, the United States, and Mexico.**

Efforts need to continue to develop mutually acceptable formats for reporting and processing emission inventories in all three countries. This will improve the ability to understand and apply emission inventory across international boundaries. Future input formats must provide for uncertainty measures and additional metadata that describe the source and pedigree of inventory inputs. It may be appropriate to convene a panel of experts from across the North American inventory development and use community to define and implement standards for emission inventories, perhaps under the umbrella of ongoing coordination by the Commission for Environmental Cooperation (CEC).

Discussion

As indicated in Chapter 3, comparability of the emission inventories is essential for effective joint analyses, air-quality modeling, and reporting, such as that required under the Canada-U.S. Air Quality Agreement. The National Emission Inventory Input Format (NIF) used in the United States (and in inventories derived from the U.S. NEI) is an example of a consistent data format. Efforts are underway to export Canadian inventory data in the most current NIF. The Mexico National Emissions Inventory (MNEI) is also prepared using a derivative of NIF.

Consistent inventory structure and data requirements can help to increase the information available to be used in inventory development. In turn, this means that data generated in one location may be applicable nationally or internationally, resulting in improved data for all locations. Even where data are not appropriate for simple transfer across borders, harmonizing data and inventory structure will help to reduce the broad range of different measurement and data analysis methods that may now be required. Furthermore, harmonized data and inventory structure makes it easier to compare inventories with one another. In each instance, increasing the harmonization results in less uncertainty and more rapid dissemination of the data.

This recommendation goes beyond simply revising the data input format. The inventories themselves need to be consistent with one another to the greatest extent possible. The challenge for this consistency can be seen when one examines the broad range of inventories presented in Chapter 3. Many of these have been developed in near-isolation from the others, which significantly adds to the differences that arise when inventories are combined or compared.

In addition, issues such as industrial confidentiality and other stakeholder concerns must be appropriately addressed. The need for compatibility will have to be balanced against the different approaches that may be taken in each country.

At a minimum, a standard reporting format is needed for units, chemical names, industries, and similar fundamental data. The use of common coding schemes (e.g., SCC, NACE, and pollutant codes) and data interchange formats such as the NIF can go a long way in ensuring that the country inventories are compatible and readily useable. While progress is being made in this regard, it is necessary to continue ensuring that a common data format is used, with the inclusion of the proper metadata and documentation to understand the content and limitations of the emission inventories.

7.1.5 Improve User Accessibility

Finding: **The accessibility of emission inventories or emission models presently is very limited because of the sheer size of the databases, and the cumbersome manner in which the data have been reported and archived. Improved accessibility to emission data is critical for the needs of the user community.**

Recommendation: **Improve user accessibility to inventory data through the Internet or other electronic formats.**

High priority attention is needed to substantially improve user accessibility to inventory data. An investment is needed in all three nations and at different governmental levels to improve accessibility, through the Internet or other electronic formats. For instance, the creation of a file transfer protocol (FTP) site to host the detailed emission inventory and related modeling files for the three countries could satisfy some of the requirements of the modeling community.

Discussion

Information technologies have progressed tremendously since the advent of modern emission inventories. In many ways, inventories have taken advantage of these tools, particularly with regard to data analysis and reporting. However, in other respects, inventories have not incorporated many of the technological advances that can help inventories be as responsive as possible. Application of modern data management techniques can provide significantly improved user accessibility to inventory data, and can also improve the ability of inventory developers to incorporate new information into inventories as they are developed and updated.

There are numerous commercial and government examples to draw from in designing an accessible inventory system. An application that makes the U.S. NEI available from a conveniently accessible, GIS-based web site can be found at http://map.ngdc.noaa.gov/website/al/nei99_v3/viewer.htm. The Canadian GIS-based site to access the Canadian NEI can be found at http://gis.ec.gc.ca/npri/root/main/main.asp. EPA's AIRS database is another example of making data accessible to the public. It should be noted that accessibility cannot be achieved simply by application of the appropriate technology. Data handling procedures and agreed-upon data formats and protocols (see Recommendation 7.1.4 on compatibility) are equally important to achieving effective user accessibility.

These approaches may require some investment in information technology infrastructure, but are more likely to require investment in expertise. Although much of the infrastructure is in place, there may be instances in which necessary access to high-speed networks does not exist and must be installed. It is more likely to be the case that the appropriate knowledge of and experience with data management techniques, database development and maintenance, and related topics will need to be obtained. This is particularly true for smaller agencies that will be least likely to afford an additional person on staff or the contract expense needed to provide these services.

Pooling resources at the regional level may be one approach to addressing these resource requirements.

7.1.6 Assess and Improve Emission Projections

Findings: **Emission projections are critical to developing control strategies for attaining air-quality standards and goals and evaluating future year impacts associated with national rulemakings.**

Currently recommended approaches have only had limited evaluation and may not be applicable to the range of emitted compounds being recommended for inclusion in inventories.

Recommendation: **Emission projection methodologies for all emission inventory sectors should be reviewed for North America.**

A retrospective analysis of practical growth estimation techniques should be undertaken. Non-proprietary models or approaches for estimating emissions changes should be developed for all emission sectors.

Discussion

A baseline emission inventory is important because it describes emissions for a given timeframe. However, because emissions are not static over time, baseline emissions will not accurately represent emissions for a future year. Emission projections account for the effects of future growth and emission controls. The U.S. EPA has developed the Economic Growth Analysis System (EGAS) to support emission activity level forecasting. The latest version of EGAS (4.0) provides default emission activity growth factors for the period 1996-2020 for nearly 10,000 source classification codes for each county in the continental United States. It is important to note that the growth factors in EGAS are defaults and that forecasters should rely on more specific information whenever it is available. However, other growth estimation techniques exist and a thorough intercomparison would shed light on the accuracy and uncertainties associated with these techniques. (Some intercomparisons have taken place and are underway; these should be broadened to more areas and source categories.)

The Integrated Planning Model (IPM) is a proprietary model that is relied upon for preparing electric generating unit emission projections in the contiguous United States. A public domain approach would better serve the needs of the users of these emissions projections.

7.1.7 Quantify and Report Uncertainty

Finding: **The emission inventories, processors and models of Canada, the United States, and Mexico are poorly documented for uncertainties; as a result, the reliability of the emission estimates is questionable.**

Quantifying uncertainties results in a clearer understanding of the reliability of information and more robust policy decisions.

Recommendation: **Develop guidance, measures, and techniques to improve ways to quantify and report uncertainty.**

High priority attention should be given to improving ways to quantify and report uncertainty in emission estimates. The most effective inventories are those that provide the appropriate levels of accuracy and temporal, spatial, and compositional resolution needed to address the issue at hand. In order to most fully understand the "appropriate" levels of accuracy, resolution and completeness needed for an inventory, methods to quantify uncertainty and evaluate accuracy must be applied where possible and developed where needed. Guidance on applying these methods is needed by inventory developers at all levels, including means by which uncertainties propagate from emission and activity measurements through to final inventories.

Discussion

Clear and quantitative measures of uncertainty provide guidance to policy makers regarding the subsequent uncertainties associated with different policy decisions. As the reliability of emission inventories increases, the difference between predicted and actual impacts of decisions based on inventory data will decrease, which will lead to a greater capability to formulate effective air-quality management strategies.

It is necessary to provide clear and comprehensive guidance about the tools required and the processes that inventory developers need to follow in order to incorporate uncertainty measurements into inventories. Such guidance would provide information on definitions, uncertainty measurements, and interpretation of results. This would aid both inventory developers and users to better understand the broader topic of uncertainty as well as the details of how it is put into practice. In addition, such guidance would help to minimize confusion about terms, methods, and results, allowing a more informed and accurate comparison of uncertainty across different inventories.

The most effective means of collecting and developing uncertainty measures in a systematic manner is to incorporate uncertainty analysis into the routine steps of developing data for an inventory. Quantifying variability, documenting data sources, and comparing results with other, independent measurements can, and should, be done as emission or activity measurements are taken. The results of uncertainty analyses should be made available concurrently with the primary measurement results.

Equally important and complementary is conducting retroactive evaluation of the resultant inventories. In Chapter 5, several methods of quantifying uncertainty in a "top-down" manner were presented and can be practically applied in many cases. Crucial to many of these methods are independent tests of emission estimates, many of which involve comparing ambient data to emission estimates.

Many new options are being developed to test or evaluate emission inventories involve innovative applications of emerging measurements and techniques (e.g., those described in Chapter 6). Where resources are available and uncertainties in emissions are significant, every effort should be made to use these techniques to improve emission estimates that have a significant bearing on investments in emission controls.

7.2 IMPLEMENTING THE RECOMMENDATIONS

It is increasingly clear that the effects of degraded air quality are no longer restricted to areas in or near major cities; in fact, a systematic increase in background pollutants owing to intercontinental transport is increasingly evident. Successful air-quality management will therefore increasingly require understanding of cross-border emissions. In the context of North America, clearly and accurately tabulated emissions from Canada, the United States, and Mexico are critical to ensuring the achievement of air-quality management goals. Some weaknesses in the inventories of the three countries can inhibit the ability of each to devise strategies that can be implemented locally or regionally to achieve air-quality goals. Similarly, gaps in state-level inventories can result in ineffective air quality management strategies in downwind states.

Investments across borders are therefore crucial, and in some cases may be more critical than investments locally. Pollutant formation and transport does not respect political borders; resources must likewise be allocated to address the most critical inventory needs if we are to have the most accurate information upon which to base air-quality management decisions. Clearly, successful air-quality management strategies cannot be developed in isolation. Weaknesses in inventories at any level or in any country therefore lead to greater uncertainties and less robust decision-making for all involved, highlighting the need for cooperation and mutual support.

Resource support for inventory development and refinement is crucial to improving the accuracy of emission inventories and must be continued. Continued support from the United States to Mexico's inventory improvement efforts remains a key need. Likewise, U.S. federal support to states, tribes, and regional planning organizations must continue for national inventories to even keep pace with growing data needs. Similarly, Canadian national support to the development of provincial and regional inventory efforts is crucial and must continue.

Successful cooperation will recognize that the priorities will differ among the three countries, and among the states, provinces, and regions within the countries. Continued, and even strengthened, organizational interaction is just as crucial, if not more so, to the development of accurate and mutually beneficial inventories as continued financial support. In all cases, interactions across governmental boundaries must be continued and enhanced wherever possible.

While it is beyond the scope of this document to lay out a detailed program plan for accomplishing the recommendations in this Chapter, NARSTO believes that substantial improvements need to be made in the next 10 years. Interim milestones should be established to support regulatory deadlines in all three countries and appropriate jurisdictions. Over the past 20 years various assessment and regulatory drivers have spiked commitments to improving emissions inventories and inventory related activities. These activities, such as the 1985 NAPAP Emission Inventory, implementation of the requirements of the 1990 Clean Air Act Amendments, the collection of hourly emission data using CEMS, the collection of air toxics data by Canada, and the development of a national emission inventory for Mexico, have all required the commitment of resources by many stakeholders and resulted in significant advances in emission inventories. Similarly, the significant increase in resources to the ambient monitoring program for $PM_{2.5}$ since 1997 resulted in significant improvement in the quality and availability of ambient data. NARSTO believes that attaining the accuracy, timeliness, and usefulness of emission inventories described in the recommendations above will require a substantial increase in funding over current levels. This should not be construed to mean the current emission inventories are inadequate to support current regulatory activities; rather, it is the recognition that emission inventory programs need to be significantly enhanced in order to meet the expectations in the future. A more precise estimate of the required increase would require an assessment of current investments in the development of inventory data at the local, state/provincial, regional, and national levels, and a comparison of the current investment with the above recommendations. It is likely that increases that range from double to an order of magnitude of current investments will be required to achieve emission inventories that are robust and accurate. As shown by the experience in Texas, when there is great uncertainty about emissions that affect major decisions about emission control, cooperative efforts by government, affected industry, and academia to improve emission inventories are costly but can improve the scientific basis for air quality controls and increase the expected effectiveness of those controls.

7.3 CONCLUSIONS

Emission inventories are the often unnoticed first step in developing or, in some cases, identifying, air-quality management strategies. Indeed, as noted above emission inventories are the foundation upon which these strategies are built. Enormous progress has been made over the past three decades in improving air quality across North America, due to the application of good scientific and technical information by air-quality managers. To continue this progress and achieve the quality of environment the people of North America expect, allocation of adequate attention and resources to the state of the foundation – emission inventories – is critical. This Assessment has set forth an ambitious vision and made clear recommendations as the first step toward ensuring that the progress of the past is maintained and that future progress can be effectively achieved.

References for Chapter 7

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APPENDIX A. LISTS OF AGENCIES AND CONTACTS

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
Alabama	Alabama Department of Environmental Management, Air Quality Division	http://www.adem.state.al.us/AirDivision/AirDivisionPP.htm	Huntsville Jefferson County	http://ci.huntsville.al.us/NatRes/, http://www.jcdh.org/
Alaska	Alaska Department of Environmental Conservation, Division of Air and Water Quality	http://www.state.ak.us/local/akpages/ENV.CONSERV/dawq/dec_dawq.htm/	Anchorage, Fairbanks North Star Borough	http://www.ci.anchorage.ak.us/healthesd/air.cfm http://www.co.fairbanks.ak.us/transportation
Arizona	Arizona Department of Environmental Quality, Air Quality Division	http://www.adeq.state.az.us/environ/air/index.html	Maricopa County Pima County Pinal County	http://www.maricopa.gov/envsvc/Airqual.asp http://www.deq.co.pima.az.us/air http://co.pinal.az.us/AirQual/
Arkansas	Arkansas Department of Environmental Quality, Air Division	http://www.adeq.state.ar.us/air/default.htm	No Local Agencies	No Local Agencies
California	California Air Resources Board	http://www.arb.ca.gov/homepage.htm	Amador County Antelope Valley Bay Area Butte County Calaveras County Colusa County El Dorado County Feather River Glenn County Great Basin Imperial County Kern County, Lake County Lassen County Mariposa County Mendocino County	http://www.amadorapcd.org, http://www.avaqmd.ca.gov http://www.baaqmd.gov http://www.dcn.davis.ca.us/go/bluesky/ http://www.co.calaveras.ca.us/departments/env.html http://www.dcn.davis.ca.us/go/bluesky http://co.el-dorado.ca.us/emd/apcd/index.html http://home.jps.net/fraqmd/ http://www.dcn.davis.ca.us/~bluesky, http://www.co.kern.ca.us/eh/ehs.htm http://www.co.mendocino.ca.us/aqmd http://www.mdaqmd.ca.gov

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
			Modoc County Mojave Desert Monterey Bay North Coast Northern Sierra Northern Sonoma County Placer County Sacramento San Diego County San Joaquin Valley San Luis Obispo County Santa Barbara County Shasta County Siskiyou County South Coast Tehama County Tuolumne County Ventura County Yolo-Solano	http://www.mbuapcd.org http://www.northcoast.com/~ncuaqmd http://www.nccn.net/~nsaqmd http://www.placer.ca.gov/airpollution/airpolut.htm http://www.airquality.org http://www.sdapcd.co.san-diego.ca.us http://www.valleyair.org http://www.slocleanair.org http://www.sbcapcd.org http://www.co.shasta.ca.us/Departments/Resourcemgmt/drm/aqmain.htm#top, http://www.aqmd.gov http://www.vcapcd.org http://www.ysaqmd.org
Colorado	Colorado Department of Health, Air Pollution Control Division	http://www.cdphe.state.co.us/ap/aphom.asp	Boulder County Boulder Fort Collins Denver Denver Regional Air Quality Council El Paso Jefferson County Larimer County Mesa County Pueblo, Tri-County Weld County	http://www.ci.boulder.co.us/environmentalaffairs/air_quality/aq_clear_air.html, http://www.denvergov.org/Environmental_Protection http://www.raqc.org http://www.co.el-paso.co.us/health http://206.247.49.21/ext/dpt/health/ehs/environm.htm http://www.co.larimer.co.us/depts/health/ehs/air1.htm http://www.co.mesa.co.us/health

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO				
State	State Agency	State Agency URL	Local Agency	Local Agency URL
				http://www.tchd.org/environmental.html http://www.co.weld.co.us/departments/enviropublichealth.html
Connecticut	Connecticut Department of Environmental Protection, Bureau of Air Management	http://dep.state.ct.us/air2/prgacti.htm	Bridgeport Bristol-Burlington Greenwich Milford New Haven Stamford Stratford	http://ci.bridgeport.ct.us/departments/health/environmental_health.aspx, http://www.ci.bristol.ct.us/BBHealth/BBHmain.htm http://www.greenwichct.org/services/Health%20department.htm http://www.ci.milford.ct.us/health.html http://www.cityofnewhaven.com/govt/gov21.htm#4 http://www.cityofstamford.org/HealthDepartmentEnvironmentalHealth/main.htm http://www.townofstratford.com/depts/health.htm
Delaware	Delaware Department of Natural Resources and Environmental Control, Division of Air & Waste Management	http://www.dnrec.state.de.us/air/aqm_page/aqm_nets.htm	No Local Agencies	No Local Agencies
District of Columbia	Department of Health, Environmental Health Administration, Air Quality Division	http://dchealth.dc.gov/services/administration_offices/environmental/services2/air_quality/index.shtm	No Local Agencies	No Local Agencies
Florida	Florida Department of Environmental Protection, Division of Air Resource Management	http://www.dep.state.fl.us/air/	Broward County Dade County Hillsborough County Jacksonville	http://www.co.broward.fl.us/air.htm http://www.miamidade.gov/derm/air/home.asphtp://www.epchc.org/air.htm http://www.coj.net

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
			Manatee County Orange County Palm Beach County Pinellas County Polk County Reedy Creek Improvement District Sarasota County	http://www.co.manatee.fl.us http://www.orangecountyfl.net/dept/CEsrvcs/epd http://www.doh.state.fl.us/chdpalmbeach/env/airqual/airquality.html http://www.co.pinellas.fl.us/BCC/Environ/default.htm#Air%20Quality http://www.polk-county.net/Environment_Services/Natresources/index.htm http://www.state.fl.us/rcid Sarasota County
Georgia	Georgia Department of Natural Resources, Environmental Protection Division, Air Protection Branch	http://www.dnr.state.ga.us/dnr/environ	No Local Agencies	No Local Agencies
Hawaii	Hawaii Department of Health, Clean Air Branch	http://www.state.hi.us/health/eh/cab	No Local Agencies	No Local Agencies
Idaho	Idaho Division of Environmental Quality, Air Quality Program	http://www2.state.id.us/deq/air/air1.htm	No Local Agencies	No Local Agencies
Illinois	Illinois Environmental Protection Agency, Bureau of Air	http://www.epa.state.il.us/air	Bedford Park Chicago Cook County East St. Louis McCook	http://www.ci.chi.il.us/Environment/AirToxPollution/ http://co.cook.il.us/agencyDetail.php?pAgencyID=7
Indiana	Indiana Department of Environmental Management, Office of Air Quality	http://www.in.gov/idem/air	Anderson Evansville Gary Hammond	http://www.ci.hammond.in.us.environmental/index.htm http://www.indy-enviro.org/air.htm

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
			Indianapolis Lake County St. Joseph County Vigo County	http://www.vigocountyin.com/air.htm
Iowa	Iowa Department of Natural Resources, Air Quality Bureau	http://www.iowacleanair.com	Polk County Linn County	http://www.airquality.co.polk.ia.us http://www.air.linn.ia.us
Kansas	Kansas Department of Health and Environment, Bureau of Air and Radiation	http://www.kdhe.state.ks.us/bar	Johnson County Shawnee County Wichita Wyandotte County	http://www.sharetheair.com http://www.wichitaenvironment/air_quality.asp http://www.toto.net/daq/
Kentucky	Kentucky Department for Environmental Protection, Division for Air Quality	http://www.air.ky.gov	Louisville Metro	http://www.apcd.org
Louisiana	Louisiana Department of Environmental Quality, Office of Environmental Services	http://www.deq.state.la.us	No Local Agencies	No Local Agencies
Maine	Maine Department of Environmental Protection, Bureau of Air Quality	http://www.state.me.us/dep/air/homepage.htm	No Local Agencies	No Local Agencies
Maryland	Maryland Department of the Environment, Air and Radiation Management Administration	http://www.mde.state.md.us/arma	Allegany County Anne Arundel County Baltimore Baltimore County Carroll County Frederick County Garrett County Harford County Montgomery County	http://www.hereintown.net/~dressman/achd/environmental.html http://www.dhmh.state.md.us/ http://www.co.ba.md.us/p.cfm/agencies/deprm/index.cfm http://frederickhealth.org/environment/community.htm http://www.garretthealth.org

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO				
State	State Agency	State Agency URL	Local Agency	Local Agency URL
			Prince George's County Washington County	http://www.co.ha.md.us/health/ER/solidwaste.htm http://www.co.mo.md.us/services/dep/AQ/home.html http://www.goprincegeorges.com/Government/AgencyIndex/Health/environmental.asp?h=20&s=&n=20, http://www.washhealth.org/html/ehair.htm
Massachusetts	Department of Environmental Protection, Bureau of Waste Prevention	http://www.state.ma.us/dep/bwp/planeva.htm#air	Boston Fitchburg	http://www.ci.boston.ma.us/environment/pollution.asp, http://www.ci.fitchburg.ma.us
Michigan	Department of Environmental Quality, Air Quality Division	http://www.michigan.gov/deq	Grand Rapids Macomb County	http://www.grand-rapids.mi.us/departments/epsd/default.asp
Minnesota	Minnesota Pollution Control Agency, Policy and Planning Division, Major Facilities, Air Quality Section	http://www.pca.state.mn.us/air/index.html	Bloomington Minneapolis Richfield St. Louis Park	http://www.ci.bloomington.mn.us/cityhall/dept/commdev/envserv/envserv.htm/ , http://www.ci.minneapolis.mn.us/citywork/city-coordinator/environment/air.html, http://www.ci.richfield.mn.us/officials/commissions/advisoryboardofhealth.html , http://www.stlouispark.org/index.html
Mississippi	Mississippi Department of Environmental Quality, Office of Pollution Control, Air Division	http://www.deq.state.ms.us/newweb/opchome.nsf/pages/air	No Local Agencies	No Local Agencies
Missouri	Missouri Department of Natural Resources, Division of	http://www.dnr.state.mo.us/deq/apcp/homeapcp.htm	Independence Kansas City Springfield	http://www.indepmo.org/ http://www.kcmo.org/health.nsf/web/environ?opendocument

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
	Environmental Quality, Air Pollution Control Program		St. Louis St. Louis County	http://springfield.missouri.org/gov/health/air_qual.htm http://stlouis.missouri.org/citygov/airpollution/, http://www.stlouisco.com/doh/environ/airpolut.html#airpollut
Montana	Montana Department of Environmental Quality, Air and Waste Management Bureau	http://www.deq.state.mt.us/pcd/awm/index.asp	Cascade County Missoula Yellowstone County	http://www.co.missoula.mt.us/ http://ci.billings.mt.us/government/boards/pollution.htm
Nebraska	Nebraska Department of Environmental Quality, Air Quality Division	http://www.deq.state.ne.us/AirDivis.nsf/Pages/Air/	Lincoln Omaha	http://www.ci.lincoln.ne.us/city/health/environ/pollu/index.htm http://www.ci.omaha.ne.us/
Nevada	Nevada Division of Environmental Protection, Bureau of Air Quality	http://www.ndep.state.nv.us/bapc/index.htm	Clark County Washoe County	http://www.co.clark.nv.us/air_quality, http://www.co.washoe.nv.us/Health
New Hampshire	New Hampshire Department of Environmental Services, Air Resources Division	http://www.des.state.nh.us/ard_intro.htm	No Local Agencies	No Local Agencies
New Jersey	New Jersey Department of Environmental Protection, Division of Air Quality, Air Quality Management	http://www.state.nj.us/dep/aqm/	Essex Elizabeth Hudson Middlesex County	http://www.essexregional.org http://www.elizabethnj.org/cityroster/deporg/departmenthealth.htm
New Mexico	New Mexico Environment Department, Air Quality Bureau	http://www.nmenv.state.nm.us/aqb	Albuquerque	http://www.cabq.gov/airquality/index.html
New York	New York Department of Environmental	http://www.dec.state.ny.us/we	Albany County Erie County	http://www.albanycounty.com/departments/health/programs/home.htm#Environmental,

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
	Conservation, Division of Air Resources	bsite/dar/index.html	Interstate Sanitation Commission Nassau County New York Niagara County Onondaga County Rockland County Suffolk County Westchester County	http://www.erie.gov/environment/compliance/compprog.phtml, http://www.ci.nyc.ny.us/html/dep/home.html http://www.healthyniagara.com/environmental/index.htm http://www.ongov.net/other http://www.co.rockland.ny.us/health/envmiss.htm#BureauofAirPollutionControl, http://www.co.suffolk.ny.us/health/eq http://www.co.westchester.ny.us/health/environ%20health.html
North Carolina	North Carolina Department of Environment and Natural Resources, Division of Air Quality	http://daq.state.nc.us	Cleveland County Cumberland County Forsyth County Guilford County Mecklenburg County Western Counties	http://publichealth.sr_ahec.org/cumberland http://www.co.forsyth.nc.us/envaffairs/ http://www.co.guilford.nc.us/governent/publichealth/envhealth/hhhome.html http://www.co.mecklenburg.nc.us/coenv/air/aqhmpg.htm http://www.wncair.org/
North Dakota	North Dakota Department of Health, Division of Air Quality	http://www.health.state.nd.us/ndhd/environ/ee	No Local Agencies	No Local Agencies
Ohio	Ohio Environmental Protection Agency, Division of Air Pollution Control	http://www.epa.state.oh.us	Akron Canton Cincinnati Cleveland Dayton (RAPCA) Hamilton County Lake County Mahoning-Trumbull	http://156.63.18.80/ http://www.cantonhealth.org/serv03.htm, http://www.rcc.org/oem/aq.html rogers@city.cleveland.oh.us http://rapca.org http://www.hcdoes.org/airqmd.htm, http://www.lcghd.org/eh/apc.htm

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
			Portsmouth Toledo	http://www.ychd.com/airpollution.html
Oklahoma	Oklahoma Department of Environmental Quality, Air Quality Division	http://www.deq.state.ok.us/air1/air.html	No Local Agencies	No Local Agencies
Oregon	Oregon Department of Environmental Quality, Air Quality Division	http://www.deq.state.or.us/aq/index.htm	Lane County	http://www.lrapa.org/
Pennsylvania	Pennsylvania Department of Environmental Protection, Bureau of Air Quality	http://www.dep.state.pa.us/dep/deputate/airwaste/aq/default.htm	Allegheny County, Philadelphia	http://www.achd.net, http://www.phila.gov/health/units/ams/index.html
Rhode Island	Rhode Island Department of Environmental Management, Office of Air Resources	http://www.state.ri.us/dem/programs/benviron/air/index.htm	No Local Agencies	No Local Agencies
South Carolina	South Carolina Department of Health and Environmental Control, Bureau of Air Quality	http://www.scdhec.gov/baq	No Local Agencies	No Local Agencies
South Dakota	South Dakota Department of Environment and Natural Resources, Air Quality Program	http://www.state.sd.us/denr/DES/AirQuality/airprogr.htm	No Local Agencies	No Local Agencies
Tennessee	Tennessee Department of Environment and Conservation, Division of Air Pollution Control	http://www.state.tn.us/environment/apc/index.html	Chattanooga Knox County Memphis Nashville	http://www.apcb.org/ http://aqm.co.knox.tn.us, http://www.co.shelby.tn.us/county_gov/divisions/health_serv/environ_health/index.htm/, http://healthweb.nashville.org/env/env_air_pollu

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
				tion.html
Texas	Texas Commission on Environmental Quality, Policy and Regulations Division	http://www.tnrcc.state.tx.us	Austin Dallas El Paso Fort Worth Galveston County Harris County Houston Lubbock San Antonio	http://www.ci.austin.tx.us/airquality http://www.dallasair.org http://www.ci.el-paso.tx.us/city_resources/health/index.htm http://www.fortworthgov.org/dem/airpg.htm http://www.gchd.org/pages/pollution_ctl/index.htm http://www.hd.co.harris.tx.us/pcd/pcd.htm http://www.ci.houston.tx.us/departme/health/airqualitypage.html http://healthdept.ci.lubbock.tx.us http://www.ci.sat.tx.us/pubwrks/envsvcs/air_quality_home_page.htm
Utah	Utah Department of Environmental Quality, Division of Air Quality	http://www.eq.state.ut.us/eqair/aq_home.htm	Salt Lake City	http://www.slvhealth.org/html/airpol.html
Vermont	Vermont Department of Environmental Quality, Air Pollution Control Division	http://www.anr.state.vt.us/dec/air/	No Local Agencies	No Local Agencies
Virginia	Virginia Department of Environmental Quality, Air Quality Division	http://www.deq.state.va.us/air/	Alexandria Arlington County Fairfax County Roanoke	http://ci.alexandria.va.us/city/health/environmental_health.html, http://www.co.arlington.va.us/des, http://www.co.fairfax.va.us/gov/dpwes/environmental/air.htm, http://www.ci.roanoke.va.us/engineer/index.html

Table A.1. U.S. State and Local Agencies from STAPPA/ALAPCO

State	State Agency	State Agency URL	Local Agency	Local Agency URL
Washington	Washington Department of Ecology, Air Quality Program	http://www.ecy.wa.gov/programs/air/airhome.html	Benton County Northwest Counties Olympic Region Puget Sound (Seattle), Southwest Counties Spokane County Yakima County	http://www.bcaa.net, http://www.nwair.org, http://www.orcaa.org, http://www.pscleanair.org, http://www.swcleanair.org, http://www.scapca.org/, http://co.yakima.wa.us/cleanair/default.htm
West Virginia	West Virginia Department of Environmental Protection, Division of Air Quality	http://www.dep.state.wv.us/daq/index.html	No Local Agencies	No Local Agencies
Wisconsin	Wisconsin Department of Natural Resources, Bureau of Air Management	http://www.dnr.state.wi.us/org/aw/air/index.htm	Eau Claire, Madison Milwaukee County	http://www.ci.eau-laire.wi.us/Departments/home.html, http://www.ci.madison.wi.us/health/envhlth.htm, No URL listed
Wyoming	Wyoming Department of Environmental Quality, Air Quality Division	http://deq.state.wy.us/aqd.htm	No Local Agencies	No Local Agencies

Table A.2. Contacts for Obtaining Local and Regional Mexican Emission Inventories

State	Institution	Name	E-mail	Web-site	Address
Aguascalientes	Subsecretaria de Ecologia	Marco Antonio Acero Varela	subecoags@infosel.com	http://www.aguascalientes.gob.mx/	Colonia 110, Zona Centro
Baja California	Direccion de Ecologia	Enrique Villegas Ibarra	evillegas@baja.gob.mx	http://www.bajacalifornia.gob.mx/ecologia/entrada.htm	Mexicali Bulevar Benito Juarez esq. Fco. I. Montejano no.1 Col. Cantu 21230
Baja California Sur	Secretario de Planeación Urbana, Infraestructura y Ecología	Ing. Guillermo Jáuregui Moreno	sepui@latinmail.com	http://www.gbcs.gob.mx/	I. La Católica e/ Allende y Bravo, Palacio de Gobierno
Campeche	Secretaria de Ecologia	Dr. Manuel Angulo Romero	ecologia@campeche.gob.mx	http://www.campeche.gob.mx/Gobierno/Secretarias/ecologia.htm	Plaza Comercial Ah-Kim-Pech Local 517 Col. Centro C.P. 24000
Chiapas	Instituto de historia Natural y Ecologia	Ing. Pablo Enrique Muench Navarro	ihne@chiapas.gob.mx	http://www.chiapas.gob.mx/funcionarios/estatal.asp?Id=e06162203200207	Calzada a Cierro Hueco S/N Col. El Zapotal AP No. 6, Tuxtla Gutierrez
Chihuahua	Secretaria de Desarrollo Urbano y Ecologia	Roberto Cano Hermosillo	not available	http://www.chihuahua.gob.mx/default.asp	Libertad y 13. No. 5 Col. Centro C.P. 31000
Coahuila	Instituto Coahuilense de Ecolog[ia	Ing. Sergio Avilés Garza	sergio.aviles@ecoah.org	http://servidor.seplade-coahuila.gob.mx/portal/page?_pageid=34,68247,34_73288&_dad=portal&_schema=PORTAL	Victoria # 608 1er piso, Col. Centro, Saltillo Coahuila, C.P. 25000
Colima	Direccion de Ecologia	Gustavo Mérida Ramírez	not available	not available	not available

Table A.2. Contacts for Obtaining Local and Regional Mexican Emission Inventories

State	Institution	Name	E-mail	Web-site	Address
Distrito Federal	Secretaria de Medio Ambiente	Claudia Sheinbaum Pardo	sheinbaum@dgpa.df.gob.mx	www.sma.df.gob.mx	Plaza de la Constitución no. 1 y Pino Suárez, 3er piso, Centro Histórico, Del. Cuauhtémoc, C.P. 06068
Durango	Secretaria de Recursos Naturales	Ing. Francisco Javier Salas García	secretariaderecursosnaturales@durango.gob.mx	http://www.durango.gob.mx/depe/ver.asp?id=10	Blvd. Armando del Castillo Franco # 99A
Estado de México	Secretaría de Ecología	Arlette López Trujillo	gemse@edomex.gob.mx	http://www.edomexico.gob.mx/portalgem/se/	Conjunto Sedagro Lado Sur si número, Rancho San Lorenzo, Metepec 52140
Guanajuato	Insituto de Ecología	Dr. Roberto A. Contreras Zárate	institut@guanajuato.gob.mx	http://www.guanajuato.gob.mx/index.html	Calle Aldana S/N Esq. Subida al Panteón Nuevo, Col. Pueblito de Rocha Guanajuato
Guerrero	not available	not available	not available	not available	not available
Hidalgo	Consejo Estatal de Ecología	Lic. Adrána Durán García	aduran@prodigy.net.mx	http://www.hidalgo.gob.mx/gobierno/entidades/entidad.asp?entidadID=8	José Ma. Iglesias # 100 Col. Centro C.P. 42000, Pachuca de Soto, Hidalgo
Jalisco	Secretaría del Medio Ambiente para el Desarrollo Sustentable	Ing. Ramón Humberto Gonáles Núñez	not available	http://semades.jalisco.gob.mx/site/index.htm	Av. Cubilete # 2955 Jardines del Sol, C.P. 45050
Michoacán	Secretaría de Urbanismo y Medio Ambiente	Guillermo Vargas Uribe	suma@michoacan.gob.mx	http://www.michoacan.gob.mx/gobierno/dependencia/suma.htm	Escarcha no. 272 Fraccionamiento Prados del Campestre
Morelos	Comisión Estatal del Agua y Medio Ambiente	Ing. Edmundo Javier Bolaños Aguilar	ceama@morelos.gob.mx	http://www.edomorelos.gob.mx/e-gobierno/DirCEAMA/	Palacio de Gobierno 2º piso Jardín Juárez Col. Centro C.P. 62000 Cuernavaca Morelos

Table A.2. Contacts for Obtaining Local and Regional Mexican Emission Inventories

State	Institution	Name	E-mail	Web-site	Address
Nayarit	not available	not available	not available	not available	not available
Nuevo Leon	Agencia de Protección al Medio Ambiente y Recursos Naturales	Emilio Rangel Woodyear	emilio.rangel@mail.nl.gob.mx	http://gobierno.nl.gob.mx/EstructuraOrganica/SectorParaestatal/Organigramas/AgenciaProteccion	Alfonso Reyes 1000, Col. Regina Interior Parque Niños Héroes
Oaxaca	Instituto Estatal de Ecología	Ing. Jose Luis Bustamante del Valle	ecologiaoax@prodigy.net.mx	http://www.oaxaca.gob.mx/ecologia/	LIBRES # 511-A CENTRO OAXACA, OAX. C.P. 68000
Puebla	Secretaría de Desarrollo Urbano, Eología y Obras Públicas	Lic. Carlos Palafox Vázquez	subecol@yahoo.com	http://www.sedurbecop.pue.gob.mx/	not available
Queretaro	Secretaría de Desarrollo Sustentable	RENATO LÓPEZ OTAMENDI	sedesu@queretaro.gob.mx	http://www.queretaro.gob.mx/sedesu/	Av. Blvd. Bernardo Quintana # 204 Col. Carretas
Quintana Roo	Secretaría de Desarrollo Urbano y Medio Ambiente	Ing. Jorge Mariano Morales Calzada	simapqro@prodigy.net.mx	http://www.quintanaroo.gob.mx/nuestrogobierno/flash/ng1.htm	Carretera Chetumal-Bacalar km 2.5 Col. Viveros los Mangos, C.P. 77040, Chetumal, Q. Roo
San Luis Potosí	Secretaría de Ecología y Gestión Ambiental	Ing. Rodolfo Arturo Treviño Hernández	segam_rtrevino@slp.gob.mx	http://www.segam.gob.mx/	Cuauhtemoc #1205, Col. Capitán Caldera C.P. 78250, San Luis Potosí, S.L.P.
Sinaloa	Subsecretaria de Desarrollo Urbano y Ecología	Gabriel Yánez Pérez	gabriel_yaez@yahoo.com.mx	http://laip.sinaloa.gob.mx/LAIP/Secretaria/SPD/	Ave. Insurgentes s/n, Col. Centro Sinaloa

Table A.2. Contacts for Obtaining Local and Regional Mexican Emission Inventories

State	Institution	Name	E-mail	Web-site	Address
Sonora	Secretaría de Infraestructura Urbana y Ecología	Faustino Félix Bustamante	siue@hmo.megared.net.mx	http://www.siue.gob.mx/	Blvd. Hidalgo y Comonfort No. 35, 3er. Piso Col. Centenario C.P. 83260 Hermosillo, Sonora.
Tabasco	Secretaría de Desarrollo Social y Protección del Medio Ambiente	Graciela Trujillo de Cobo	secretario@sedespa.gob.mx	http://www.sedespa.gob.mx/	Paseo de la Sierra No. 425 Col. Reforma, C.P. 86080, Villahermosa
Tamaulipas	Secretaría de Desarrollo Urbano y Ecología	ING. JUAN MIGUEL GARCIA GARCIA	sdu@tamaulipas.gob.mx	http://www.tamaulipas.gob.mx/sedue/default.asp	*Carretera a Soto la Marina KM. 5.6, Cd. Victoria, Tamaulipas, C.P. 87000*
Tlaxcala	Coordinación General de Ecolog[ia	Biol. Roberto Acosta Pérez	ecologia_titular@tlaxcala.com.mx, ecologia@tlaxcala.com.mx	not available	Jardín Botánico S/N Tizatlán, Tlaxcala
Veracruz	Coordinación Estatal de Medio Ambiente	Biol. Celso Hernández Aponte	medioambiente@sdmaver.gob.mx	not available	Fco. I. Madero, Esq. Juárez Planta Alta, Xalapa, Ver.
Yucatán	Secretario de Ecología	Luis Jorge Morales Arjona	luis.morales@yucatan.gob.mx	http://www.yucatan.gob.mx/index.htm	Calle 64 No. 437 entre 53 y 47-A Col. Centro C.P. 97000, Mérida, Yucatán
Zacatecas	Instituto de Medio Ambiente del Estado de Zacatecas	Dra. Virginia Bañuelos Quezada	vikybg@mail.com.mx	http://www.zacatecas.gob.mx/	Blvd. López Portillo #30 2do piso Col. La Florida Guadalupe, Zac

Table A.3. Contacts for Obtaining Local and Regional Canadian Emission Inventories

Province (P)/ Territory (T)	Department	Name	E-mail	Web-site	Address
Newfoundland (P)	Department of Environment & Conservation	Jeff Fillier	JFillier@mail.gov.nf.ca	http://www.gov.nf.ca/env/	Jeff Fillier Nfld. Dept. of Environment 4th Floor, West Block Confederation Building P.O. Box 8700 St. John's, NF A1B 4J6
Prince Edward Island (P)	Department of Fisheries, Aquaculture and Environment	Todd Fraser	ktfraser@gov.pe.ca	http://www.gov.pe.ca/af/agweb/index.php3	K. T. Fraser PEI Dept. of Fisheries, Aquaculture and Environment Jones Building, 11 Kent Street P.O. Box 2000 Charlottetown, PEI C1A 7N8
Nova Scotia (P)	Department of the Environment and Labour	Barbara Bryden	brydenba@gov.ns.ca	http://www.gov.ns.ca/enla/	Barb Bryden Resource Management and Environmental Protection Nova Scotia Department of Environment & Labour. P.O. Box 2107 Halifax, NS B3J 3B7
New Brunswick (P)	Department of Environment and Local Government	Sean Fortune	sean.fortune@gnb.ca	http://www.gnb.ca/0009/index.htm	Sean Fortune Acid Rain Program Specialist New Brunswick Department of the Environment 364 Argyle Street P.O. Box 6000 Fredericton, New Brunswick E3B 5H1
Quebec (P)	Environnement Québec	Gérard Houle	gerard.houle@menv.gouv.qc.ca	http://www.menv.gouv.qc.ca/accueil/plan.htm	Gérard Houle, ing, Ministère de l'Environnement 675 Boul. René-Lévesque est, 9ième étage Boite 71 Quebéc City, Québec G1R 5V7

Table A.3. Contacts for Obtaining Local and Regional Canadian Emission Inventories

Province (P)/ Territory (T)	Department	Name	E-mail	Web-site	Address
Ontario (P)	Ministry of the Environment	Peter Wong	wongpe@ene.gov.on.ca	http://www.ene.gov.on.ca/environet/onair/splash.htm	Peter Wong Ontario Ministry of Environment 125 Resources Road, East Wing Etobicoke, Ontario M9P 3V6
Manitoba (P)	Manitoba Conservation	Jean Van Dusen	jvandusen@gov.mb.ca	http://www.gov.mb.ca/conservation/index.html	Jean Van Dusen Manitoba Conservation 123 Main Street, Suite 160 Winnipeg MB R3C 1A5
Saskatchewan (P)	Saskatchewan Environment	Chris Gray	cgray@serm.gov.sk.ca	http://www.se.gov.sk.ca/	Chris Gray Environmental Protection Branch Saskatchewan Environment and Resource Management Rm 224, 3211 Albert St. Regina, Saskatchewan S4S 5W6
Alberta (P)	Alberta Environment	David Slubik	dave.slubik@gov.ab.ca	http://www3.gov.ab.ca/env/air/EMR/index.html	Dave Slubik Alberta Environment 9820-106 Street Edmonton, Alberta T5K 2J6
British Columbia (P)	B.C. Ministry of Water, Land and Air Protection	Tony Wakelin	Tony.Wakelin@gems5.gov.bc.ca	http://wlapwww.gov.bc.ca/air/industrial/index.html	Tony Wakelin B.C. Ministry of Environment, Lands & Parks Air Resources Branch P.O. Box 9341, Stn. Prov. Govt. Victoria, B.C., V8W 9M1
British Columbia (GVRD) (Local Government)	Greater Vancouver Regional District	Kelly Der	kelly.der@gvrd.bc.ca	http://www.gvrd.bc.ca/air/emissions.htm	Kelly Der Greater Vancouver Regional District Air Quality Department 4330 Kingsway Burnaby, British Columbia V5H 4G8

Table A.3. Contacts for Obtaining Local and Regional Canadian Emission Inventories

Province (P)/ Territory (T)	Department	Name	E-mail	Web-site	Address
Yukon Territory (T)	Department of Environment	Pat Paslawski	pat.paslawski@gov.yk.ca	http://www.environmentyukon.gov.yk.ca/main/index.shtml	Pat Paslawski A/Manager, Standards and Approvals Environmental Protection and Assessment Branch Yukon Environment Box 2703 Whitehorse, Yukon Y1A 2C6
Northwest Territories (T)	NWT Resources, Wildlife & Economic Development	Graham Veale	graham_veale@gov.nt.ca	http://www.rwed.gov.nt.ca/RWED/	Graham Veale Northwest Territories Resources, Wildlife & Economic Development 7th Floor Scotia Centre 5102 - 50th Ave. Yellowknife, NWT X1A 3S8
Nunavut (T)	Department of Sustainable Development			http://www.gov.nu.ca/sd.htm	

APPENDIX B. CARBONACEOUS AEROSOLS

Carbonaceous aerosols consist of fine particles, mostly less than 1 micrometer (µm) in diameter, which are usually classified as either black carbon (BC)—essentially but not identically the same as elemental carbon (EC) (Bond et al., 2004)—or organic carbon (OC), in which the carbon is bonded to other elements. The importance of carbonaceous aerosols to global radiative forcing has been stressed in a number of important papers and commentaries in recent years (Hansen et al., 2000; Hansen and Sato, 2001; Andreae, 2001; Penner et al., 2001; Jacobson, 2001, 2002; Chameides and Bergin, 2002). The ability of carbonaceous aerosols to modify local meteorology and climatology in regions where emissions are high, like China and India, has also been postulated [Ackerman et al., 2000; Ramanathan et al., 2001; Lelieveld et al., 2001; Menon et al., 2002; Dickerson et al., 2002]. Carbonaceous aerosols have been the subject of a number of global and regional modeling studies aimed at linking source distributions with ambient concentrations and light absorption measurements through the simulation of atmospheric transport, chemistry, and removal (Liousse et al., 1996; Chameides et al., 1999; Tegen et al., 2000; Koch, 2001; Chin et al., 2002, 2003; Cooke et al., 2002; Menon et al., 2002; Hansen et al., 2002; Jacobson, 2002; Chung and Seinfeld, 2002). These models require as input some representation of the strength and spatial distribution of primary emissions. The development of a reliable dataset of emissions of carbonaceous aerosols, however, has not been easy. This section reviews the progress that has been made to date to understand primary carbonaceous aerosol emissions.

Because of the strong and important link to global climate change, the impetus for developing aerosol emission estimates initially came from the global and regional climate modeling community. The earliest work (Turco et al., 1983; Ghan and Penner, 1992) tentatively placed annual, global BC emissions in the range of 2 to 12 Tg. Then, in a seminal paper, Penner et al. (1993) derived the first reliable BC emission estimates. By studying the ratios of BC to "smoke" and SO_2 measurements, they proposed that BC emissions could be inferred from observed BC/S ratios in different parts of the world. A global annual emission value of 23.8 Tg was obtained by this method. A second method presented in the same paper—based on rather crude BC emission factors and the global use of diesel fuel, coal, wood, and bagasse—yielded an estimate of 12.6 Tg for the year 1980. Biomass burning from land clearing was estimated to produce a further 5.7 Tg. Liousse et al. (1996) modified and extended the work of Penner et al. (1993) to yield estimates of 6.6 Tg for fossil-fuel use and 5.6 Tg for biomass burning of all kinds.

Simultaneously with the paper of Liousse et al., the first paper was published that estimated global BC emissions using specific emission factors and disaggregated fuel use applied to a wide variety of source types (Cooke and Wilson, 1996). Their estimates were 8.0 Tg from fossil-fuel combustion and 6.0 Tg from biomass burning. Two drawbacks to this work were that it was based on old (1984) fuel use data and that it omitted biofuel combustion, which is known to be a big contributor to global BC emissions. But, most significantly, Cooke and Wilson used inappropriate emission factors for large sources such as coal-fired power-plants and industrial boilers, failing to appreciate that the bulk of fine particle emissions from such sources is not carbonaceous but mineral in nature. An update of this paper was published (Cooke et al., 1999), in which the estimate of fossil-fuel BC emissions was reduced to 6.4 Tg for bulk BC (BC particles of all sizes) and 5.1 Tg for submicron BC (only BC particles <1µm in diameter). Many deficiencies of the original work remained. The inventories of Penner et al. (1993), Cooke and Wilson (1996), and Cooke et al. (1999) have been the sources of emissions for the modeling studies cited at the beginning of this paper. Köhler et al. (2001) developed a global inventory of BC emissions from road traffic (2.4 Tg for 1993), partly based on Cooke and Wilson (1996).

Despite uncertainties in the magnitude of BC emissions, one thing was clear from this early work: China and India generate a sizeable proportion of global BC emissions, due to the widespread and often uncontrolled burning of coal; Chameides and Bergin (2002) showed that these two countries together produce fully 25% of global BC emissions. In order to gain a better perspective on BC emissions in China, Streets et al. (2001) conducted a detailed investigation of technologies and fuels, part of which consisted of a thorough review and assessment of the literature on fine particle emissions by combustion experts. Through this process, a more robust set of emission factors was developed for the various source types, coordinated with available measurements of $PM_{2.5}$ and PM_{10} emission factors and appropriate submicron and carbonaceous fractions. The paper stressed the high uncertainty associated with BC emission factors, due to the wide variety of combustion conditions found in different types of combustors. Streets et al. (2001) determined that the residential burning of coal in a traditional stove has a BC emission factor of 3.7 g kg^{-1} (central estimate). In contrast, the BC emission factor for a large coal-fired boiler using an electrostatic precipitator is only about 0.0001 g kg^{-1}. Emissions are low because the very high temperatures and efficient mixing of air and fuel in large boilers readily oxidize any fine carbon particles leaving the combustion zone; it is primarily mineral matter that escapes and is captured in the particulate control device or passes through into the atmosphere. This latter value is in sharp contrast to the value of 1 g kg^{-1} chosen by Cooke and Wilson for industrial coal combustion (including power plants). A new Asian emission inventory for the year 2000 was developed for the NASA TRACE-P program and the NSF/NOAA ACE-Asia program (Streets et al., 2003a,b). This inventory included estimates of Asian BC emissions based on the emission factors of Streets et al. (2001). It was estimated that Asian BC emissions in 2000 were 2.5 Tg, of which China generated 1.1 Tg and India 0.6 Tg.

The final step in this process to date has been the extension of the China and Asian emissions work to a new global inventory (Bond et al., 2004), which applied emission factors updated from Streets et al. (2001) to 1996 global fuel use at the national level (IEA, 1998a,b) in more than 100 sector/fuel/technology categories. Global BC emissions according to this new inventory are 8.0 Tg in total (consisting of 3.0 Tg from fossil-fuel combustion, 1.7 Tg from biofuel combustion, and 3.3 Tg from open biomass burning). This estimate is significantly lower than previous estimates. The increase in fuel use between the early 1980s and the mid-1990s is insufficient to offset the decrease in the emission estimate caused by lowering the emission factors of large stationary sources. (Bond et al. (2004) present a detailed analysis of the causes of differences between the new inventory and its predecessors.) Sources of uncertainty in our knowledge of present-day BC and OC emissions are also estimated by Bond et al. (2004).

Global emissions of OC were first estimated by Liousse et al. (1996) to be about 62 Tg (organic matter emissions of 81 Tg divided by 1.3). Biomass burning contributed 34 Tg, fossil-fuel combustion 22 Tg, and natural sources 6 Tg. The estimate by Liousse et al. for combustion emissions was based on assumed OC/BC ratios, not direct measurements, and attempted to account for secondary aerosol production. Subsequently, Cooke et al. (1999) derived primary emission values of 10.1 Tg bulk OC and 7.0 Tg submicron OC from fossil-fuel combustion, though the same caveats apply as to their BC estimates. In a later modeling study, Cooke et al. (2002) doubled their emission estimate to 14 Tg submicron OC, presumably to account for secondary formation of OC. The new OC estimates by Bond et al. (2004) are 2.4 Tg from the combustion of fossil fuels, 5.8 Tg from the combustion of biofuels and 25 Tg from open biomass burning, for a total of 33 Tg; these authors have not attempted to account for secondary OC formation.

Though many uncertainties still remain, we are approaching a reasonable level of understanding of global emissions of primary BC and OC. Studies are underway to test the Bond et al. (2004) emission estimates against currently available field observations; and we expect that iteration among emissions, atmospheric measurements, model results, and combustion tests will result in improved understanding of the present-day magnitude of carbonaceous aerosol emissions.

The first estimates of aerosol emissions in North America were extracted from these global inventories. It is only recently that an aerosol emission inventory was developed specifically for the United States by Battye and Boyer (2002). This work should be considered as preliminary, however, and it has not yet been incorporated into any official U.S. EPA inventories.

Table B.1 reviews emission estimates for the United States, Canada, and Mexico, as they are reported in the various global and regional emission inventories. BC emissions from fossil-fuel combustion and other anthropogenic activities in the United States are in the range of 300-400 Gg C yr^{-1}. The uncertainty surrounding North American BC estimates from “contained” combustion (fossil fuels plus biofuels) is reported by Bond et al. to be high; their value is 472 Gg C yr^{-1}, with a high-low range of 300-600 Gg. BC emissions from open biomass burning in the U.S. are in the range of 50-150 Gg C yr^{-1}. The value from Bond et al. for North America is 148 (50-450) Gg C yr^{-1}. Large inter-annual variation is associated with biomass burning emission estimates. Canadian and Mexican emissions, to the extent they have been quantified, are also listed in Table B.1. Emissions of OC are less well known. Bond et al. estimate 531 Gg C yr^{-1} from contained combustion in the United States and 744 (330-1,110) Gg C yr^{-1} for all of North America. For open biomass burning the estimates for OC emissions are 836 Gg C yr^{-1} for the United States and 1,735 (600-3,700) Gg C yr^{-1} for North America. Wildfires in Mexico and Canada contribute significantly to the OC emission estimate for North America.

An attempt has been made to infer U.S. emissions of carbonaceous aerosols by inverse modeling, using observations made at 45 IMPROVE sites. Park et al. (2003) obtained an estimate for U.S. EC emissions of 750 Gg from modeling and measurement integration based on a priori estimates from Cooke et al. (1999) and other sources. 600 Gg was from fossil-fuel combustion, 80 Gg was from biomass burning, and 70 Gg from biofuel use. This is higher than the inventory values of Battye and Boyer (2002) and Bond et al., which agree closely at a total BC value of about 430 Gg for all sources in the United States; but it is within the uncertainty range of the inventory studies, and it is influenced by the higher a priori value used. The OC estimate for the United States was 3,110 Gg, of which 520 Gg was from fossil-fuel use, 890 Gg from biofuel use, 600 Gg from biomass burning, and 1,100 Gg from biogenic sources (not included in the other inventories). Again, these are higher than the values from Bond et al. (2004).

Table B.1. Estimates of North American Emissions of Carbonaceous Aerosols (Gg C yr^{-1})

Source	Year of Data	Fuel	Particle Size	Species	U.S.A.	Canada	Mexico	North America	Global
Penner et al. [1993][a]	1980	fossil fuel[b]	bulk	BC	270		20	320	6,640
		biofuel[c]	bulk	BC	120		60	350	5,970
Cooke and Wilson [1996][d]	1984	fossil fuel	bulk	BC				1,270	7,970
		biomass[e]	bulk	BC				90	5,980
Cooke et al. [1999][d]	1984	fossil fuel	bulk	BC				550	6,390
			submicron	BC				490	5,060
Battye and Boyer [2002][f]	1999	fossil fuel[g]	submicron	BC	320				
		biomass[e]			112				
Bond et al. [2004]	1996	fossil fuel[g]	submicron	BC	375	42	56	472	4,821
		biomass[e]			61	52	35	148	3,280
Cooke et al. [1999][d]	1984	fossil fuel	bulk	OC				480	10,120
			submicron					390	7,010
Bond et al. [2004]	1996	fossil fuel[g]	submicron	OC	531	58	155	744	8,908
		biomass[e]			836	631	269	1,735	25,425

Notes:

[a] Estimated by "fuel use" method, rather than BC/S ratio method. No open biomass burning reported.
[b] Domestic and commercial coal use and diesel fuel use only.
[c] Wood and bagasse only.
[d] No biofuel combustion included.
[e] Open biomass burning only.
[f] Based on EPA's National Emission Inventory V.2.
[g] Includes biofuel combustion.

Table B.2 presents U.S. emissions from the two recent inventories by emitting sector. The estimates are similar in total magnitude, but some significant differences are found at sub-sector level. One difference is believed to arise from different classifications of industrial nonroad diesel equipment. But worthy of further investigation are differences for onroad diesel vehicles, aircraft, and residential fuel combustion. A review and reconciliation of emission factors for the component source types would likely resolve the differences.

Table B.2. BC Emissions by Sector and Source Type

Source Type	**BC Emissions (Gg C yr^{-1})**	
	Bond et al. [2004]	**Battye and Boyer [2002]**
Transportation	***231***	***246***
Non-road diesel	33[a]	91[a]
On-road diesel	101	65
Non-road gasoline	0	20
Aircraft	47	17
On-road gasoline	25	16
Marine	10	16
Diesel locomotives	0	11
Miscellaneous fuel combustion	14	10
Open Burning	***61***	***116***
Stationary Fuel Combustion	***140***	***36***
Residential	79	22
Utility, industrial, commercial	61[a]	14[a]
Industrial Process, incineration	***9***	***9***
Fugitive Dust	n/a	***24***
Livestock	n/a	***5***
Total	***441***	***433***

Notes:
[a] Classification differences regarding industrial diesel nonroad equipment.

Recent papers have stressed the difficulties in developing BC and OC emission factors from the available data on particulate mass (PM) emissions (Bond et al., 1998, 2004; Streets et al., 2001; Battye and Boyer, 2002). Most measurements of PM emissions report total mass, because the important differences in the behavior of PM with different chemical compositions have only recently received attention. Where measured emission factors of black and organic carbon are not available, they are usually estimated based on mass emission measurements, usually of PM_{10} or $PM_{2.5}$, combined with data on the submicron and carbonaceous fractions of the emissions, as follows:

$$EF = EFPM \times fsub \times fC \times fcont$$

where,

EF = the BC or OC emission factor (g kg^{-1});
$EFPM$ = the bulk particulate emission factor (usually of $PM_{2.5}$ or PM_{10}) (g kg^{-1});
$fsub$ = fraction of particles with diameters <1 µm;
fC = fraction of the particulate matter that is carbon; and
$fcont$ = fraction of the fine particles that penetrate any control device present.

For many sources, measurements of fsub and fC are extremely scarce. Often they must be inferred from measurements on presumed similar sources. Uncertainties in the values of these two fractions are probably the largest sources of error in BC and OC emission factors. Not all concerns about our understanding of current emissions of carbonaceous aerosols have been removed at the present time. Inconsistencies are still found between modeled aerosol concentrations and optical properties that use current inventories and field measurements of the same quantities. These may or may not be related to the reliability of current emission estimates; only additional research will tell. But to the extent that they are associated with emissions problems, such factors as missing sources and incorrect emission factors may still exist in the 1996 global inventory of Bond et al. and the 1999 U.S. inventory of Battye and Boyer.

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