Representing Freight in Air Quality and Greenhouse Gas Models

DETAILS

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NATIONAL COOPERATIVE FREIGHT RESEARCH PROGRAM

NCFRP REPORT 4

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NATIONAL COOPERATIVE FREIGHT RESEARCH PROGRAM

America's freight transportation system makes critical contributions to the nation's economy, security, and quality of life. The freight transportation system in the United States is a complex, decentralized, and dynamic network of private and public entities, involving all modes of transportation—trucking, rail, waterways, air, and pipelines. In recent years, the demand for freight transportation service has been increasing fueled by growth in international trade; however, bottlenecks or congestion points in the system are exposing the inadequacies of current infrastructure and operations to meet the growing demand for freight. Strategic operational and investment decisions by governments at all levels will be necessary to maintain freight system performance, and will in turn require sound technical guidance based on research.

The National Cooperative Freight Research Program (NCFRP) is a cooperative research program sponsored by the Research and Innovative Technology Administration (RITA) under Grant No. DTOS59-06-G-00039 and administered by the Transportation Research Board (TRB). The program was authorized in 2005 with the passage of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). On September 6, 2006, a contract to begin work was executed between RITA and The National Academies. The NCFRP will carry out applied research on problems facing the freight industry that are not being adequately addressed by existing research programs.

Program guidance is provided by an Oversight Committee comprised of a representative cross section of freight stakeholders appointed by the National Research Council of The National Academies. The NCFRP Oversight Committee meets annually to formulate the research program by identifying the highest priority projects and defining funding levels and expected products. Research problem statements recommending research needs for consideration by the Oversight Committee are solicited annually, but may be submitted to TRB at any time. Each selected project is assigned to a panel, appointed by TRB, which provides technical guidance and counsel throughout the life of the project. Heavy emphasis is placed on including members representing the intended users of the research products.

The NCFRP will produce a series of research reports and other products such as guidebooks for practitioners. Primary emphasis will be placed on disseminating NCFRP results to the intended end-users of the research: freight shippers and carriers, service providers, suppliers, and public officials.

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FOREWORD

By William C. Rogers
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NCFRP Report 4: Representing Freight in Air Quality and Greenhouse Gas Models presents an evaluation of the current methods used to generate air emissions information from all freight transportation activities and discusses their suitability for purposes such as health and climate risk assessments, prioritization of emission reduction activities (e.g., through State Implementation Plans), and public education. The report is especially valuable for (1) its identification of the state of the practice, gaps, and strengths and limitations of current emissions data estimates and methods and (2) its conceptual model that offers a comprehensive representation of freight activity by all transportation modes and relationships between modes. This report will better inform the near-term needs of public and private stakeholders regarding the quality of emissions data and guide future research that links freight activities with air emissions.

An efficient and robust freight transportation system is essential to the continued economic well-being of the United States. Demand for freight transportation has been growing rapidly, but that growth has conflicted with concerns about the health effects of air pollution and greenhouse gas emissions that contribute to global warming. For instance, according to the Environmental Protection Agency, transportation-related activities account for 28% of total U.S. greenhouse gas emissions. Further, as freight movement continues to grow, its emissions will account for a greater share of the transportation sector's carbon footprint. Although there are known data limitations, including the lack of actual emissions measurements to validate model estimates, given concern over public health, decisionmakers at all levels of government are proceeding with efforts to regulate emissions, often through freight operations controls.

Under NCFRP Project 16, ICF International was asked to

1. Describe the current state of practice for estimating freight air emissions;
2. Catalog existing data and data sources used to define categories of freight transportation-related air emissions;
3. Describe the strengths and limitations of current methods, models, and data;
4. Identify and assess alternative measurement techniques, data sources, and approaches that can enhance the utility and quality of emissions calculations for freight transportation;
5. Develop a conceptual model for freight transportation activities that reflects current understanding and anticipated improvements in data and analytical methods relating freight transportation activity to emissions; and
6. Identify future opportunities for improving accuracy and reducing uncertainty in freight activity and emission data across all modes.

CONTENTS

SUMMARY

Representing Freight in Air Quality and Greenhouse Gas Models

The purpose of *NCFRP Report 4: Representing Freight in Air Quality and Greenhouse Gas Models* is to review and evaluate current methods used to estimate air emissions from freight transportation activities and determine their suitability for decision making and public education. All freight modes are represented, including heavy-duty trucks, rail, ocean-going vessels, harbor craft, cargo handling equipment, and air freight. To the extent possible, three geographic scales are analyzed for each mode, namely at the national, regional, and local/project levels.

This report is organized by transportation mode since many emission models and methods used to estimate freight emissions are specific to each mode. Methods, models, and parameters are discussed for each freight mode. The accuracy of models to estimate emissions is described for each mode as well as the data collection process and system boundaries. Pollutants of concern include greenhouse gas emissions, criteria pollutants, and air toxics.

The application of freight emission models in influencing government decisions is also discussed. Freight emissions can directly affect decisions over how public (and private) funds are spent on infrastructure projects and associated mitigation measures. They are used in the preparation of environmental documents to satisfy National Environmental Policy Act (NEPA) and related state statutes, and in analyses required under the General Conformity regulations. Emission estimates also can serve as inputs to dispersion models that use meteorological information to simulate the atmospheric dispersion of pollutants and estimate resulting spatial concentrations.

The examination of accuracy and uncertainty of methods and models in this report is done mostly on a qualitative basis, identifying strengths and weaknesses, as well as evaluating the parameters that have the largest impact on final emissions and highest uncertainty relative to others. The evaluation of methods, models, and parameters is done for each transportation mode at the national, state, and local/project-level scales.

At the national level, the report examines the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (*1*) and the National Emissions Inventory (*2*). These approaches differ from other mode-specific transportation methodologies in that they span all modes, and are better analyzed independently of individual modal methodologies. For regional and project-level scales, the analysis is mode specific.

For heavy-duty trucks, the report examines MOBILE6.2 and EMFAC2007, which are the currently approved models for preparing SIPs, conformity analyses, and project-level analysis to fulfill NEPA/CEQA requirements. In addition, MOVES2009 and CMEM also are examined. Issues regarding the application of these models to regional and project-level scales also are discussed. (Note, MOVES2009 will soon replace MOBILE as the approved emissions model for these applications.)

For rail, this report examines methods at the regional and project-level scales that estimate fuel consumption from different rail parameters. These include allocation techniques from traffic density, active track, number of switchers or hours, number of employees, and time-in-notch calculations. The uncertainties in these estimation techniques and the input parameters are discussed.

For ocean-going vessels, three basic methods for calculating emissions at ports are discussed, namely (1) a detailed methodology where considerable information is gathered regarding ships entering and leaving a given port, (2) a mid-tier method that uses some detailed information and some information from surrogate ports, and (3) a more streamlined method in which detailed information from a surrogate port is used to estimate emissions at a "like" port. Uncertainty in both methodology and input parameters is discussed.

For harbor craft, there are no established models. Emissions are estimated by a number of techniques depending upon geographic scale. Uncertainty in freight-related harbor craft emission estimates from these methodologies can be attributed to process uncertainty (i.e., degree to which the methods accurately represent actual emissions) and parameter uncertainty (i.e., uncertainty in the individual elements used for calculations). These are discussed in this report.

Generally, cargo handling equipment (CHE) emissions at ports are estimated using either the NONROAD or OFFROAD emission models—or methods similar to those in the models. Two general categories of methods are used to estimate CHE emissions. These are referred to as the "best practice" and "streamlined" methodologies. Both methods are discussed and the relative uncertainties examined.

The representation of freight activity in air transportation is perhaps the most challenging among all modes because air freight, unlike other modes, also is transported in passenger aircraft. Emissions associated with the transport of freight by aircraft were analyzed using two modeling approaches, namely FAA's System for Assessing Aviation's Global Emissions (SAGE) and the Emissions and Dispersion Modeling System (EDMS), which also was developed by FAA. These methods and the variety of input parameters are discussed and analyzed.

The report discusses air quality models and how air quality concentrations are assessed from the emission estimates for each transportation mode and scale. The associated uncertainties are examined as well.

The report includes a Conceptual Model that offers a comprehensive representation of freight activity in the United States, covering all modes and relationships between modes. For this model to be effective in improving emissions estimates, it captures the factors in freight movements and freight equipment that most influence emissions. The Conceptual Model provides the link between economic activity, freight transportation activity, freight-related emissions, and associated health effects.

Finally, the report presents five recommended areas for research that offer great promise for improving freight emissions estimates.

CHAPTER 1

Introduction and Research Summary

1.1 Objective

The objective of this report is to review and evaluate current methods used to estimate air emissions from freight transportation activities and determine their suitability for decision making and public education. All freight modes are represented, including heavy-duty trucks, rail, ocean-going vessels, harbor craft, cargo handling equipment, and air freight. To the extent possible, three geographic scales are analyzed for each mode, namely at the national, regional, and local/project levels. The regional scale can apply to areas within one state or areas comprising multiple states.

1.2 Report Organization

This report is organized as follows:

- **Chapter 1:** report summary including objectives, report organization, study framework, and a summary of each subsequent chapter;
- **Chapter 2:** detailed discussion of how freight emissions estimates are used and applied by public- and private-sector stakeholders;
- **Chapter 3:** detailed review of the current state of the practice for estimating freight emissions across all modes and geographic scales, and evaluation of current methods and models used to estimate emissions from freight transportation, including an analysis of strengths and weaknesses of the main methods and models, an assessment of process uncertainty of these methods and models, and an assessment of parameter uncertainty related to the inputs required by these methods and models;
- **Chapter 4:** development of a Conceptual Model for freight transportation activity as it relates to emissions calculations. The Conceptual Model offers a comprehensive representation of freight activity in the United States, covering all modes and relationships between modes; and
- **Chapter 5:** provision of five research statements to improve the estimation of freight transportation emissions.

1.3 Study Framework

This report is organized by transportation mode, since many emission models and methods to estimate freight emissions are specific to each mode. Three elements are discussed for each mode:

- **Methods:** the most currently applicable and widespread methods to estimate and forecast freight emissions in the public domain are discussed and evaluated. A method is defined as a step-by-step approach on how to estimate vehicle and freight activity, how to develop emission factors, and how to calculate freight emissions. A method generally includes the use of several input parameters, as well as one or more models;
- **Models:** current models used to estimate freight activity, emission factors, and total emissions; and
- **Parameters:** input parameters are used in both methods and models to define fuel and vehicle/vessel characteristics, estimate emission factors, and calculate emissions.

The complexity, accuracy, and precision of methods, models, and input parameters depend on the following three factors:

- **Magnitude of mode emissions:** all else being equal, it is expected that modes with the greatest emissions will have more data available, better documented methods, and more established models. As a result, methods, models, and input parameters to estimate trucking emissions tend to be more detailed than for other modes;
- **Data collection process:** the data collection process has an effect on the level of detail, complexity, and accuracy of data. The data collection process is influenced by (1) the number of freight activity generators, (2) the regulatory

requirements for data reporting, and (3) the role of agencies overseeing the data collection. The data collection process has an effect on the complexity of methods because modeling might be required to compensate for a lack of available data (e.g., if vehicle activity is not collected by vehicle type, alternate methods are necessary to estimate the share activity by vehicle type). Additionally, if different data sources and models are based on different levels of data detail, the integration of data types and the application of data by models could also become more complex; and

- **System boundaries:** the issue of system boundaries is especially critical for the modes that have an international segment, such as marine and aviation. Allocation of emissions or fuel use to a specific system boundary may be difficult in cases where the fuel used in a region was not purchased in that same region, as it is the case in the rail, marine, and aviation sectors.

For most modes, the discussion is divided in three geographic scales: national, regional, and project level. Because the two main national methods to estimate emissions—*Inventory of U.S. Greenhouse Gas Emissions and Sinks* (hereafter referred to as the EPA GHG Inventory) (*1*) and the National Emissions Inventory (the NEI) (*2*)—include all modes, the discussion of national methods is done separately from the mode-specific discussions. Regional and project-level methods are mode specific, so they are examined by transportation mode.

1.4 Pollutants of Concern

Pollutants of concern in this study include greenhouse gases, criteria pollutants, and toxic air pollutants.

1.4.1 Greenhouse Gases

Carbon dioxide (CO_2), the primary greenhouse gas (GHG) associated with the combustion of diesel (and other fossil fuels), accounts for over 95% of the transportation sector's global warming potential-weighted GHG emissions. Methane (CH_4) and nitrous oxide (N_2O) together account for about 2% of the transportation total GHG emissions. Both gases are released during fuel consumption, although in much smaller quantities than CO_2, and are also affected by vehicle emissions control technologies. (*3*) More information on GHG pollutants, including sources, and methods to calculate emissions, is presented in Section 3.1.1.

1.4.2 Criteria Pollutants

Criteria air pollutants (CAPs) are those for which either the federal government and/or the California state government have established ambient air quality standards based on short- and/or long-term human health effects. The federal government, via the EPA has established national ambient air quality standards (NAAQS) for the following six pollutants:

1. Ground-level ozone (O_3),
2. Carbon monoxide (CO),
3. Particulate matter (PM) less than 10 (PM_{10}) and 2.5 ($PM_{2.5}$) microns,
4. Nitrogen dioxide (NO_2),
5. Sulfur dioxide (SO_2), and
6. Lead (Pb).

When specifically discussing diesel emissions, PM is often referred to as diesel PM (DPM). Other emissions inventories measure larger classes of nitrogen oxides (NO_X) and sulfur oxides (SO_X). NAAQS values typically are the maximum average level of ambient concentration acceptable under the law; in some cases, states may set more stringent standards or include other pollutants than those listed here.

Although not a criteria pollutant, organic species are often considered along with criteria pollutants because they are chemical precursors for ground-level ozone. Depending on the report or methodology, these gases are referred to in various forms as volatile organic compounds (VOCs), reactive organic gases (ROG), total organic gases (TOG), hydrocarbons (HC), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), and diesel exhaust organic gases (DEOG). (Each has a specific definition depending on which species is included in the group but, in general, all are involved in reactions with NOx to form ozone. Strictly, total organic gases and total hydrocarbons contain species considered to be nonreactive, but may be grouped here for practicality.) Although each term defines specific subsets of VOCs, references to these terms in various methodologies all refer to the same class of VOC pollutants. Also, PM typically is expressed as primary PM (i.e., the amount emitted directly), as opposed to secondary PM, which is formed in the air from chemical reactions involving ammonia and other species.

1.4.3 Toxic Air Pollutants

Toxic air pollutants, also known as air toxics, hazardous air pollutants (HAPs), toxic air contaminants (TACs), mobile source air toxics (MSATs), and non-criteria air pollutants (NCAPs), are contaminants found in ambient air that are known or suspected to cause cancer, reproductive effects, birth defects, other health effects, or adverse environmental effects, but do not have established ambient air quality standards. HAPs may have short-term and/or long-term exposure effects.

EPA currently has implemented programs to reduce emissions of 188 HAPs, (*4*) however 1,033 total HAPs are listed by

EPA as related to mobile source emissions (*5*) and of these, 644 are components of diesel exhaust, including benzene, cadmium, formaldehyde, and 1,3-butadiene. In California, diesel particulate matter typically is the toxic air contaminant of primary concern; however, there are no specific annual limits on its emissions. HAP pollutants broadly fall into two categories—heavy metals and hydrocarbons—and are often calculated as a fraction of PM and VOC emissions.

Many environmental review documents report air toxics, but the methods for estimating and reporting these emissions are not uniform. The study team relied heavily on a recent report on the preparation and reporting of air toxics in NEPA documents. (*6*)

1.5 Application of Freight Emissions

Freight transportation emissions estimates influence government decisions in a number of ways. In some instances, the estimation of freight emissions directly affects decisions over how public (and private) funds are spent on infrastructure projects and associated mitigation measures. This can occur in the preparation of environmental documents to satisfy NEPA and related state statutes, and in analyses required under the General Conformity regulations. In many other instances, freight emissions clearly influence government policy and program decisions, but the linkage is less direct. For example, studies of health impacts of diesel exhaust rely heavily on freight emissions estimates. Some of these studies have been very influential in shaping air quality policy and diesel emission reduction programs, but there may not be a direct connection between a particular study and a government decision.

The attention given to different pollutants depends on the purpose and scale of analysis. GHG emissions from freight are most commonly considered at the state or national scale, as part of GHG inventories and climate change action plans. One of the most important applications of criteria pollutant emissions estimates is at the regional scale, as part of the development of state implementation plans (SIPs) to satisfy the Clean Air Act. Criteria air pollutant estimates are also critical at the project level to satisfy environmental review under NEPA as well as General Conformity (e.g., for ports and airports). Estimation of air toxics emissions is not mandated as it is for criteria air pollutants. Estimating air toxics emissions is done at the project level when there are heightened concerns about health impacts. National- and regional-scale air toxics analysis has been oriented toward research and serves to identify priorities for mitigation efforts and further research.

Emissions estimates are often reported as is, without further processing. For example, emissions estimates are used for comparison among project alternatives under NEPA and for comparison of project emissions against the General Conformity thresholds. In the regional transportation planning context, highway emissions are summed and compared to the regional emissions budget for Transportation Conformity purposes. GHG inventories also report emissions estimates without further processing.

Emissions also can serve as inputs to dispersion models that use meteorological information to simulate the atmospheric dispersion of pollutants and estimate resulting spatial concentrations. Dispersion models are used for project analysis when there are concerns about air pollution hot spots, particularly regarding PM and CO. They are used at the regional scale as part of the SIP development process to determine the reductions necessary to achieve the NAAQS. To conduct a health risk assessment, dispersion models feed exposure models, which use data on the demographics, activities, and commuting habits of residents of an area, and calculate the air pollution concentrations to which they are exposed.

Given the diversity in application of freight emissions estimates, the required accuracy of the estimates varies widely. Some applications require a point estimate to be compared to an absolute threshold (e.g., a General Conformity determination or SIP emissions budget). Others involve a comparison of the relative difference in emissions (e.g., NEPA project alternatives) or a comparison over time (e.g., climate change plan). The level of accuracy also depends on whether the freight emissions are reported or processed in isolation or combined with emissions from other sources. Freight transportation dominates the emissions or air quality impacts in some cases, while in other cases freight is a relatively small contributor to the impact.

1.6 Evaluation of Current Methods

Quantitative estimates of overall accuracy and uncertainty associated with different methods and models could not always be provided. There are not enough data to make such a quantitative assessment with a good degree of confidence. As a result, the examination of accuracy and uncertainty was done mostly on a qualitative basis, identifying strengths and weaknesses of methods and models, as well as evaluating the parameters that have the largest impact on final emissions and highest uncertainty relative to others. The following subsections summarize the evaluation of methods, models, and parameters for each transportation mode at the national, state, and local/project level scales.

1.6.1 National

At the national level, EPA uses two separate methodologies, reported in the EPA GHG Inventory (*1*) and the NEI, (*2*) to estimate emissions across all sectors of the economy. These approaches differ from other mode-specific transportation methodologies in that they span all modes and are best analyzed independently of individual modal methodologies.

The EPA GHG Inventory calculates emissions through a fuel-based analysis. The inventory allocates emissions to each transportation mode, and to subcategories within each mode according to fuel consumption and fuel type. Total GHG emissions are calculated as a function of each fuel's carbon content. Although the EPA GHG Inventory does not disaggregate freight and nonfreight emissions, it lists modal categories in sufficient detail to make such disaggregation possible, albeit while introducing uncertainties into the calculations. Fuel used in international cargo movements by both marine and aircraft is not counted, and the resulting emissions are generally not allocated to any nation.

Although the EPA GHG Inventory uses a straightforward approach to calculating emissions, the NEI methodology is comparatively more complex. Because the emissions of criteria air pollutants and air toxics depend on vehicle type, age, and activity, the NEI relies on separate methodologies for each transportation mode. In addition, the NEI has much more geographic detail than the EPA GHG Inventory. Although the EPA GHG Inventory only presents emissions at the national level, the NEI allocates emissions to the state and county levels.

The two national methodologies have sources of uncertainties in the calculation of individual modal emissions and in the evaluation of nationwide inventories. This section focuses on uncertainties that occur in the nationwide analysis, which are primarily associated with the national collection of fuel data and its subsequent allocation to individual transportation modes. National uncertainties include the following:

- The EPA GHG Inventory allocates national fuel use to transportation sectors through different (and unrelated) data sources. For example, the transportation allocation is calculated by comparing an estimate of transportation activity (e.g., vehicle-miles, ton-miles) with industrial and commercial activity (e.g., fuel expenditures, productivity), and uncertainties arise from determining the allocation based on data that are not closely related.
- The EPA GHG Inventory then allocates transportation fuel use to each mode and vehicle type. This step is challenging because the quality of data varies between modes. Modal activity is measured through individual data sources such as the Federal Highway Administration (FHWA) for on-road vehicles, Association of American Railroads (AAR) for rail, and Federal Aviation Administration (FAA) for aircraft. Although Class I railroads are required to report 100% of fuel consumption nationwide, fuel consumed by Class II and III railroads, as well as other modes, is based on sampling. It is not clear how the uncertainty in one data set would compare to the uncertainty in other sets. Although these uncertainties do not significantly affect the quantification of emissions from the transportation sector, they have an effect on the modal breakdown of emissions.
- Further uncertainties arise from the aggregation or disaggregation of emissions between geographic scales. The NEI calculates emissions at several geographic scales, from national to county level. However, for most modes, data are supplied at only one scale, such as the regional level for aircraft or the national level for rail. The NEI methodology then either aggregates regional emissions to determine national emissions, or distributes national emissions among individual states and regions. The process of scaling emissions adds uncertainty to the results, as more assumptions on emissions at each level are included in the process.

In addition to the process uncertainties described above, the parameters used in national methods also are subject to uncertainties associated with errors or biases in the data sets. The parameters shown in Exhibit 1-1 are used in allocating fuel consumption to the transportation sector and to individ-

Exhibit 1-1. National parameters.

Parameter	Methods/Models	Impact on Emissions	Parameter Uncertainty
Marine Equipment Inventory	NEI	Low/Moderate	High
Nonroad Equipment Inventory	NEI	Low/Moderate	Moderate
On-road Fleet Mix	NEI	Low/Moderate	Low/Moderate
Rail GIS Data	NEI	Low/Moderate	Low/Moderate
Economic Sector Activity Data	GHG Inventory	Moderate/High	High
Modal Activity Data	GHG Inventory, NEI	Moderate/High	High
Modal Emissions Factors	NEI	Moderate/High	Moderate
Fuel Carbon Content	GHG Inventory	High	Low
Fuel Supply Data	GHG Inventory	High	Low

ual modes, and are used in one or both of the EPA national methods.

The effect of fuel parameters varies depending on their impact on emissions and uncertainty in their measurement. Parameters such as "fuel supply data" have a high impact but low uncertainty, while parameters such as "marine equipment inventory" have low impact but high uncertainty. These relationships are shown qualitatively in Exhibit 1-1. The derivation of these individual values is presented in the pedigree matrix shown in Section 3.2.4. Criteria to assign scores in the pedigree matrix are included in Appendix A.

1.6.2 Heavy-Duty Trucks

The distinction between on-road passenger and freight vehicles is usually clear, with passenger vehicles assumed to be automobiles, light-duty trucks with a gross vehicle weight rating (GVWR) of less than 8,500 lbs, and buses, while heavy-duty trucks are those with GVWR of more than 8,500 lbs. However, there are trucks with a GVWR of more than 8,500 lbs that do not move freight. Some examples are utility trucks used for service and repair of utility infrastructure, tow trucks, and daily rental trucks. Because it is virtually impossible to separate the activity and emissions of nonfreight heavy-duty trucks from freight trucks, and because nonfreight heavy-duty trucks are relatively insignificant compared to freight trucks, generally no attempt is made to distinguish between the two.

MOBILE6 and EMFAC2007 are the approved models for SIPs, conformity analyses, and project-level analysis to fulfill NEPA/CEQA requirements. MOVES2009 is the new EPA model that will eventually replace MOBILE6 when fully implemented, and CMEM is the most established microsimulation emission model. The evaluation also includes a regional and local method, both of which rely on either MOBILE6 or EMFAC2007. The main drivers of uncertainty associated with these methods and models are as follow:

- Emission models like MOBILE6 and EMFAC are ill-suited for project-level analyses if key local factors that have a significant impact on emissions (e.g., average speed, truck age distribution, vehicle-miles traveled [VMT] share by truck type) are not available. Additionally, these models do not consider road grade, actual vehicle weight, or aerodynamic characteristics of vehicles, all of which have a strong effect on engine power requirements and, consequently, on emissions.
- The representation of local and regional factors (e.g., truck age distribution, mileage accumulation, VMT share by truck type) by national defaults is a source of substantial uncertainty. This issue is important because many agencies do not have access or resources to collect local data, and rely on national defaults to represent project-level and regional emissions. This is more of a problem with MOBILE6 than EMFAC2007, given that the latter includes data at the county level.
- The incorporation of congestion effects on emissions is a complex issue and topic of much recent debate. MOBILE6 and EMFAC2007 are not well suited to accurately incorporate such effects since they rely on speed correction curves to differentiate emissions by average speed. Previous research has indicated that the use of average speed is not a good proxy for congestion levels. To accurately capture the congestion effects on emissions, a modal emission model (e.g., CMEM) should be used; MOVES2009 also will provide a platform to enable analyses that incorporate the effects of congestion on emissions through a binning approach. A similar discussion applies to truck operations at intermodal yards or distribution facilities, since their operational profiles are very different from long-distance over-the-road trucks.
- There are several concerns about estimating truck VMT from travel demand models or truck counts. First, the estimation of truck VMT generally does not consider enough truck categories to match the number of truck categories in emission models. Second, when used for forecasting truck VMT, travel demand models often do a poor job of representing the complex trip generation and trip distribution patterns of commercial vehicles. Third, the accuracy of average speed at the link level is questioned given that it is not measured directly but is instead estimated from vehicle volume and road capacity. (Link-level speed data may become more precise in coming years with widespread rollout of intelligent transportation systems [ITS] to monitor traffic performance along road segments.) Finally, a high number of time periods is necessary to properly capture the speed variations throughout the day, which increases the computation requirements substantially.
- Many key parameters for emission analyses are based on the Vehicle Inventory and Use Survey (VIUS), which characterizes the truck population in the United States. (*7*) Examples include truck age distribution and mileage accumulation. Because the last version of VIUS was published in 2002 and the 2007 version was canceled, there are concerns about how outdated such parameters are (e.g., introduction of new diesel emission standards).
- In most emission analyses, the distribution of emissions throughout a day, week, month, or year typically is not available. The temporal distribution of emissions is an important input to air quality analyses because ambient temperature and humidity are key factors in air dispersion and in the formation of secondary pollutants.
- The ability of emission models to incorporate the effects of emission reduction strategies depends on the nature of the strategy. For those that affect VMT, such impacts can be

clearly defined. The effects of strategies that affect truck fuel efficiency (e.g., aerodynamic devices) and emission factors (e.g., diesel particulate filters) need to be post-processed after the model runs. For those strategies that have an effect on congestion levels (e.g., incident management, congestion pricing), only modal emission models are able to capture such effects.

The uncertainty analysis of heavy-duty trucks also included an evaluation of the most important input parameters to emission calculations. The two most important factors to characterize the relevance of a parameter in the context of this study are the impact on final emissions and the level of uncertainty in the parameter estimates. Exhibit 1-2 provides a qualitative representation of the relative importance of different parameters for truck emission calculations.

The most important considerations regarding the parameters in Exhibit 1-2 are as follow:

- Truck VMT and emission factors are certainly the most important parameters in this study, given their high impact on final emissions. As previously indicated, there are concerns about estimating total truck VMT with travel demand models, but the level of uncertainty associated with emission factors is higher because of the amount of test data, the fact that most emission factors rely on a limited number of driving cycles, the fact that some models still rely on engine certification data (rather than chassis dynamometer data), and a lack of test data for all truck categories.
- The share of VMT by truck type is also a key factor since emission rates depend substantially on vehicle weight, which is directly correlated with truck class. The main source of uncertainty is that rarely is truck activity data provided with enough level of detail to accurately disaggregate it into enough truck categories.
- In the case of modal emission models, driving cycles are a direct input to emission calculations and have a high impact on final emissions. For those models that do not rely on driving cycles directly for emission calculations (e.g., MOBILE6, EMFAC2007), driving cycles are important in the calculation of emissions to the extent that a good mix of driving cycles is used to provide a good representation of emission factors. The uncertainty associated with driving cycles can be quite high due to the wide variations in vehicle behavior in real-world traffic conditions.
- For those projects that rely on project-derived truck VMT data, or those that estimate truck VMT data from commodity flows, it is necessary to have a good estimate of empty miles since they have a direct influence on VMT. Because of a lack of data sources on empty miles, information generally is obtained from very aggregated data and, therefore, uncertainty can be quite high.

1.6.3 Rail

Because the vast majority of rail activity in the United States is handled by freight railroads, most methods to calculate rail emissions are specifically tailored to freight. Additionally, identifying freight and passenger traffic is relatively straightforward because freight rail activity is reported separately from passenger rail activity. The only exception is the EPA GHG Inventory, where diesel fuel consumption needs to be disaggregated between freight and passenger railroads.

In addition to methods that calculate rail emissions at the national level (EPA GHG Inventory and the NEI), there are other methods at the regional and local/project level scales that estimate fuel consumption by different rail parameters. The only model that calculates rail fuel consumption is the Train Energy Model, which is not analyzed because it is used

Exhibit 1-2. Truck parameters.

Parameter	Methods/Models	Geographic Scale	Impact on Emissions	Parameter Uncertainty
VMT Share by Time of Day	All	Regional/Local	Low/Moderate	Moderate/High
Fuel Type Distribution	All	All	Moderate	Low/Moderate
Average Speed	MOBILE6, EMFAC2007	Regional/Local	Moderate	Moderate
Classification of Truck Types	All	All	Moderate	Moderate
Mileage Accumulation	All	All	Moderate	Moderate
Empty Miles	All	All	Moderate	High
Truck Age Distribution	All	All	Moderate/High	Moderate
VMT Share by Truck Type	All	All	Moderate/High	Moderate/High
Driving Cycle	CMEM	Local	Moderate/High	High
Truck VMT	All	All	High	Moderate/High
Emission Factors	All	All	High	High

in very isolated cases. The main sources of uncertainty associated with these methods are as follow:

- Although Class I railroads are required by the Surface Transportation Board (STB) to report 100% of fuel consumption nationwide, there are concerns about published rail activity. First, there is a lack of published rail activity for a specific region, so local/project level and regional analyses need to either collect data from local railroads (which is generally challenging) or apportion nationwide or statewide data to regions, which brings many methodological issues described later in Section 3.4 of this report. Second, the accuracy of county-level gross ton-mile (GTM) data reported by railroads is largely questioned.
- Many local/project level and regional emission analyses rely on a single measure of fuel consumption index (GTM per gallon) to convert traffic density to fuel consumed. However, correction factors for grade and commodity group can be used to minimize the uncertainty associated with the use of a single measure of fuel efficiency. (*8*)
- For those analyses that cannot rely on traffic density (because it is not reported by railroads), the use of active track or number of employees to apportion nationwide or statewide fuel consumption can result in emission estimates that are highly uncertain.
- The accurate calculation of switch emissions in railyards requires high levels of data because the variation in activity levels per switcher and duty cycles can be substantial. As a result, analyses that rely on default parameters (e.g., average number of hours per switcher) can be highly uncertain.

The uncertainty analysis of rail also included an evaluation of the most important input parameters to emission calculations. The two most important factors to characterize the relevance of a parameter in the context of this study are the impact on final emissions and the level of uncertainty in the parameter estimates. Exhibit 1-3 provides a qualitative representation of the relative importance of different parameters for rail emission calculations.

The most important considerations regarding the parameter uncertainty are as follow:

- In addition to emission factors, fuel consumption is the most relevant parameter due to its direct impact on emissions. The uncertainty associated with fuel consumption estimates can vary dramatically. For example, if fuel consumption is measured directly, either at the national scale or by a participating railroad at a local project, estimates can be quite accurate. However, if fuel consumption is estimated by means of active mileage, then errors associated with this method will propagate to the estimates of fuel consumption.
- Emission factors also have a direct impact on emissions, and the associated uncertainty can be quite high due to a lack of testing data and the wide variation present in the current testing data. Such variation is partly derived from the use of different locomotive types for the development of testing data.
- The share of time in idle mode has a strong effect on emission factors, but there is rarely enough information about locomotive duty cycles at the project level, or there is a measure of uncertainty associated with a "typical" duty cycle. This will likely become less of an issue as railroads implement idle control systems on their fleet (e.g., BNSF has idle control systems in approximately 70% of their fleet).
- EPA emission standards for locomotives are defined as "tiers." The distribution of locomotives across these tiers is an important factor when deriving a composite emission

Exhibit 1-3. Rail parameters.

Parameter	Methods/Models	Geographic Scale	Impact on Emissions	Parameter Uncertainty
Locomotive Type	All (Explicit in Local)	All	Moderate	Moderate/High
Empty Miles	All	Local	Moderate	Moderate
Locomotive Tier Distribution	All	All	Moderate/High	Moderate
Equipment Type	All (Explicit in Local)	All	Moderate/High	Moderate/High
Duty Cycles	All (Explicit in Regional/Local)	Regional/Local	Moderate/High	High
Employees	Emissions by Employees	Regional/Local	High	Low
Miles of Active Track	Emissions by Active Track	Regional/Local	High	Low
Number of Switch Locomotives	Emissions by Switchers	Regional/Local	High	Low
Hours by Switch Locomotive	Emissions by Hours	Regional/Local	High	Moderate
Traffic Density	Emissions by Traffic Density	Regional/Local	High	Moderate/High
Emission Factors	All	All	High	High
Fuel Consumption	National	National	High	High

factor, since emission rates vary widely under different standards. Emission results can be very uncertain if the locomotive tier distribution is not available from the participating railroads.

- Information to describe rail activity data (e.g., traffic density, number of switch locomotives, hours by switch locomotive, miles of active track, number of employees) have a direct impact on emissions, but the level of uncertainty with those estimates varies depending on the parameters. For example, miles of active track, number of employees, and number of switch locomotives are virtually deterministic estimates, and thus have no uncertainty. However, the issue of whether they provide a good proxy for fuel consumption is still a source of uncertainty for fuel consumption estimates. Other estimates such as number of hours per switch locomotive or traffic density are subject to higher uncertainties since they need to be estimated based on limited information from railroads.
- For those projects that rely on project-derived rail activity, or those that estimate rail activity from commodity flows, it is necessary to have a good estimate of empty miles, since they have a direct influence on rail activity. Because of a lack of data sources on empty miles, information is generally obtained from very aggregated data (i.e., railroads report both loaded and empty car-miles by car type nationwide), and thus uncertainty can be quite high.

1.6.4 Waterborne: Ocean-Going Vessels

Emissions from ocean-going vessels (OGVs) are usually determined at and around ports because these are the entrances and clearances of cargo into the regions of modeling interest. They are estimated using information on number of calls at a particular port, engine power, load factors, emission factors, and time in like modes.

There are three basic methods for calculating emissions from OGVs at ports, namely (1) a detailed methodology where considerable information is gathered regarding ships entering and leaving a given port, (2) a mid-tier method that uses some detailed information and some information from surrogate ports, and (3) a more streamlined method in which detailed information from a surrogate port is used to estimate emissions at a “like” port. The detailed methodology requires significant amounts of data and resources and produces the most accurate results. The mid-tier and streamlined methods require less data and resources but produce less accurate results.

Since all current methods and models estimate emissions at ports, the geographic distinctions (i.e., national, regional, and local/project scale analyses) are less meaningful than in other sectors. Generally, to estimate national OGV emissions, all major ports are modeled and emissions are added together. For a regional approach, such as that done by the California Air Resources Board (CARB) to estimate California marine vessel emissions, a similar approach is taken where emissions at the major California ports are estimated and then added together. The difference really relies upon whether a detailed, mid-tier, or streamlined method is used for the individual ports and the data collected.

The main sources of uncertainty associated with these methods are as follow:

- Emissions are linearly related to the number of calls. Accurate assessment of the number of ship calls is critical because there can be errors depending upon the source of the data and the geographic boundaries of the analysis.
- In the detailed and mid-tier approaches, propulsion power is determined directly from Lloyd’s Register of Ships data. On the other hand, auxiliary power is estimated from surveys that produce ratios of auxiliary power to propulsion power by ship type. More accurate determination of auxiliary power would improve emission calculations.
- In the detailed approach, propulsion load factors are calculated using the Propeller Law as defined in Section 3.5.2. There are inherent errors in applying that law to all ships and speed ranges. Currently the Propeller Law is universally accepted as the method to use to determine propulsion load factors and it is doubtful that significant errors would result from these calculations. In addition, knowledge of vessel speed approaching ports may be limited.
- Auxiliary load factors have been determined from limited surveys. More precise determination of auxiliary engine load factors, particularly during hotelling, would provide more accurate results.
- Emission factors for ships were determined for a small subset of engines. Although most ships use similar engines, this set does not represent a large enough sample to be accurate. This is particularly true of PM emissions. Measurement techniques of PM emissions vary and there is sensitivity to sampling methodology (e.g., tunnel length). PM emission factors need a more robust data set to determine them accurately. In addition, current thinking is to estimate $PM_{2.5}$ emission factors as 92% of PM_{10} emission factors. Various studies have estimated $PM_{2.5}$ emissions from 80% to 100% of PM_{10} emissions. Therefore a more accurate determination of $PM_{2.5}$ emission factors is needed.
- Low load adjustment factors to emission factors when the propulsion engine load factor is below 20% also need reviewing. The current methodology as discussed in Section 3.5.2 is based upon limited data and rough curve fits. Improvement of the low load adjustment factors can result in more accurate emission calculations when ships are near ports.
- Current emission factors were determined for engines built before year 2000 when the International Maritime Organization (IMO) set NO_x emission standards on OGV engines.

Exhibit 1-4. OGV parameters.

Parameter	Methods/Models	Geographic Scale	Impact on Emissions	Parameter Uncertainty
Boiler Emission Factors	Detailed	All	Low/Moderate	Moderate/High
Boiler Loads	Detailed and Mid-Tier	All	Low/Moderate	High
Fuel Type	Detailed	All	Moderate	Moderate
Port Selection	Mid-Tier and Streamlined	All	Moderate	Moderate
Auxiliary Emission Factors	Detailed	All	Moderate	Moderate/High
Auxiliary Load Factors	Detailed and Mid-Tier	All	Moderate	High
Auxiliary Power	Detailed and Mid-Tier	All	Moderate	High
Propulsion Power	Detailed and Mid-Tier	All	Moderate/High	Low/Moderate
Calls	All	All	Moderate/High	Moderate
Time in Modes	Detailed	All	Moderate/High	Moderate
Propulsion Emission Factors	Detailed	All	Moderate/High	Moderate/High
Propulsion Load Factors	Detailed and Mid-Tier	All	Moderate/High	Moderate/High

More testing is needed to determine the emission factors for engines built after 2000 as well as for future IMO Tier II and Tier III NO_x emission standards.

- In the mid-tier and streamlined methodologies, selecting a typical port that is like the port to be modeled is of utmost importance. EPA has provided some guidance on how to select the typical port, and a list has been provided based upon detailed inventories prepared at the time. As more ports prepare detailed inventories, this list should be expanded.

The uncertainty analysis of OGVs also included an evaluation of the most important input parameters to emission calculations. Exhibit 1-4 is based on the relative rankings of variability in the input parameters and relative impact on total emission estimates for each parameter.

1.6.5 Waterborne: Harbor Craft

A wide range of commercial harbor craft (H/C) operate in the vicinity of ports, including assist tugboats, towboats, and pushboats, ferries and excursion vessels, crew boats, work boats, government vessels, dredges and dredging support vessels, commercial fishing vessels, and recreational vessels. Many of these vessels serve purposes other than just direct goods movement. To focus the present discussion on freight movements only, only those commercial H/C directly involved in goods movement—tug and towboat operations responsible for moving barges—are considered in this analysis. Section 3.6 provides a detailed discussion of H/C emissions calculations and uncertainties.

There are no common models with the capability to estimate emissions from these vessels; neither CARB's OFFROAD nor EPA's NONROAD model consider commercial H/C. Instead, estimates of emissions from tug and towboats and other commercial H/C may be made through other methodologies. The differentiation of these methods is due to geographic scale.

The best practice or streamlined approaches discussed in EPA's *Current Methodologies* (*9*) comprise the local H/C method, and are treated here as the same methodology. They rely on various sources for the necessary parameters and generally draw on the methodologies of the NONROAD or OFFROAD models. Differences in these methodologies are chiefly dependent on the amount of data directly collected rather than derived through surrogates. Two additional, specific H/C methodologies are EPA's national-scale Regulatory Impact Analysis (RIA), and CARB's analysis of statewide H/C emissions.

Total uncertainty in freight-related H/C emissions from these methodologies can be attributed to process uncertainty (i.e., degree to which the methods accurately represent actual emissions) and parameter uncertainty (i.e., uncertainty in the individual elements used for calculations). Three potentially significant sources of process uncertainty for H/C are as follow:

- The appropriateness and representativeness of the characterizations,
- The groupings used to categorize H/C, and
- The potential for bias in inputs.

There are a variety of primary and secondary parameters that feed into the overall uncertainty and include effects of characterization of engine deterioration and engine age distribution, both of which are noted to influence total uncertainty of estimated emissions. The six principal input parameters used to determine H/C emissions—and therefore the main

Exhibit 1-5. Harbor craft parameters.

Parameter	Methods/Models	Geographic Scale	Impact on Emissions	Parameter Uncertainty
Auxiliary Engine Population	EPA RIA Method, CARB H/C Method	National, Regional	Moderate	High
Engine Power	All	All	Moderate/High	Low/Moderate
Activity	All	All	Moderate/High	Moderate/High
Emission Factors	All	All	Moderate/High	Moderate/High
Load Factors	All	All	Moderate/High	Moderate/High
Main Engine Population	EPA RIA Method, CARB H/C Method	National, Regional	Moderate/High	High

drivers of uncertainty—are listed in Exhibit 1-5. These six primary parameters have their relative contribution to overall uncertainty, which is based on the relative rankings of variability in the input parameters and relative impact on total emission estimates for each parameter.

1.6.6 Cargo Handling Equipment

Cargo handling equipment (CHE) is used to move freight at ports and other intermodal facilities that transfer goods between modes. The diversity of CHE types in use is related to the diversity of freight handled. Similarly, the amount of CHE and its activity are related to the overall amount of freight throughput for a given facility. Depending on the type, use, and number of CHE, their emissions can be significant contributors to overall goods movement emission inventories. Thus, determining emissions from container terminal CHE is important in any land-side emission inventory. Due to their use solely to move goods, all CHE emissions are related to freight. Section 3.7 discusses CHE emissions calculations and uncertainties in detail.

Generally, CHE emissions from freight activities at ports are estimated using either the NONROAD or OFFROAD emission models—or methods similar to those in the models. Two general categories of methods are used to estimate CHE emissions. These are referred to as the best practice and streamlined methodologies. (*10*) Generally, these two differ only in the level of direct information collected and employed in the calculations, as follows:

- The best practice methodology dictates surveys of all equipment to establish correct parameters and then employs the NONROAD or OFFROAD models.
- The streamlined methodology allows for a greater degree of freedom in collecting direct information by substituting surrogate, or otherwise derived, information. It may then either use the models or adjust the methodologies of the models themselves for the available information.
- A special case, third methodology is used in CARB's CHE inventory, which essentially employs the best-practice methodology without directly using the OFFROAD model.

Total uncertainty in the methods used to calculate CHE emissions is due to both process and parameter uncertainty. Three potentially significant sources of process uncertainty are as follow:

- The appropriateness and representativeness of the model characterizations of CHE,
- The groupings used to categorize CHE, and
- The potential for bias in survey results, inventory counts, or inventory scaling methods.

Uncertainty in input parameters is another driver of uncertainty in total calculated emissions. There are a variety of primary and secondary parameters that feed into overall uncertainty, but the five principal input parameters used to determine CHE emissions—and therefore the main drivers of uncertainty—are listed in Exhibit 1-6.

1.6.7 Air Transportation

The representation of freight activity in air transportation is perhaps the most challenging among all modes because unlike other modes, goods are transported both in freight and passenger aircraft. Emissions associated with the transport of freight by aircraft were analyzed using the following two modeling approaches:

- The primary method for national and regional emission analysis in the United States is FAA's System for Assessing Aviation's Global Emissions (SAGE). This model may also be extended to global-scale emission inventories.
- The Emissions and Dispersion Modeling System (EDMS) was developed by FAA to specifically address the impacts of airport emission sources, including ground-level sources

Exhibit 1-6. CHE parameters.

Parameter	Methods/Models	Geographic Scale	Impact on Emissions	Parameter Uncertainty
Engine Power	All	All	Moderate/High	Low/Moderate
Activity	All	All	Moderate/High	Moderate/High
Emission Factors	All	All	Moderate/High	Moderate/High
Load Factors	All	All	Moderate/High	Moderate/High
Equipment Population	All	All	Moderate/High	High

and associated support activity. FAA requires the use of the model in performing air quality analyses for aviation sources. The model can separate aircraft by mode (cargo) but does not distinguish aircraft that carry both cargo and freight.

The main drivers of the uncertainty associated with aircraft emissions below 3,000 ft follow in order of importance:

- Landing and takeoff procedures mainly consist of engine throttle setting, rate of climb/descent, and flight speed. These parameters have been found to be the most important, accounting for 30% to as much as 70% of the total variance of the emissions.
- Idle emission rates are uncertain, particularly below the 7% power setting, and these errors may be large and tend to be an under prediction.
- Other important sources of uncertainty in most emissions data include certification data, the variability of emissions inherent among engines in the fleet, and the change in emissions with the age of the engine.

Aircraft emission models operate at the individual flight level. They use information on model aircraft performance, fuel consumption, trip origination, trip length, type of aircraft, destination, flight position, and flight plan, as well as additional factors such as capacity and delay to estimate emission strength. The models do not have the current capability to separate freight-only travel from freight and passenger operations.

Exhibit 1-7 qualitatively shows how the various input parameters impact emissions and their relative uncertainty to other model input parameters. The largest uncertainties and greatest impacts on emissions are associated with aircraft emission certification because the actual emissions vary widely between aircraft engines and are optimized for the four certification points. Other important parameters affecting emissions deal with the operational characteristics or performance data—particularly the throttle setting used during take-off and landing. In projecting future emissions, moderate uncertainty exists in activity because air cargo is sensitive to economic uncertainties. How emissions change with engine age has not been well studied, but with the very high maintenance standards, these deterioration changes are anticipated to be minimal. Testing the effects of engine age on NOx emissions at certification points has shown a 4% bias in engine emissions with age. (*11*) The best-understood data parameters are the flight position information because most flight location information is captured with FAA radars.

Exhibit 1-7. Aircraft parameters.

Parameter	Impact on Emissions	Parameter Uncertainty
Emission Certification	Low	Moderate/High
Aircraft Weight	Low/Moderate	Low/Moderate
Engine Age	Low/Moderate	Moderate/High
Flight Position	Moderate	Low/Moderate
Retirement Parameters	Moderate	Moderate/High
On-Time Performance (Capacity and Delay)	Moderate/High	Low
Future Activity Projections	Moderate/High	Moderate
Fuel Flow Rate	Moderate/High	Moderate/High
Aircraft Operations	Moderate/High	Moderate/High
Aircraft Performance (Throttle Setting)	Moderate/High	High
Emission Certification	High	Moderate/High

1.6.8 Air Quality

Air quality refers to the level of contaminants in ambient air. It is assessed through measurements and/or numerical model applications. Many freight-related air quality impacts are assessed by modeling studies that couple freight emissions inventories—as discussed throughout this report—with meteorological and other data to estimate concentrations of pollutants resulting from atmospheric releases from goods movement activities.

This discussion focuses on how these concentrations are assessed from the emission estimates discussed in this chapter, and the associated uncertainties. As such, this section does not review the uncertainties in any given model or the uncertainties in any other parameter input to these models, but rather on the emissions-relevant model parameters and processes.

Most commonly, one of the two following general methods will be employed in air quality modeling:

- **Grid Modeling** for national and regional scales (typically for citywide and larger analyses) and
- **Dispersion Modeling** for local/project scales (facility to citywide analyses).

Total uncertainty in predicted concentrations in either method is due to uncertainty in the emission inputs as well as the uncertainties in all other inputs (e.g., meteorology, chemistry) and model formulations. Total uncertainty is generally unquantifiable for Photochemical Grid Models (PGMs), but sensitivity to individual inputs for specific scenarios may be characterized. For dispersion modeling methods, too, this value is generally unquantifiable. However, the uncertainty due to calculated emission rate may be characterized directly from the input uncertainty given its linear nature and lack of other complicating factors. Sensitivity to other emission parameters may be assessed for any particular scenario.

Goods movement emissions are commonly represented as mobile/line (e.g., trucking) or area/volume (e.g., cargo handling equipment) sources. Some sources may be represented as point sources (e.g., hotelling OGVs). In air quality modeling, the representation of emissions strength, location, size, shape, and temporal profile all influence concentration. Other exhaust parameters that may be considered include emission release height, exit temperature, exit velocity, stack diameter, and initial plume size. Other indirect parameters (e.g., shape of buildings, terrain in the region) will also influence concentration. Most of these parameters are not included in a typical emission inventory.

Total uncertainty in predicted concentrations from freight movement represented using a dispersion methodology is due to uncertainty in the following:

- Emission input parameters;
- All other input parameters (e.g., meteorology); and
- Methodology (e.g., model formulation and choice).

Total uncertainty is generally unquantifiable. However, principal emission-related drivers of uncertainty include those shown in Exhibit 1-8. Unlike Sections 3.2 through 3.8, which are directly related to emissions, the "uncertainty" for all air quality parameters is shown here as "high," due to characterization of the variation in values. This is because this variance itself varies greatly between methods, models, and applications.

1.7 Conceptual Model

The Conceptual Model described in Section 4 offers a comprehensive representation of freight activity in the United States, covering all modes and relationships between modes. In order for this model to be effective in improving emissions estimates, it captures the factors in freight movements and freight equipment that most influence emissions.

Exhibit 1-8. Emission-related air quality parameters.

Parameter	Methods/Models	Geographic Scale	Impact on Emissions	Parameter Uncertainty
Source Orientation, Size, and Shape	All	All	Low/Moderate	High
Emission Temporal Profile	All	All	Moderate	High
Exhaust Temperature/Buoyancy Parameters	All (If Plume Rise Is Considered)	All	Moderate	High
Initial Plume Size and Shape	All	All	Moderate	High
Release Height	All	All	Moderate	High
Source Location	All	All	Moderate	High
Emission Rate	All	All	Moderate/High	High

The Conceptual Model serves several purposes as follow:

- It estimates multimodal emissions associated with specific supply chains, transportation corridors, and geographic regions.
- It assists shippers, carriers, and logistics providers in incorporating emissions in the planning and operations of their logistics activities.
- It assists public agencies in incorporating emissions in the planning of transportation infrastructure, transportation investment decisions, and development of transportation regulations and/or voluntary programs.
- It identifies elements of freight activity that are not well represented by available data and methods.
- It identifies how new and emerging freight data and methods relate to existing data and methods, and how they can present a more comprehensive picture of freight movement.
- It identifies opportunities to link mode-specific freight activity data and tools in a unified framework that spans multiple modes and possibly geographic and temporal dimensions.
- It identifies the major sources of potential error propagation and identifies the steps in emissions calculations that warrant improvement.

The Conceptual Model provides the link between economic activity, freight transportation activity, freight-related emissions and associated health effects. The Conceptual Model does not address economic activity directly, but rather uses economic activity to forecast freight activity. At the other end of the spectrum, the Conceptual Model does not model dispersion of emissions or health effects. Instead, it plans for the spatial and temporal allocation of emissions, which will provide the necessary inputs for dispersion models and health risk assessments.

The Conceptual Model includes the definition of all processes necessary for the calculation, allocation, and evaluation of freight-related emissions. Based on a set of input parameters, the Conceptual Model will include a set of equations to calculate emissions. The emission outputs will be associated with either a product (or quantity of a given commodity), freight activity (e.g., measured in ton-miles), link, node, or a geographic area. Lastly, the Conceptual Model includes the spatial and temporal allocation of emissions.

1.8 Recommended Research Areas

Five recommended areas for research that offer great promise for improving freight emissions estimates were developed by the study team. Although these five research statements are mode-specific, the link between modes can be addressed with the implementation of the Conceptual Model.

Each of these areas will improve both the Conceptual Model and modeling of these modes in general. These recommended research areas have been written as research statements with background, objectives, description of tasks and funding requirements described in each research area. This will provide the beginnings for NCFRP to develop statements of work and requests for proposals for future work. The five research areas recommended in Chapter 5 are as follows:

- Improving the allocation of national transportation emissions,
- Refining road project-level emission estimates methodologies,
- Improving rail activity data for emission calculations,
- Improving parameters and methodologies for estimating marine goods movement emissions, and
- Improving air freight emission calculations.

CHAPTER 2

Application of Freight Emissions

This chapter documents the ways that freight transportation emissions are applied to support decisions on public policy, infrastructure investments, and transportation system operations. A solid understanding of how freight emissions estimates are used is necessary in order to assess the uncertainties and potential sources of error in the emissions estimation process.

In many cases, freight emissions estimates are prepared in response to federal or state regulations. These include the National Environmental Policy Act (NEPA) and similar state laws, the Clean Air Act and National Ambient Air Quality Standards (NAAQS), and federal conformity regulations. In other cases, freight emissions estimates are used in non-mandatory studies that serve to educate stakeholders and guide government programs or policy.

Freight emissions estimates are used in several basic ways. In some instances, the emissions estimates themselves are reported and used by stakeholders to inform decisions. In other cases, emissions estimates are fed into air quality dispersion models, which then may feed exposure estimates and health risk assessments. In many applications, freight emissions are combined with emissions from other mobile sources, or even with point and area sources, before they are processed and reported. In these cases, the impact of the freight component of the emissions on the ultimate decision may not be clear.

The set of applications described in this section is by no means comprehensive. The applications included in this section are intended to be the most common and prominent, but the use of freight emissions estimates is almost limitless.

2.1 National- and State-Scale Applications

National- and state-scale applications of freight emissions include GHG estimates as part of the EPA GHG Inventory (1) and state climate action plans, as well as national- and state-scale studies of the health impacts of pollutant emissions.

2.1.1 EPA GHG Inventory

Freight transportation is a significant contributor to U.S. GHG emissions, contributing 26% of transportation GHG emissions and 7% of total U.S. GHG emissions in 2005. (*1*) These emissions are reported in the official EPA GHG Inventory, which is prepared annually by the EPA. Preparation of the inventory fulfills the U.S. commitment as a signatory to the United Nations Framework Convention on Climate Change.

The EPA GHG Inventory reports six primary GHGs identified by the IPCC; three of these—CO_2, N_2O, and CH_4—are produced by, and reported for, the transportation sector. The GHG inventory reports these emissions by year (going back to 1990), fuel, and vehicle type. Some of the fuel/vehicle categories encompass entirely freight sources (e.g., medium- and heavy-duty trucks); others encompass both freight and nonfreight sources (e.g., rail, commercial aircraft).

As a complement to the EPA GHG Inventory, EPA has also conducted studies that examine transportation GHG emissions in greater detail, including an examination of trends for each mode and projections. (*12*) Another EPA-sponsored research study examined the causes for the rapid increase in freight-related GHG emissions since 1990. (*13*)

The purpose of the National GHG Inventory is to provide a common and consistent mechanism for all nations to estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change. The EPA GHG Inventory and complementary studies do not directly affect decisions regarding public policy or infrastructure investment. The studies do influence federal programs, however, including EPA programs targeting the freight sector. For example, in the early part of this decade, EPA used inventory data to highlight the contribution of trucking to GHG emissions, which contributed to the development of the voluntary SmartWay freight efficiency program.

2.1.2 State Climate Action Plans

Many states have estimated GHG emissions from freight transportation as part of state climate change action plans. More than 30 states have developed climate plans. This process typically starts with the development of a GHG inventory and forecast for the state, using methods laid out in EPA's State Greenhouse Gas Inventory Tool. The inventory and forecast is an essential step in identifying effective GHG mitigation strategies.

Following the inventory and forecast, freight emissions are estimated when the benefits and costs of specific GHG mitigation strategies are evaluated. Most state climate action plans include recommendations for one or two freight-focused mitigation strategies. The most common are truck idle reduction, truck fuel efficiency improvements, and freight mode shift to more fuel efficient modes.

Like the EPA GHG Inventory, state climate plans estimate the six primary GHGs identified by the IPCC, and include three of these gases for freight sources: CO_2, N_2O, and CH_4. Emissions of the three gases are combined to be reported in terms of CO_2 equivalent. Exhibit 2-1 shows a typical example of how transportation GHG emissions are presented in a state climate action plan.

In most states, the estimate of freight GHG emissions in the state climate action plan does not directly influence public- or private-sector decision making. The state agencies or stakeholder groups that develop recommendations for mitigation strategies may refer to the inventory and forecast as a way to identify those strategies with the largest potential benefit. In reality, however, the selection of mitigation strategies typically is based on which strategies are thought to be feasible and cost effective, not on which sources contribute the most to the state's emissions.

In states that have mandatory GHG reduction requirements, the emission inventory will be critical for determining compliance with reductions in future years. Approximately 20 states have established GHG reduction targets; to date, only California has mandated an economy-wide emissions cap that includes enforceable penalties.

When individual mitigation strategies are analyzed, the estimate of freight emissions reduction is often done in a relatively simplistic manner, given the time and resource constraints on plan development. The estimation of emissions reduction and cost effectiveness could potentially influence a decision by the state to adopt a policy or implement a program. To date, however, there are few examples of state climate action plans leading to the adoption of GHG mitigation strategies focused on the freight sector. Again, California is an exception, implementing or considering several regulations and programs to reduce freight emissions pursuant to AB 32, Global Warming Solutions Act, mandating GHG reductions. (*14*) These efforts include the following:

- Ship electrification at ports (adopted December 2007),
- Ocean-going vessel speed reduction (proposed),
- Clean ship measure (proposed),
- Port drayage truck rule (adopted December 2007),
- Commercial harbor craft educational program (proposed), and
- Expanded regulations on transport refrigeration units (proposed).

In these instances, the estimation of GHG impacts is a key factor in the state's decision to pursue these measures.

2.1.3 National- and State-Level Health Risk Assessments

EPA has sponsored numerous studies of the public health effects of air pollution. Many of these studies begin with esti-

Exhibit 2-1. Example state transportation GHG emissions by source type, 1990–2020.

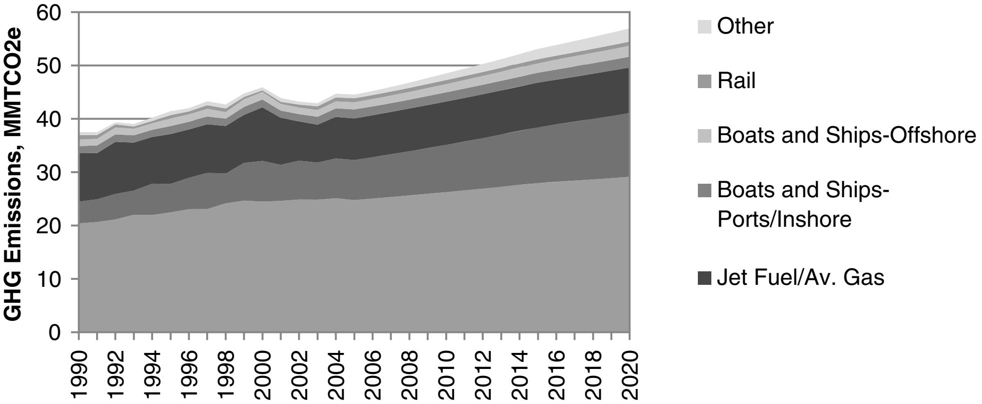
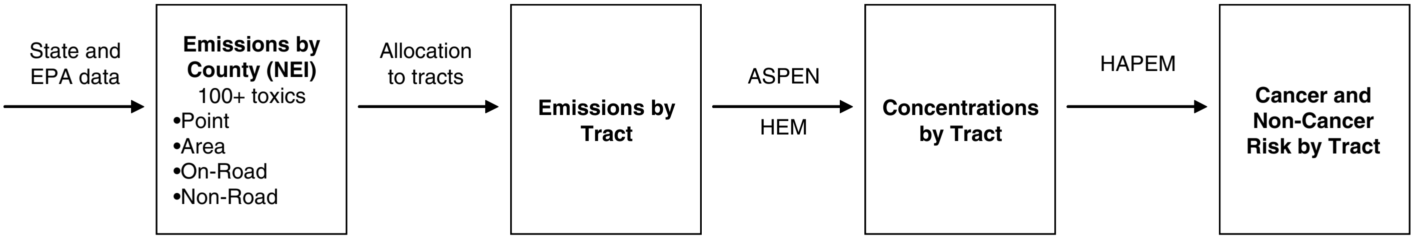


Exhibit 2-2. National air toxics assessment process (simplified).



mates of emissions, including freight emissions. One of the most influential studies is the National Air Toxics Assessment (NATA). (*15*) NATA produces screening-level estimates of cancer and non-cancer health effects of air toxics by census tract for the entire United States. NATA studies have been performed for 1996, 1999, and 2002, and work is continuing on studies for 2005 and 2008.

As shown in Exhibit 2-2, NATA starts with county-level emissions estimates from the NEI. The NEI includes all emissions sources (point, area, on-road mobile, and nonroad mobile) and is developed by state air quality agencies and EPA for more than 100 air toxics as well as criteria pollutants. It includes emissions from trucks, locomotives, marine vessels, aircraft, and nonroad equipment, although the emissions estimates can be simplistic due to the broad geographic scale. County-level emissions in the NEI are allocated to census tracts using spatial surrogates. Dispersion modeling is used to estimate tract-level pollutant concentrations. For mobile and area sources, dispersion modeling is done using the Assessment System for Population Exposure Nationwide (ASPEN) model; for point sources, dispersion modeling is done using the Human Exposure Model (HEM). (Both these models are exposure models that include dispersion modules.) The Hazardous Air Pollutant Exposure Model (HAPEM) is used to estimate exposure, using tract-level data on activity patterns and demographics.

Because of its broad scope, NATA is primarily a screening tool, and EPA advises not to use the results by themselves to identify toxics hotspots or pinpoint specific risk values by census tract. EPA uses the results of assessments in a variety of ways, including the following:

- Set priorities for improving emission inventories,
- Direct priorities in expanding EPA's air toxics monitoring network,
- More effectively target risk reduction activities,
- Identify pollutants and industrial source categories of greatest concern,
- Help set priorities for the collection of additional information, and
- Improve understanding of the risk from air toxics.

Another example of a national-scale health risk assessment is the work that supports the periodic review of the NAAQS. Under the Clean Air Act, EPA is required to periodically review the NAAQS and, if warranted, modify them to protect public health and welfare. The decision to modify the NAAQS is based on epidemiological studies and on exposure modeling. Review of the NAAQS also involves advice from an independent Clean Air Scientific Advisory Committee (CASAC).

EPA has recently completed exposure modeling for the NAAQS review for two pollutants, NO_2 and SO_2. (*16–17*) The studies focused on a small number of specific geographic locations, including Atlanta and Philadelphia for NO_2 review, and several counties in Missouri for SO_2 review. Like NATA, the exposure modeling starts with emissions data from the National Emission Inventory, although roadway emissions were estimated using roadway link traffic volumes from regional travel demand models. Dispersion modeling was done using AERMOD, and exposure modeling was done using the Air Pollution Exposure Model (APEX). These studies result in estimates of the number of individuals exposed to different benchmark levels of air pollution, as illustrated in Exhibit 2-3.

The results of this exposure modeling supports the NAAQS review process and, in combination with results from epidemiological studies, could lead to change in the NAAQS, with far-reaching consequences for public agencies and industry in affected regions.

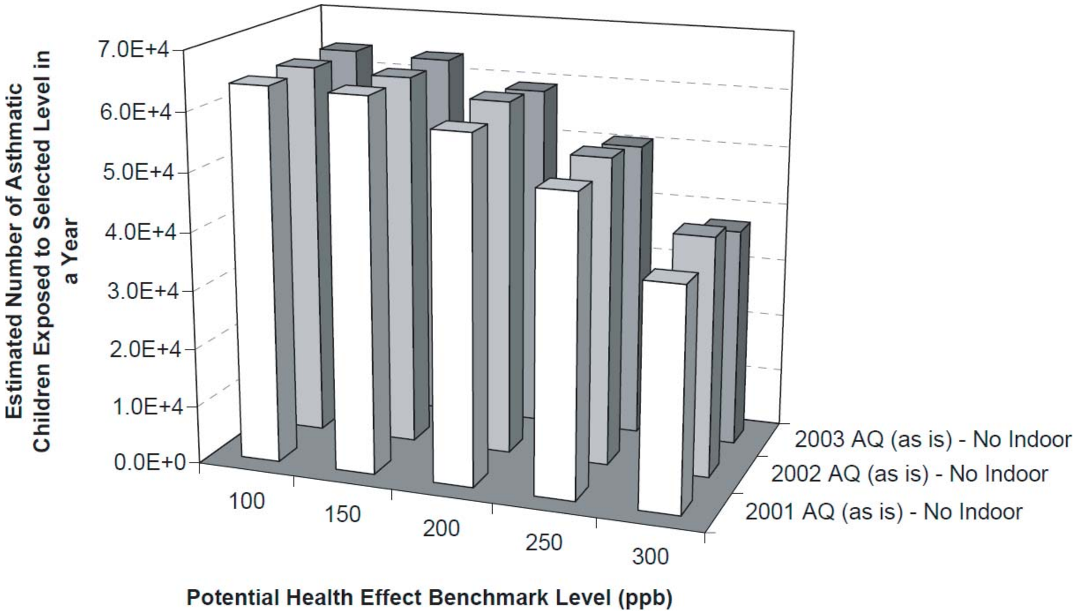
2.2 Regional-Scale Applications

Regional-scale application of freight emissions estimates includes the development of state implementation plans (SIPs) and related Transportation Conformity determinations, as well as regional-scale health risk assessments.

2.2.1 SIP Development

When measured concentrations of a criteria pollutant within a geographic region are below those allowed by the NAAQS, EPA designates the region as an attainment area for that pollutant; regions where concentrations of criteria pollutants exceed federal standards are called *nonattainment areas.* Former

Exhibit 2-3. Example of estimated number of asthmatic children with at least one NO_2 exposure at or above health effect benchmark levels.



Source: *Risk and Exposure Assessment to Support the Review of the NO_2 Primary National Ambient Air Quality Standard*, EPA-452/R-08-008a (Washington, D.C.: EPA, November 2008), p. 199.

nonattainment areas that have attained NAAQS are designated as maintenance areas. Each nonattainment area is required to develop and implement a SIP that documents how the region will reach attainment levels within periods specified in the Clean Air Act.

The SIP typically includes (1) a discussion of the region's air quality issues, (2) a demonstration (using regional dispersion and photochemical modeling) of the emission reductions that are needed to decrease concentrations of the nonattainment pollutants to below the NAAQS, (3) a discussion of the regulations or programs proposed (usually by the state air quality agency for the area) to achieve the necessary emissions reductions, (4) an analysis of the emissions impacts of the selected set of regulations or programs, and (5) evidence of federally enforceable commitments the agency has made to implement the proposed regulations or programs. The attainment demonstration establishes the target emissions level—the "emissions budget"—that the area must achieve in order to attain the NAAQS.

The SIP inventory estimates primary emissions (those produced directly by a source) of the nonattainment pollutant. The SIP modeling estimates secondary emissions (those produced by chemical reactions of precursor pollutants in the atmosphere). Thus, the inventory must also include emissions of any precursors to the nonattainment pollutant, and the modeling includes their atmospheric reactions that produce the nonattainment pollutant.

The regional emissions inventory is a critical element of the SIP process because all modeling of concentrations depends on knowledge of the emissions in the nonattainment area (and sometimes the emissions upwind of the area as well). The regional emissions inventory is forecast to future years and compared to the emissions budget in order to track the area's progress over time toward attainment. The emission inventory identifies the contribution of each source type to the area's total emissions. The emission inventory informs the air quality agency's planning process for developing, evaluating, and selecting emission reduction strategies. Emission inventory information also helps the agency allocate resources most efficiently to produce the greatest emissions reductions at the lowest cost.

Some attainment areas or regions within attainment areas voluntarily develop emission inventories for planning purposes. These purposes may include voluntary emission reduction initiatives and development of emission reduction strategies in areas that anticipate becoming nonattainment areas in the near future.

Regional emission inventories follow the EPA classification scheme that divides emission sources into point, area, and mobile categories. Point sources are stationary sources that have a stack or other definable location from which emissions emanate (e.g., fossil-fueled electric power plant). Calculation of the point source emissions inventory is relatively straightforward because characteristics of many sources are obtain-able from their required air quality permits. Area sources are generally point sources that are too small to inventory individually, such as small dry cleaning establishments. Area source emissions are estimated using economic and demographic information where source-specific data are unavailable. Mobile sources usually are divided into on-road and off-road components for inventory purposes. On-road mobile sources consist of cars, trucks, motorcycles, and buses. Off-road mobile sources consist of several diverse groups such as construction equipment, railroad locomotives, ships and boats, port cargo handling equipment, aircraft, and aircraft ground support equipment. Accordingly, in a regional emissions inventory, the sources of freight-related emissions are classified almost exclusively as on-road and off-road mobile sources.

Since passage of the Clean Air Act Amendments (CAAA), EPA has tightened its emission standards considerably on nearly all source categories. Many nonroad sources are subject to retrofit requirements reducing emissions at the time of overhaul. This reduces emissions better than regulation that only addresses freshly manufactured equipment. Until recent years, the nonroad mobile source category was a relative exception. As emission control requirements on other sources, including highway vehicles, have become stricter, their relative shares of the total emissions inventory have shrunk. As a result, the off-road mobile source category, which had been less heavily regulated and includes many engines with long lifetimes and consequent slow rates of replacement with cleaner models, contributes an increasing share of the total emissions. In recent years EPA, state air quality agencies, and port/airport operators have focused greater regulatory attention on off-road mobile sources. This has included adoption of retrofit requirements for in-use (as opposed to new) equipment. Because a large proportion of off-road mobile sources are associated with freight transport, the importance of freight-related emission calculations for the off-road components of regional emission inventories is increasing.

2.2.2 Transportation Conformity

Section 176(c) of the Clean Air Act (CAA) prohibits federal agencies from taking actions in nonattainment or maintenance areas that do not "conform" to the area's SIP. The purpose of this conformity requirement is to ensure that general activities do not interfere with meeting the emissions targets in the SIPs, do not cause or contribute to new violations of the NAAQS, and do not impede the ability to attain or maintain the NAAQS. The conformity rules apply only to criteria pollutants. The EPA has issued two sets of regulations to implement CAA Section 176(c), as follow:

- **Transportation Conformity Rules** (40 CFR 51, Subpart T), which apply to transportation plans, programs, and projects funded under Title 23, U.S. Code, or the Federal Transit Act. Highway and transit infrastructure projects funded by FHWA or the Federal Transit Administration (FTA) usually are subject to transportation conformity. A region's FHWA-required long-range transportation plan also is subject to Transportation Conformity.
- **General Conformity Rules** (40 CFR 51, Subpart W) apply to all other federal actions not covered under Transportation Conformity. The General Conformity Rules established emissions thresholds, or *de minimis* levels, for use in evaluating the conformity of an action. General Conformity typically applies at the project-scale for airports, seaports, and military bases.

In metropolitan regions within nonattainment areas, the federally designated metropolitan planning organization prepares the FHWA-required long-range transportation plan, which is subject to Transportation Conformity, as previously noted. The conformity demonstration for the plan is based on an emissions inventory for the highway system in the region subject to the plan. This inventory usually is coordinated with, or is a subset of, the nonattainment area's regional mobile source emissions inventory. Exhibits 2-4 and 2-5 present example emissions tables from a regional conformity determination for a long-range transportation plan.

Freight trucks are included in the traffic data (counted or projected traffic volumes by road segment) that are input to the travel modeling that supports the plan's inventory calculations. Although diesel-fueled trucks are relatively high emitters of NO_X and $PM_{2.5}$ on a per vehicle basis, the emission

Exhibit 2-4. Example of VOC emissions tables from a regional conformity determination for a long-range transportation plan.

	VOC Emissions (Tons per Summer Day)			
Year	Region Action Emissions	Statewide Action Emissions	Emissions Budget	Difference (Action – Budget)
2000	n/a	166.5	n/a	n/a
2007	22.7	62.0	86.7	-24.7
2010	18.7	49.7	86.7	-37.0
2020	13.5	29.8	86.7	-56.9
2030	12.9	28.7	86.7	-58.0

Exhibit 2-5. Example of NO_X emissions tables from a regional conformity determination for a long-range transportation plan.

	NO_X Emissions (Tons per Summer Day)			
Year	Region Action Emissions	Statewide Action Emissions	Emissions Budget	Difference (Action – Budget)
2000	n/a	287.9	n/a	n/a
2007	63.8	174.1	226.4	-52.3
2010	48.3	129.2	226.4	-97.2
2020	24.3	45.4	226.4	-180.9
2030	20.2	34.7	226.4	-191.6

inventories for most Transportation Conformity demonstrations do not analyze trucks as a separate source category because truck volumes are a relatively small fraction of total traffic volumes and most long-range transportation plans contain few dedicated freight facilities. In contrast, where a nonattainment area is considering truck-oriented strategies to reduce emissions, the mobile source inventory for the area's SIP may address heavy-duty diesel trucks in greater detail, especially in $PM_{2.5}$ nonattainment areas.

2.2.3 Regional Health Risk Assessments

Freight emissions figure prominently in many health risk assessments because freight transportation is a major source of diesel PM in many areas. A number of regions have prepared health risk assessments to better understand the relationship between emissions and public health at the metropolitan scale. Major studies include the following:

- Multiple Air Toxics Exposure Study III (MATES III) in the Los Angeles metropolitan area is led by the South Coast Air Quality Management District. (*18*)
- Puget Sound Air Toxics Evaluation, led by the Puget Sound Clean Air Agency in conjunction with Washington State Department of Ecology. (*19*)
- Portland Air Toxics Assessment (PATA), led by the Oregon Department of Environmental Quality with Portland METRO and EPA. (*20*)
- Houston Exposure to Air Toxics Study (HEATS) is a collaborative study involving local universities, state, federal, and local government agencies, and research organizations. (*21*)

These studies typically begin with a detailed inventory of air emissions, including the six priority mobile source air toxics (MSATs) defined by EPA as acetaldehyde, acrolein, benzene, 1,3-butadiene, diesel particulate matter, and formaldehyde. (*22*) Air quality modeling is then used to estimate resultant average pollutant concentrations throughout the region. Several different air quality modeling tools have been used for these studies, including CAMx (for MATES III) and CALPUFF (for PATA). Ambient air pollution monitoring data are typically compared to modeled concentrations in order to assess the accuracy of the model.

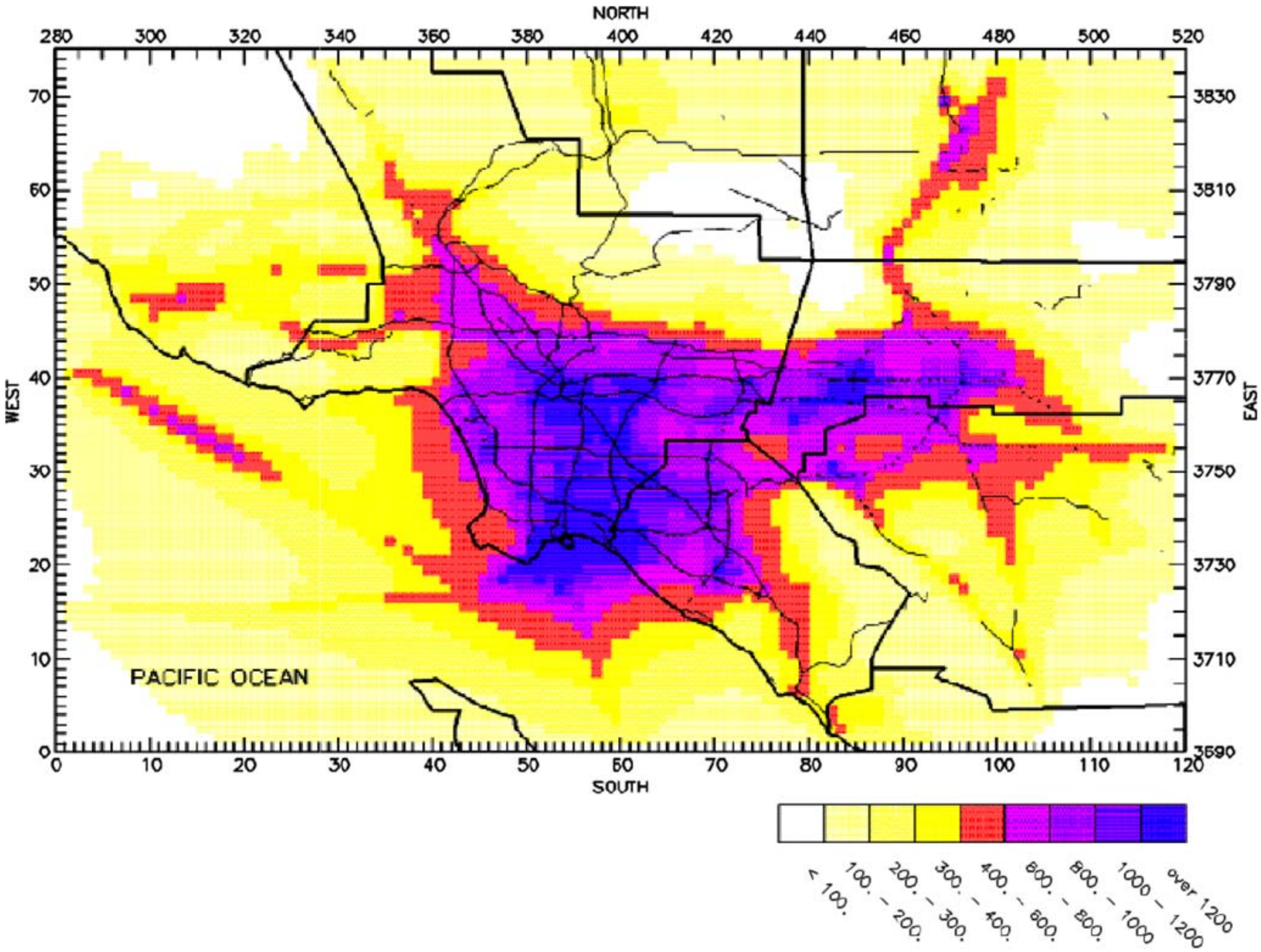
The health risk assessments then use exposure models to link ambient concentrations of pollutants with population, activity, and other parameters to determine overall population exposure. An exposure model attempts to characterize the activities and movement of individuals within a given area, usually a census area, and from that estimate a range of concentrations to which that population would be subject. For example, in a given census tract there are young children and the elderly who remain indoors most hours of the day, older children who go to school or play outdoors, workers who commute to other areas, and others with a range of activities. Varying ranges of activities expose individuals to different amounts of outdoor ambient air, or outdoor air as it infiltrates buildings. An exposure model uses information from each census tract to estimate the range in age of the population, their activities, and commuting habits, and calculates a range of concentrations to which they are exposed. (*20*)

Toxicity factors for each pollutant are combined with exposure estimates to estimate health risk—the probability of an adverse health outcome. Risk can then be illustrated on a map as shown in Exhibit 2-6.

In most of these studies, diesel particulate matter is the dominant source of cancer risk. For example, the MATES III study found that the cancer risk from air toxics in the Los Angeles region is about 1,200 per million, and about 84% of that risk comes from diesel exhaust. In many cases, freight transport is the largest source of diesel emissions.

Regional health risk assessments are used by regional, state, and federal agencies to develop more effective strategies to reduce risks to residents. In places like the Portland and Seattle regions, which are in attainment for PM and ozone, the studies have been used to support planning and investments in diesel emission reduction programs. Although these areas do not violate federal air quality standards, they are still interested in reducing the negative health impacts of air toxics emissions. For example, the PATA study is described as a "key step in a community planning process to reduce air toxics in the Portland area." (*23*)

Exhibit 2-6. Example of regional-scale model estimate of cancer risk.



Source: *Multiple Air Toxics Exposure Study III (MATES III)*, South Coast Air Quality Management District at http://www.aqmd.gov/prdas/matesIII/matesIII.html.

2.3 Project-Scale Applications

At the project scale, freight emissions estimates can directly affect the go/no-go decision for a project, or can influence decisions to invest in mitigation measures. Project-scale applications include the comparison among project alternatives and assessment of air quality compliance as required by NEPA and similar state statutes. They can include project-scale emissions estimates to satisfy the Conformity Regulations. They also can include emissions estimates for discrete freight facilities and terminals, including railyards, seaports, and airports.

2.3.1 NEPA and Similar State Processes

Requirements

NEPA is the foundation of environmental impact analyses in the United States and usually provides the forum in which project-level emission estimates are made and air quality impacts evaluated. Under NEPA, a project must be assessed if it involves a "major federal action significantly affecting the quality of the human environment." (*24*) Every project must be evaluated to determine whether it meets this threshold. Some federal agencies maintain lists of Categorical Exclusions (CEs) that specify project types that the agency presumes will not have a significant impact. Normally, CEs do not require detailed emissions analysis. Projects that could have a significant impact require either an environmental assessment (EA) if the agency believes the potential for significant impacts is low or an environmental impact statement (EIS) if the agency believes the potential for significant impacts is high. The methods for estimating freight emissions are essentially the same for EA and EIS, although the level of detail may be greater for an EIS.

Most large transportation infrastructure projects—whether or not dedicated to freight—fall under NEPA because they entail funding, permitting, or other approval by a federal agency. For many projects, the application of NEPA is clear because federal jurisdiction occurs directly, often with several agencies and actions. For example, a new interstate highway would carry truck traffic and might involve FHWA funding, consultation on endangered species with the U.S. Fish and Wildlife Service, and wetlands permits from the Army Corps of Engineers, among others. For other freight projects, the event that triggers NEPA may not be obvious; for example, a state DOT that is sponsoring a truck stop project may support part of the project from FHWA grant funds. An airport may construct a cargo facility that would not require federal involvement but the project appears on the Airport Layout Plan, and a change to the Airport Layout Plan requires approval by the FAA. From the NEPA perspective, most transportation infrastructure projects involve emissions from multiple vehicles or sources, only a portion of which happen to be hauling freight. Emissions analyses under NEPA treat freight-related emissions in greater or lesser detail depending on the magnitude and significance of emissions from the freight-related activities that would be served by, or affected by, the project. The level of rigor and detail for the freight emissions analysis is largely a project-specific decision.

Freight railroad projects may trigger NEPA due to funding by FRA or permitting by other federal agencies as in the highway example above. Freight railroad projects that consist only of operational changes rather than infrastructure construction also may trigger NEPA if they fall under the jurisdiction of the federal Surface Transportation Board (STB). Several types of economic actions, including certain railroad mergers, acquisitions, and proposals for new services over existing railroad lines, require STB approval and consequent NEPA review.

Several states, including Washington, Massachusetts, and California, have statutes similar to NEPA that establish state-level environmental review processes. The state-level review processes have various triggers that differ from state to state. Triggers include type of project, size of project, cost of project, requirement for a state agency permit, and use of state funds. Some state processes mandate preparation of NEPA-like documents that cover impacts to all resource areas (air quality, water quality, etc.), while other processes may include only the subject matter of the triggering event (e.g., a project that must obtain an access permit for an entrance that fronts a state highway might be required only to analyze traffic impacts). Projects located in California are subject to the California Environmental Quality Act (CEQA) process. Unlike most state processes, CEQA and its implementation by California's air quality management districts (sub-state regional agencies to which California has delegated some air quality regulatory authority) often necessitate more complex air quality analysis and more mitigation effort than NEPA does. In many cases, the state-level review proceeds concurrently with NEPA, and the lead agency produces a single environmental impact document that satisfies both NEPA and the state review process. A few municipalities have their own environmental review processes that are similar to NEPA and may require similar air quality analysis.

Types of Emissions Estimated under NEPA

Project-level emissions analyses under NEPA and similar state laws focus primarily on the criteria pollutants. However, as concern about MSATs has mounted, FHWA and state DOTs have increasingly received requests for MSAT analysis in agency-funded EISs. The issue of air toxics has been raised with several major highway projects around the country, resulting in lengthy deliberations and, in some cases, litigation. (*25–26*) At the same time, the FAA has also received increasing requests for MSAT analysis in its EISs for airport projects. Airport projects typically involve MSAT emissions from multiple source classes including aircraft, on-road vehicles, and off-road sources such as aircraft ground support equipment (GSE) and construction equipment. Experience in the early 2000s with MSAT analysis for major EISs at large airports such as Los Angeles International, (*27*) Chicago O'Hare (*28*) and Philadelphia International (*29*) led to FAA's issuance of interim MSAT guidance. (*30*) California agencies have long required MSAT analysis as well as health risk assessment in CEQA environmental impact reports (EIRs), which are the California state-level counterpart to NEPA EISs. Most projects focus on priority MSATs because they represent the bulk of total health risk. The MATES III study identifies DPM as the primary cancer risk factor out of all MSATs. Proximity to transportation facilities, typically roadways, has been established as a primary factor leading to community exposure and potentially increased risk.

HAPs other than MSATs are normally not evaluated separately in NEPA analyses of transportation projects. MSATs as a class, and priority MSATs in particular, should be good surrogates for all relevant HAPs because most are species of VOC or PM. The speciation distributions of VOC emissions are generally similar for broad classes of transportation sources. The speciation of PM emissions differs markedly between gasoline and diesel sources, but less so within the diesel source classes. In most cases, if emissions of priority MSATs are insignificant, then emissions of other transportation HAPs also will be insignificant and need not be analyzed in detail.

Requests during NEPA, CEQA, and state-level scoping to include GHG emissions have become commonplace and many agencies now routinely require these GHGs in project emission estimates. The White House Council on Environmental Quality (CEQ) issued draft NEPA guidance on climate change in 1997 that was never finalized. (*31*)

NEPA Application: Comparison of Proposed Project Alternatives

Emissions estimates are used for purposes of disclosure and agency decision making. NEPA requires that project impacts be disclosed to the public and that the sponsoring agency make a determination as to whether the impacts of the project would be "significant." Potentially, the most important use of emission estimates is to assist the agency in selecting which alternative to implement from the set of project alternatives. In NEPA and similar processes, the alternative selection must consider air quality impacts as well as impacts on other resource areas. For purposes of alternative selection, the absolute magnitude of a project's air quality impact may be less important than the relative differences or ranking of air quality impacts among the alternatives and the directional trend in predicted emissions over time.

Air quality impacts are characterized by emissions for overall or regional-level comparisons among alternatives and for purposes of compliance with the EPA Transportation Conformity and General Conformity Rules. Where localized impacts are a concern, emissions data are used for input to dispersion modeling that estimates the pollutant concentrations at specific locations for comparison to the NAAQS and state standards for criteria pollutants. NAAQS have not been established for MSATs, although some states have established guidelines for ambient MSAT concentrations. If significant MSAT impacts are anticipated, the dispersion model results may be used as input to a human health risk assessment. Most project-related health risk assessments are conducted in California under CEQA and agency processes for air quality permitting of stationary emission sources.

No ambient standards exist for GHGs. Most analyses report GHG emissions by project alternative and may provide a simple comparison of project GHG emissions to the total GHG emissions in the region or state. Climate change impacts of GHGs usually are treated as a cumulative impact under NEPA. Currently, the state of the practice for project-level GHG/climate change analysis is evolving.

For many projects, especially highways, the emissions from project alternatives may differ very little in relative terms. For such projects, the influence of emissions on agency decisions tends to be slight at most. This is true for both highway projects in general and also for the portion of emissions from freight trucks, since most highway projects do not involve dedicated truck facilities that would necessitate a separate accounting of truck emissions. However, if the geographic variation of the project alternatives is large (multiple corridors or diverse communities), then the equity considerations of where the impacts would occur may loom larger in agency review and public comment than considerations of the magnitude of emissions. These concerns often are addressed in the socioeconomic and environmental justice sections of an EA/EIS, and therefore the air quality analysis would be sufficiently detailed to support evaluation of these resource areas. Highway impacts of MSATs and PM are related mostly to heavy-duty diesel trucks and, as a result, the freight component of the project emissions must be accounted for in these analyses.

Railroad projects may be entirely freight-related or may include passenger train movements and possibly effects on highway traffic volumes due to project-induced changes in modal shares. Port projects are usually dominated by freight movement and involve emissions mostly from diesel engine sources. For these projects, almost all of the project impact comes from freight. Airport emissions usually are dominated by emissions from passenger aircraft and GSE, followed by motor vehicles accessing the airport. Air freight may be carried in dedicated cargo aircraft, which are a small proportion of the total flights at most airports, as well as "belly cargo" in passenger aircraft. For these reasons, the emissions due to freight as opposed to passenger operations at an airport can be difficult to separate within the total aircraft and GSE emissions.

The results of emissions calculations may be presented in various ways depending on the project and the intended audience. Exhibit 2-7 presents an example of a table showing the emissions estimate for a single project alternative at an airport. Exhibit 2-8 presents an example of an EIS emissions comparison among all alternatives for a highway project.

NEPA Application: Ambient Air Quality Standards Compliance and Health Risk Assessment

Local air quality impacts in the project vicinity are evaluated using dispersion modeling that produces estimated pollutant concentrations at specific locations of interest (known as receptors). Typical receptors include residences, health care facilities, educational facilities, and recreational areas. The estimated concentrations are compared to the NAAQS and other applicable standards to determine compliance and the significance of the impacts. Dispersion modeling typically is conducted as part of project analysis under NEPA and similar state review processes, but also may be performed for project-level Transportation Conformity evaluations, applications for funding or air quality permits, and planning studies. Because concentrations are being compared to numerical standards, the absolute levels of impact must be calculated and it is important to choose calculation methods that yield the greatest possible confidence in the numerical results.

The decision on whether to model the ambient pollutant concentrations or health risks due to a project is based on an assessment of whether the project's impacts are likely to be significant. Under NEPA, the threshold of significance for concentrations is commonly taken to be the NAAQS. Under

Exhibit 2-7. Example emissions estimate for a single alternative for an airport project.

	Projected Emissions (kg/Day)		
Source Categories	**VOCs**	**NOx**	**CO**
Aircraft Sources[1]			
Air carriers	350	4,300	3,337
Commuter aircraft	61	459	640
Cargo aircraft	21	309	194
General aviation	304	61	499
Total aircraft sources	736	5,129	4,669
Ground Service Equipment[2]	234	294	5,670
Motor Vehicles			
Parking/curbside	16	5	112
On-airport vehicles	60	79	851
Total motor vehicle sources	76	84	963
Other Sources[3]			
Fuel storage/handling	475	0	0
Miscellaneous sources	9	211	33
Total other sources	484	211	33
Total airport sources	1,530	5,717	11,335

Notes:

[1] Calculations for 2020 are based on taxi times based on the proposed Airport Improvements Planning Project.

[2] Includes vehicles and equipment converted to alternative fuels based on the 2004 fleet mix.

[3] Includes the central heating and cooling plant, emergency electricity generation, and other stationary sources.

NEPA and similar review processes, public or agency comments during project scoping may indicate sufficient concern to perform modeling even if impacts are expected to be insignificant. Some agencies have issued quantitative guidelines based on traffic volumes, aircraft operations, proximity to receptors, or similar criteria that determine whether dispersion modeling should be conducted for a project. At other agencies, the decision may be based on professional judgment informed by precedent, the results of previous projects, or the current state of modeling practice. Similar considerations apply to a decision on whether to conduct a health risk assessment for a project.

For highway projects and other projects involving highway traffic access (potentially almost any type of freight project), criteria pollutant impacts are modeled at "hotspots," which are locations at which relatively high emissions are expected to occur due to traffic congestion. Hotspot modeling is used to assess impacts of CO, PM, and sometimes NO$_X$. Typical hotspot types include signalized intersections, roadway/rail grade crossings, and other locations where queuing occurs such as toll plazas and freight terminal entrances. Most agency guidance specifies use of the EPA CAL3QHC model, or the California DOT (Caltrans) CALINE4 model in California. Prior to dispersion modeling, potential hotspots normally are screened according to traffic volumes, level of service, and queuing levels with the worst locations being selected for air quality modeling. In the past, criteria pollutant impacts also

Exhibit 2-8. Example EIS emissions comparison among alternatives for a highway project (tons/year).

Pollutant	2008 Existing Conditions	2012 No-Build Alternative	Build Alternative 1	Build Alternative 2	Build Alternative 3
CO	74.92	76.02	82.49	78.56	79.63
VOC	2.77	2.88	3.28	3.04	3.10
NO$_X$	1.61	2.17	2.48	2.29	2.34
SO$_2$	0.14	0.19	0.20	0.19	0.20
PM$_{10}$	4.25	4.37	4.61	4.42	4.49
PM$_{2.5}$	4.01	4.03	4.12	4.04	4.06

were modeled at receptors along the highway itself. Emission rates from motor vehicles have decreased steadily due to EPA regulations under the CAAA and now are so low that, in most cases, agencies no longer require dispersion modeling for locations along the highway mainline if vehicles are traveling at cruise speeds.

For non-highway projects, projectwide dispersion modeling for criteria pollutants is common, and the criteria pollutant of greatest concern usually is PM. For large projects, and where specified by agency guidance (primarily in California), dispersion modeling of MSATs is used to characterize concentrations and (again, primarily in California) to support health risk assessments. The MSAT of greatest concern usually is DPM. Although the PM classes $PM_{2.5}$, PM_{10}, and DPM have unique definitions, in practice their emission rates for freight projects are similar in terms of mass emitted, because for most freight projects the primary emissions source is diesel engines and most DPM falls into the $PM_{2.5}$ size class. The most commonly specified models for this application are EPA's AERMOD and CALPUFF. In California, the Hotspots Analysis and Reporting Program (HARP) model combines dispersion modeling and health risk assessment processes. The dispersion component of HARP uses the EPA's ISC3 model, which is the predecessor of AERMOD.

2.3.2 Project-Level Conformity

As discussed in Section 2.2, the conformity regulations prevent federal actions in nonattainment or maintenance areas that interfere with meeting the emissions targets in the SIPs or contribute to new violations of the NAAQS.

Most highway projects are included in a conforming regional transportation plan or TIP and thus are subject to Transportation Conformity (Section 2.2.2) as part of the entire plan. In a few limited circumstances, a project that is located in a nonattainment or maintenance area and is subject to Transportation Conformity must perform a project-level conformity determination. The project-level conformity determination can entail emissions estimates, air quality modeling studies, consultation with EPA and state air quality agencies, and commitments to revise the SIP or to implement measures to mitigate air quality impacts. This requirement creates an incentive for agencies to have a project included in the long-range transportation plan in order to avoid the need for a project-level conformity evaluation. In many cases, and almost universally with large highway projects, the project is included in the plan's travel modeling from the outset.

The General Conformity Rules apply to all other federal actions not covered under Transportation Conformity. General Conformity typically applies at the project-scale for airports and seaports. The General Conformity Rules established emissions thresholds, or *de minimis* levels, for use in evaluating the conformity of an action. Because the General Conformity Rules have absolute emissions thresholds for project-related emission increases, it is important to estimate emissions accurately without excessive conservatism (overestimates) and to include design and operational features that will help reduce emission increases below the thresholds and avoid the need for a conformity determination.

If the net emission increases due to the project are less than these thresholds, then the project is presumed to conform and no further conformity evaluation is required. If the emission increases exceed any of these thresholds, then a conformity determination is required. The conformity determination can entail air quality modeling studies, consultation with EPA and state air quality agencies, and commitments to revise the SIP or to implement measures to mitigate air quality impacts.

The conformity process is separate from NEPA and other environmental reviews but, because the required technical studies are very similar, a conformity evaluation usually is conducted concurrently with other environmental review processes.

2.3.3 Emissions Estimates for Linear Projects

Transportation infrastructure projects that are linear in nature include highways, rail lines, and some waterways. These projects may span multiple state and local jurisdictions, and federal involvement is almost assured. Emissions estimates are required for NEPA, sometimes for conformity, and to support dispersion modeling of project impacts. In California, they may support health risk assessments as well. Project-level emission estimates for linear transportation projects generally are used only for project approval, and are not used directly in regional emission inventories or SIPs. Exhibit 2-9 presents typical characteristics of emission inventories for linear freight transportation projects. Emissions are estimated separately by type of source.

2.3.4 Emissions Estimates for Discrete Freight Facilities/Terminals

Railyard Health Risk Assessments

Locomotive emissions estimates have been used to prepare health risk assessments (HRAs) for major railyards in California. BNSF and UP agreed to prepare these HRAs for 17 individual railyards when they signed a statewide railroad pollution reduction agreement with CARB in 2005. The HRAs must be prepared based on CARB's experience in preparing the Roseville Railyard Study (*32*) as well as CARB guidance. (*33*)

Emissions are estimated for all sources within the railyards, potentially including locomotives, on-road trucks, cargo handling equipment, heavy equipment, transport refrigeration

Exhibit 2-9. Typical characteristics of emission inventories for freight transportation projects.

Project Type	Regulatory Process and Use of Emissions Estimates*					Major Features of Emissions Estimates		
	NEPA	State Env. Review	Transp. Conf.**	General Conf.**	Planning/ Initiatives	Typical Sources Included	Construction Emissions	Emissions Models Used
Linear Project								
Highway	✓	✓ (in some states)	✓	–	✓	Trucks, Cars	No	MOBILE6.2, MOVES (draft), EMFAC (in CA)
Railroad	✓	✓ (in some states)	–	✓	–	Locomotives, Trucks (Freight Diversion)	For General Conformity only	MOBILE6.2, MOVES (draft), EMFAC (in CA), off-model databases and calculations
Waterborne (e.g., Canals, Channel Dredging)	✓	✓ (in some states)	–	✓	–	Ships, Dredges, Support Vessels	For General Conformity only	Off-model databases and calculations
Discrete Facility								
Truck Stop or Terminal	S	S	S	–	S	Trucks	For General Conformity only	MOBILE6.2, MOVES (draft), EMFAC (in CA)
Railyard or Intermodal Terminal	S	S	S	S	✓	Locomotives, Trucks (Drayage), Cargo Handling Equipment	No	MOBILE6.2, MOVES (draft), EMFAC (in CA), NONROAD, OFFROAD (in CA)
Seaport	✓	✓ (in some states)	–	✓	✓	Ocean-Going Vessels, Harbor Craft, Cargo Handling Equipment, Locomotives, Trucks (Drayage), Stationary Sources, Electric Power Generation	For General Conformity only	MOBILE6.2, MOVES (draft), EMFAC (in CA), NONROAD, OFFROAD (in CA), off-model databases and calculations
Airport	✓	✓ (in some states)	S	✓	✓	Aircraft, GSE, Trucks, Cars, Buses/Vans, Fuel Handling, Stationary Sources, Electric Power Generation	For General Conformity only	EDMS, off-model databases and calculations

Notes:
* Process: ✓ Likely; – Unlikely; S Sometimes, depending on project size and federal involvement.
** Conformity rules apply in nonattainment and maintenance areas only.

units (TRUs) and refrigerated rail cars, stationary sources, and portable equipment. These emission inventories, conducted by the railroads and CARB, focus on emissions of TACs—primarily diesel PM, but also gasoline TACs such as isopentane, toluene, and benzene.

The studies start with preparation of an emission inventory, which is performed by the railroads following CARB guidance. (*34*) Emissions are reported by source type, as illustrated in Exhibit 2-10.

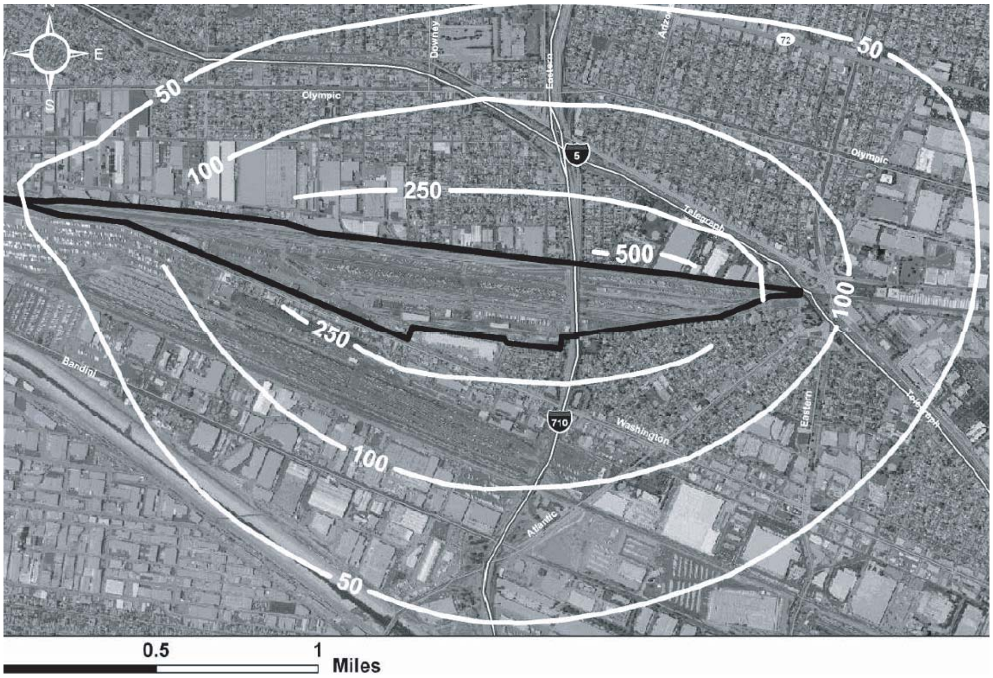
The railroads then estimated pollutant concentrations in the vicinity of the railyard using AERMOD, an EPA-approved dispersion model. In addition to the emissions, meteorological factors (including wind speed and wind direction) are key inputs to the dispersion model. CARB multiplied the resulting concentrations by cancer risk factors to estimate cancer risk, expressed as the chances of excess cancer risk per million people. Cancer risk is illustrated using isopleths—lines drawn on a map through all points of equal cancer risk. Exhibit 2-11 shows an example of this presentation.

These railyard health risk assessments are prepared under voluntary agreements and are not directly related to any regulation or government decision-making process. However,

Exhibit 2-10. Example of railyard diesel PM emissions (tons/year).

On-Site Sources	Railyard 1	Railyard 2	Railyard 3	Railyard 4	Total	% of Total
Locomotives	4.9	5.9	2.3	0.6	13.6	33%
On-Road Trucks	2.0	10.1	-	1.1	13.2	32%
CHE	4.8	4.2	-	0.4	9.4	22%
Others	0.4	3.7	0.4	1.0	5.5	13%
Total	12.1	23.9	2.7	3.1	41.7	
% of Total	29%	57%	7%	7%		100%

Exhibit 2-11. Example of estimated potential cancer risks from railyards (chances per million people).



Source: Air Resources Board, *Health Risk Assessment for the Union Pacific Railroad Commerce Railyard*, November 2, 2007. Available at http://www.arb.ca.gov/railyard/hra/up_com_hra.pdf.

HRA reports can influence public policy decisions in a number of ways. The cancer risk estimates provide compelling information to community and environmental groups advocating for emission controls. CARB uses this information to make decisions regarding new initiatives to reduce diesel emissions.

Seaport Emission Inventories

Seaports and airports have a number of similarities in activities and institutional settings that affect the estimation of emissions as well as the uses of the emissions inventory. Both seaports and airports are characterized by intermodality: passengers and goods are transported overland to the facility and then transferred to the vehicle (aircraft or ship) for the longer distance portion of the trip. Most of the mass emissions of pollutants of greatest concern for freight (NO_X, PM, GHGs) occur en route from the aircraft or ship rather than from the facility. However, the emissions from the ground access trip may be of greatest concern for NAAQS compliance and health risk because of proximity of receptors to roadways and rail lines.

Seaport or airport operators may be state agencies, public authorities, municipal departments, or private firms, and, as such, have varying degrees of legal authority and financial capability to address emissions. Private carriers (airlines, shipping lines) operate in public airspace or unmanaged international waters and are largely exempt from regulation by the seaport or airport operators. Efforts by local seaport or airport operators to regulate emissions are constrained by preemption of authority by the federal government or international agreements, and by the need to stay competitive with other ports. (*35*) Seaport or airport operators do, however, have authority to regulate the types of ground vehicles that may access the facility and vehicle operations while within the facility.

Like other projects, seaports and airport projects use project emissions estimates for purposes of NEPA and state-level review, public information, and conformity. In addition, seaports and airports may develop emission inventories for their entire facility. An emission inventory is necessary for port authorities, those doing business at ports (such as terminal operators, tenants, and shipping companies), state and local entities, or other interested parties to understand and quantify the air quality impacts of current port operations and to assess the impacts of port expansion projects or growth in port activity. Because of the wide variety of vehicles and equipment that operate in or near their facilities, seaport and airport operators may use emissions estimates to identify emission sources, quantify their contribution to facility-related emissions, and evaluate potential emission reduction strategies. The inventory can then be used to develop strategies to minimize current and projected emissions and to quantify progress. A facility emissions inventory can inform compliance with

Exhibit 2-12. Example of port emission inventory, 2005 (tons/year).

Category	PM_{10}	$PM_{2.5}$	DPM	NO_X	SO_X	CO	TOG
Ocean-Going Vessels	733	586	637	6,926	6,501	603	274
Harbor Craft	30	27	30	1,004	5	237	20
Cargo Handling Equipment	56	51	56	1,737	17	450	101
Locomotives	43	40	43	1,314	76	183	74
Heavy-Duty Vehicles	243	224	243	5,607	39	1,944	433
Total	**1,105**	**928**	**1,008**	**16,587**	**6,638**	**3,416**	**901**

regulatory requirements such as those in SIPs for criteria pollutants or city/state climate action plans for GHGs, and also inform voluntary initiatives such as a collaborative regional MSAT assessment or development of a seaport/airport environmental management system. (*36*) Exhibit 2-12 presents an example summary of a facility emissions inventory prepared by a large seaport.

Airport Emission Inventories

As noted previously, seaports and airports share many operational and institutional similarities. Airports prepare emission inventories for the same reasons that seaports do. The emission inventories play equivalent roles in airport decision making. Airport-related emissions from each type of source are calculated in the same way as for seaports, with the exception that aircraft emissions replace vessel emissions, and GSE emissions replace CHE emissions. In addition, airports typically have large fuel storage and handling operations with associated emissions from pumps, vehicles, and fuel evaporation. Exhibit 2-7 (presented previously) shows an example of a facility emissions inventory prepared by a large airport.

FAA guidance specifies that airport-related emissions of criteria pollutants and MSATs from most sources should be calculated using the FAA's Emissions and Dispersion Modeling System (EDMS). EDMS takes as inputs the same data for each individual source type as previously discussed for highway and rail projects and port facilities. EDMS calculates emissions from airborne aircraft only up to an altitude of approximately 3,000 ft, which corresponds with the average height of the atmospheric mixing layer. Emissions above this altitude generally do not disperse downward to altitudes below the mixing height and accordingly have little or no influence on ground-level air quality. FAA is currently developing a new model, the Aviation Environmental Design Tool, which is planned to eventually replace EDMS.

To date, agencies are only beginning to issue guidance on how to estimate GHG emissions associated with airports. A number of methods and assumptions have been used. The current version (5.1) of EDMS estimates CO_2, but not other GHG emissions, for aircraft only. A recent attempt to compile best practices is *ACRP Report 11: Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories.* (*37*) One assumption that can have a very large effect on the results of the emissions calculations is the allocation of aircraft en route emissions—to the departure airport, the arrival airport, or some combination—because these usually are the major portion of aviation-related emissions.

CHAPTER 3

Evaluation of Current Methods

The objective of this chapter is to evaluate the current methods used to generate air emissions information from freight transportation activities, including the following:

- Brief description of the state of the practice for the calculation of emissions related to freight transportation,
- Analysis of the strengths and weaknesses of the main methods and models,
- Assessment of process uncertainty related to the main methods and models, and
- Assessment of parameter uncertainty related to the inputs required by the main methods and models.

This chapter is organized by transportation mode, including heavy-duty trucks, rail, ocean-going vessels, harbor craft, cargo handling equipment, and aircraft. The following three additional subsections, which are not dependent on mode, are also included: (1) a discussion of general methods for emission calculations, (2) an evaluation of methods and models that estimate freight emissions at the national scale, and (3) an evaluation of how emissions estimates are used in air quality dispersion models, health risk assessments, and other applications. To the extent possible, each mode-specific subsection is divided by geographic scale.

This chapter is a combination of the results from Tasks 2 and 4. In Task 2, the project team examined the current state of practice for estimating freight transportation emissions of criteria pollutants, air toxics, and GHGs. In Task 4, the project team evaluated the current practices for estimating freight emissions, including both freight activity estimates and freight emission factors.

3.1 General Methods

Although some methods and models are mode-specific, there are standard methods that can be applied to all modes. As illustrated in Equation 1, freight emissions are generally the product of freight activity (e.g., fuel consumed, energy generated, or vehicle miles traveled) and emission factors (in grams of pollutant per measure of freight activity).

$$\text{Emissions} = \text{Freight Activity} \times \text{Emission Factor} \qquad \text{(Equation 1)}$$

Depending on data availability and the complexity of analytical methods, emissions might be calculated separately by vehicle type or other factors that affect emission factors (e.g., average speed, road level of service), and added up to a total by pollutant. With the exception of GHGs, which are summed by multiplying their respective emissions by their global warming potential, the emissions of other pollutants are always reported separately.

Some emissions models incorporate both measures of freight activity and emission factors and output total emissions, while other emissions models are used to extract emission factors only.

3.1.1 Greenhouse Gases

Transportation sources emit different gases that contribute to global warming, including CO_2, CH_4, N_2O, and hydrofluorocarbons (HFCs). Carbon dioxide is by far the most prevalent GHG emitted by transportation sources. According to the EPA GHG Inventory, nationally, more than 95% of transportation GHG emissions were in the form of CO_2 in 2004, when measured in terms of global warming potential (i.e., CO_2 equivalent emissions). (*1*) The remainder of transportation GHG emissions took the form of N_2O, 2.2%; CH_4, 0.1%; and HFCs, 2.3%. Note that GHG emissions typically are reported in terms of CO_2 equivalent to provide a common unit of measure. Other GHGs are converted into CO_2 equivalent on the basis of their global warming potential, which is defined as the cumulative radiative forcing effects of a gas over a specified time horizon in comparison to CO_2. Radiative forcing is the change in balance between radiation entering the Earth's atmosphere and radiation being emitted back into space.

Exhibit 3-1. Fuel types commonly used by different transportation modes.

Fuel	Heavy-Duty Trucks	Rail	Waterborne Vessels	Cargo Handling Equipment	Aircraft
Motor Gasoline	●		●	●	
Diesel (Distillate)	●	●	●	●	
Jet Fuel					●
Aviation Gasoline					●
Residual Fuel			●		
Electricity		●	●		
Other Fuels*	●			●	

*Other fuels include compressed natural gas (CNG), liquefied petroleum gasoline (LPG), and other alternative fuels.

Given the importance of CO_2, it is usually appropriate and acceptable for transportation GHG analyses to focus solely on this gas, particularly if resources are limited and if the analysis is designed to provide a general indication of GHG impacts.

A summary of the fuel types commonly used by various modes is provided in Exhibit 3-1.

Carbon Dioxide

The calculation procedures for estimating CO_2 from on-road and nonroad sources are conceptually the same, since CO_2 is released in direct proportion to fuel consumption, with differences in the amount of emissions by fuel type. The carbon content of a specific fuel (e.g., diesel) is the same regardless of what mode consumes it (e.g., trucks, locomotives, ships). However, the tools available to analyze emissions from nonroad sources differ from those that can be used for exclusively assessing on-road emissions. Moreover, state and local transportation agencies often have limited data on fuel consumption by nonroad modes.

The amount of CO_2 produced is a product of the amount of fuel combusted, the carbon content of the fuel, and the fraction of carbon that is oxidized when the fuel is combusted. A simple formula for the calculation of CO_2 for each fuel is as shown in Equation 2.

$$\begin{aligned} CO_2 \text{ emitted} &= \text{Fuel Combusted} \times \text{Carbon Content Coefficient} \\ &\times \text{Fraction Oxidized} \times (44/12) \qquad \text{(Equation 2)} \end{aligned}$$

Fuel combustion (in gallons for liquid fuels or cubic feet for natural gas) is converted into units of energy (Btus). The carbon content of fuel varies by type of fuel and is usually expressed in terms of units of carbon per Btu. The fraction of the carbon oxidized is a lesser consideration since it has traditionally been assumed to be 99% for all fossil fuel combustion. (Recent analyses conducted for EPA suggest that the oxidation fraction for light-duty gasoline vehicles is virtually 100%; EPA recently recommended use of the 100% fraction for transportation for its international reporting.) The factor 44/12 is the weight of CO_2 in relation to the amount of carbon in the fuel, assuming all carbon burned eventually oxidizes to form CO_2. Some carbon in fossil fuels is emitted in the form of carbon monoxide, which swiftly decays into CO_2, and volatile organic compounds, which also decay into CO_2. Consequently, the key analysis that needs to be conducted to estimate CO_2 is to determine the amount of fuel consumed by fuel type (e.g., motor gasoline, diesel, jet fuel, compressed natural gas).

Although conceptually simple, this calculation in practice is quite complex since transportation agencies do not typically collect data to track vehicle fuel consumption by fuel type. In a limited number of cases, fuel data are available and can be used directly in calculating CO_2. For instance, for GHG inventory development, state fuel tax records are often used to estimate motor vehicle fuel consumption and CO_2. The availability of direct measures of fuel consumption, however, is generally limited for transportation agencies, and fuel consumption estimates may not be available at all for project-level, corridor, or regional analysis.

Transportation modeling generally focuses on estimating vehicle-miles traveled (VMT) for motor vehicles, or passenger-miles traveled (PMT) for transit and nonroad modes. Given the primary use of VMT as a metric for transportation activity, the other key factor necessary to estimate vehicle fuel consumption is vehicle fuel economy (miles per gallon). Many factors influence vehicle fuel economy, including the following:

- The mix of travel by vehicle type and model year;
- Vehicle operating characteristics, such as speeds and accelerations, and amount of idling; and
- Other factors, like vehicle maintenance, tire pressure, and air conditioner use.

The relationships between these factors and fuel economy are not simple. For instance, the implications of vehicle operating speeds on fuel consumption are not linear and depend on vehicle type and size. Consequently, an approach that assumes an average fuel economy by vehicle category will not accurately account for the effects of transportation projects that address vehicle speeds and traffic flow. The effects of vehicle operating speeds on fuel economy also vary based on the model year and age of the vehicle; for instance, studies of vehicle fuel economy taken during the 1990s show less of a drop-off in vehicle fuel economy above 55 miles per hour than in similar studies of vehicles during the 1970s and 1980s, due to vehicle design changes affecting aerodynamics and engine operating efficiency, among other factors. (*38*) As a result, an approach that assumes a standard formula for the level of fuel consumed per mile at a certain vehicle speed will not accurately account for the effects of changes in vehicle designs over time.

Nitrous Oxide and Methane

Like CO_2, N_2O and CH_4 are released during fossil fuel consumption, but in much smaller quantities. CH_4 emissions are greater from alternative-fuel vehicles such as LNG trucks that store natural gas as a cryogenic liquid. To prevent build-up of pressure, gases are vented from the cryogenic tank, leading to fugitive emissions of CH_4. However, since the market share of LNG vehicles is very small, these fugitive emissions do not impact the overall transportation GHG inventory. The emissions rates of N_2O and CH_4 are not directly proportional to fuel consumption. N_2O and CH_4 emissions rates per mile are affected by vehicle emissions control technologies. The newest motor vehicle emission control technologies produce significantly less N_2O and CH_4 than do early emission control technologies—for instance, for a gasoline powered automobile, a vehicle with LEV technology produces only about one-third the N_2O emissions of a vehicle with Tier I emission controls. According to EPA, (*1*) N_2O and CH_4 from on-road sources declined by over 20% between 2000 and 2003 while VMT rose. As a result, emission factors for on-road vehicles are usually presented in per mile units, and analyses of these pollutants require information on VMT *and* the distribution of miles by vehicle type (e.g., automobile, light-duty truck, heavy-duty truck), fuel type (e.g., gasoline, diesel), and technology type (e.g., Tier 0, Tier I, LEV). Knowing the emissions control technology used by vehicles is very important for generating accurate results. A simple formula for the calculation of N_2O or CH_4 emissions for each individual vehicle/fuel/technology type is as shown in Equation 3.

$$\text{Emissions} = \text{VMT}_{(\text{Vehicle, Fuel, Technology Type})} \times \text{Emission Factor}_{(\text{Vehicle, Fuel, Technology Type})} \qquad \text{(Equation 3)}$$

For nonroad modes, N_2O and CH_4 are generally assumed to be proportional to fuel consumption, making the calculation relatively simple. However, with the introduction of emission control technologies to nonroad sources, such as retrofits of diesel transportation construction equipment, more detailed analysis by control technology type may be needed to accurately address the impacts of these technologies on N_2O and CH_4.

HFCs and Other Gases

HFCs are synthetic chemicals that are used in vehicle air conditioning and refrigeration systems as alternatives to ozone-depleting substances being phased out under the Montreal Protocol. Leakage of HFCs during equipment operation, servicing, and disposal also contributes to GHGs, so the level of HFCs released depends on factors such as air conditioning use and amount of refrigerated transport.

Finally, the transportation sector also contributes to emissions of several other compounds that are believed to have an indirect effect on global warming. These include ozone, carbon monoxide, and aerosols. Ozone traps heat in the atmosphere and prevents a breakdown of CH_4, but its lifetime in the atmosphere varies from weeks to months, making it difficult to estimate net radiative forcing effects. CO indirectly affects global warming by reacting with atmospheric constituents that would otherwise destroy CH_4 and ozone. Aerosols are small airborne particles or liquid droplets that have both direct and indirect effects on global warming. The most prominent aerosols are sulfates and black carbon, or soot. Sulfate aerosols also have some cooling effect by reflecting light back into space. Scientists have not yet been able to quantify the impact of ozone, carbon monoxide, or aerosols with reasonable certainty; thus, these compounds are not included in reporting GHG emissions.

3.1.2 Criteria Air Pollutants and Air Toxics

Emissions of criteria air pollutants and air toxics are not directly proportional to fuel consumption, with emissions rates per mile being affected by vehicle emissions control technologies. Therefore, emission factors for on-road vehicles are usually presented in per mile units, and analyses of these pollutants require information on VMT *and* the distribution of miles by vehicle type (e.g., automobile, light-duty truck, heavy-duty truck), fuel type (e.g., gasoline, diesel), and technology type (e.g., Tier 0, Tier I, LEV). Knowing the emissions control technology used by vehicles is very important for generating accurate results. Equation 3 shows a simple formula for the calculation of criteria air pollutants and air toxics for each individual vehicle/fuel/technology type.

For nonroad modes, the calculation of emissions of criteria air pollutants is similar but the measure of freight activity might be different (e.g., ton-miles in the case of line-haul rail).

The main difference between criteria air pollutants and air toxics is data availability. Although most models include emission factors for all criteria air pollutants, the same is not true for air toxics due to a lack of data. Instead, many models estimate emissions from air toxics based on comparative ratios from criteria air pollutants.

3.2 National Methods

At the national level, several inventories measure emissions associated with the transportation sector (see Exhibit 3-2). Each methodology discussed here is specific to classes of pollutants: greenhouse gas emissions are quantified in the EPA GHG Inventory, (*1*) and criteria air pollutants and air toxics are quantified in the NEI. (*2*) Both the EPA GHG Inventory and the NEI capture nationwide emissions across economic sectors; in addition to transportation, these inventories include industrial, commercial, and residential emission sources. Because the methodologies of these inventories are considerably broader than the mode-specific methodologies contained in Sections 3.3 through 3.8 of this report, they are detailed independently of the modal analyses. This section discusses the strengths, weaknesses, inputs, and results of the EPA GHG Inventory and the NEI.

3.2.1 Summary of Methods and Models

The purpose of EPA's national inventories is to capture national emissions across all sources and to allocate emissions to each sector. Although both the GHG Inventory and NEI report detailed emissions estimates, they differ in the complexity of analytical methods. The GHG Inventory uses a consistent methodology to calculate emissions for each category, but the NEI relies on unique methodologies across modes.

The GHG Inventory primarily relies on fuel consumption data to calculate emissions. The inventory allocates emissions to each transportation mode, and to subcategories within each mode, according to fuel consumption and fuel type. Total GHG emissions are calculated as a function of the carbon content of each fuel. Although the GHG Inventory does not disaggregate freight and non-freight emissions, it lists modal categories in sufficient detail to make such disaggregation possible, albeit while introducing uncertainties into the calculations.

Although the GHG Inventory uses a straightforward approach to calculating emissions, the NEI methodology is comparatively more complex. First, the NEI analyzes a greater number of pollutants than the GHG Inventory: 6 criteria pollutants and up to 188 air toxics. In addition, because the emissions of these pollutants depend on vehicle type, age, and activity, the NEI relies on separate methodologies for each transportation mode. Finally, the NEI has much more geographic detail than the GHG Inventory. Although the latter only presents emissions at the national level, the former allocates emissions to the state and county level. For these reasons, the NEI methodology is presented here in much greater detail than the GHG Inventory.

3.2.2 EPA GHG Inventory Methodology

In accordance with the 1992 United Nations Framework Convention on Climate Change, EPA produces an annual assessment of national greenhouse gas emissions, which spans several industries and economic sectors including transportation. The analysis is based on methodologies, guidelines, and best practices established by the Intergovernmental Panel on Climate Change (IPCC), most recently updated in 2006. (*39*) Regarding transportation, the EPA GHG analysis calculates GHG emissions by measuring fossil fuel consumption in each transportation mode. Because emissions are broken down by mode rather than activity, the EPA inventory does not directly quantify emissions associated with freight movement.

The GHG Inventory accounts for emissions of three greenhouse gases: CO_2, CH_4, and N_2O. The GHG Inventory does not measure HFC emissions. Although both CH_4 and N_2O have a greater global warming potential than CO_2 (the global warming effect of CH_4 is 21 times greater than that of CO_2, and the effect of N_2O is 310 times greater) their level of emissions is so small that their overall effect is negligible in this analysis. In the transportation sector, CO_2 accounts for 98.4% of all greenhouse gases. (*40*) Since transportation emissions of CO_2 are caused by the combustion of fossil fuels, such as gasoline, diesel, aviation fuel, and marine bunker oil, the CO_2 emissions inventory is calculated by measuring fuel consumption from each mode.

The GHG Inventory measures and reports greenhouse gas emissions on an annual basis at the national scale. Since

Exhibit 3-2. List of national methods.

Method/Model	Type	Geographic Scale	Pollutants	Freight/Passenger
EPA GHG Inventory	Method	National	GHG	Both
NEI	Method	National, State, County	CAP, HAP	Both

emissions are not allocated to the state and county level, the inventory is less data intensive, and only requires aggregated national fuel consumption data. This makes the methodology less complex and reduces uncertainties from collecting and aggregating local data, but introduces additional uncertainties in allocating national data to the transportation sector, and to each mode individually. Since GHG emissions are reported for the analysis year, the GHG Inventory does not further break down the result by season or by month. Although there is no analysis of future years, the GHG Inventory includes a comparison of current year emissions to past year emissions, back to 1990.

Inventory Structure

The EPA GHG Inventory is structured according to emissions category, including energy production, industrial processes, agriculture, and land-use change. Energy production accounts for the majority of emissions. In 2007, 80% of nationwide GHG emissions were due to fossil fuel combustion, and 26% of nationwide emissions were due to fossil fuels used in transportation. Within the transportation sector, emissions are divided by fuel type and subdivided by mode and vehicle type. Gasoline, consumed mainly by passenger cars and light-duty trucks, is the largest contributor to transportation emissions, followed by diesel fuel, consumed by heavy-duty trucks and rail, and jet fuel. Although the inventory does not separate freight and non-freight emissions, the specificity of the vehicle subcategories allows for freight emissions to be summed together across modes. Allocations are then checked against "bottom-up" fuel use data when available, such as railroad fuel consumption data from the Surface Transportation Board. (*41*)

GHG emissions are calculated using fuel-based (rather than activity-based) emission factors derived from the carbon intensity of each fuel. To perform this calculation, EPA collects data on total fuel sales and allocates fuel to each subcategory. The GHG methodology includes the steps shown in Exhibit 3-3.

Although the process of calculating total fossil fuel emissions is straightforward, the allocation steps introduce uncertainties into the methodology. Each allocation, first to the transportation sector, then to each mode and vehicle type, requires additional assumptions and estimates. Although the GHG Inventory methodology does not further allocate emissions to freight and non-freight sources, this allocation can be made using additional assumptions about the freight mix of heavy-duty trucks, rail, and commercial aircraft.

Summary of Strengths and Weaknesses. A summary of GHG Inventory methodology strengths and weaknesses is provided in Exhibit 3-4.

Analysis of Process Uncertainty. In the EPA GHG Inventory methodology, the greatest elements of uncertainty are present in the allocation of GHG emissions to the transportation sector and subsequently to individual modes. The sector-level allocation is achieved with a top-down approach that measures activity across all economic sectors. In comparison, the allocation across modes is achieved with a bottom-up approach, which applies and compares activity levels for each mode. The uncertainty resulting from each allocation is discussed here. A more thorough analysis of the parameter uncertainty surrounding each data set can be found in Section 3.2.4.

Although data on total fuel use are considered accurate, the allocation of fuel consumption data to end-use sector relies on a variety of economic and activity measurements, which may reduce the accuracy of the allocation. Since each metric has its own sources of error, the allocation of fuel using several metrics creates further uncertainty.

Exhibit 3-3. GHG Inventory methodology.

Determine total consumption by fuel type and sector	Total fuel sales, available from the Energy Information Administration (EIA) are allocated by economic sector (e.g., industrial, commercial, transportation). Data for the overall allocation are supplemented by industry surveys and other end-use consumption metrics.
↓	
Adjust transportation consumption based on activity measures	EPA reconciles the transportation fuel allocation with VMT and other activity data from FHWA, AAR, and other sources. This "bottom-up" analysis serves as a check for fuel consumption and is the basis for the allocation among transportation modes.
↓	
Allocate GHG emissions to transportation sector	CO_2 emissions are calculated based on the carbon content of each fuel; CH_4 and N_2O emissions are calculated based on an activity-based emissions factor.
↓	
Allocate transportation emissions to each mode and vehicle subcategory	For on-road vehicles, emissions are assigned based on VMT data from FHWA, specific to vehicle type. Nonroad data are assigned based on data from AAR, FAA, EIA, and other sources.

Exhibit 3-4. Analysis of strengths and weaknesses—EPA GHG Inventory methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Methodology does not rely on models of physical processes for calculation of GHG emissions.	EFs for CH_4 and N_2O are based on vehicle test data; EFs may become inaccurate if vehicle technology, maintenance, operations change.
Model sensitivity to input parameters	Since methodology is based on fuel use and activity data, it is not affected by changes in vehicle operations, maintenance, or environment.	
Ability to incorporate effects of emission reduction strategies		Methodology does not forecast alternative scenarios to show benefits of emission reduction strategies.
Representation of future emissions		Methodology does not predict future trends in GHG emissions, but it does report historical emissions beginning in 1990.
Consideration of alternative vehicle/fuel technologies	Methodology captures GHG benefits of alternative fuels by including unique GHG EFs for each fuel type.	
Data quality	High data quality. Fuel consumption and activity factors are industry standard; EFs for CH_4 and N_2O directly measured from vehicle tests.	
Spatial variability		Methodology is only applied at the national level. It does not measure emissions at the regional or local level.
Temporal variability	Methodology is not subject to temporal fluctuations, since it measures emissions at the national scale.	
Endorsements	Methodology is endorsed by EPA, UN IPCC.	

Within the transportation sector, fuel use is allocated to each mode through a comparison of modal activity factors. However, since each activity data set (i.e., VMT for on-road, ton-miles for rail) uses separate sources and methodologies, the margin of error in each data source is difficult to compare; it is not clear how the uncertainty in one would compare to the other. Although these uncertainties do not affect the quantification of emissions from the transportation sector, they do affect both the modal breakdown and the estimate of freight versus non-freight emissions.

Uncertainties in allocation are partially addressed by comparing the "top-down" allocation to "bottom-up" fuel consumption data. For example, railroads report fuel consumption data to the Surface Transportation Board. This value is compared against the determined allocation to identify the magnitude of discrepancy. This approach acts as a partial check to mitigate uncertainties in allocating fuel consumption.

Although the GHG Inventory does not separate freight-related emissions from the total transportation inventory, it does present vehicle-specific emissions in sufficient detail to allow an estimation of freight emissions. However, this estimate requires a different approach for each mode, and relies on external assumptions about the proportion of freight versus passenger travel. For example, on-road categories include both gasoline and diesel medium- and heavy-duty trucks, and the aircraft category specifies emissions from commercial aircraft.

3.2.3 EPA National Emissions Inventory

The NEI documents total emissions of criteria pollutants and air toxics nationwide. This database catalogs emissions from point, non-point, and mobile sources, with each transportation mode analyzed independently within the mobile analysis. Depending on the mode, emissions are determined using one of several possible methods: by applying computational models, by combining activity data with emission factors, or by scaling prior emission inventories by a growth factor. This section discusses how the NEI calculates modal emissions, and analyzes the strengths and weaknesses of each approach. An evaluation of analytical models (e.g., MOBILE6, NONROAD), as applied to each transportation mode, is discussed in Sections 3.3. to 3.8.

Consistent with EPA's mandates in the Clean Air Act as amended in 1990, the NEI measures nationwide emissions of 6 criteria pollutants and up to 188 air toxics. The measured criteria pollutants include CO, SO_X, NO_X, and PM. (There are two additional criteria air pollutants: lead and ozone—a secondary pollutant formed by the combination of HC and NOx.) Measured air toxics include 188 defined compounds. (*42*) However, not all HAPs are estimated by the mobile source methodologies. For example, the National Mobile Inventory Model (NMIM) only produces inventories of 50 HAPs for on-road and nonroad sources.

The NEI produces inventory data for a wide range of geographic scales, including the national, state, and county levels. This range of data presentation allows the inventory to inform air quality analyses by local, state, and federal government agencies as well as private industry. However, depending on the pollutant source, emissions data may be accurate at one geographic extent but inaccurate in other scopes or regions. For example, when source emissions are calculated in a "top-down" analysis, inventories at the state and regional level are apportioned from the national inventory. This process may introduce errors depending on the apportioning methodology and available data. Alternatively, inventories collected using a "bottom-up" approach may be accurate in certain regions with thorough data, but inaccurate in regions with little available data. These errors propagate to larger scopes as regional inventories are aggregated to the state and national level. A more thorough discussion of uncertainties in inventory apportionment and aggregation is presented later in this chapter.

The NEI presents emissions data with a limited temporal scope. The inventory is calculated on an annual basis and is not broken down using a seasonal or monthly timeframe. In addition, the inventory is only published for the current year, and does not forecast emissions for future years. However, EPA publishes historical comparisons of the current-year inventory to past NEIs, (*43*) as well as a long-range analysis of emission trends from the year 1900. (*44*)

EPA publishes the NEI on a three-year cycle; the most recent NEI was published in 2005 for the 2002 analysis year. In addition to the summary reports of emissions statistics, the NEI data are also distributed in database form. (*45*) As of 2009, EPA is finalizing the 2005 NEI, and collecting data for the 2008 analysis year inventory.

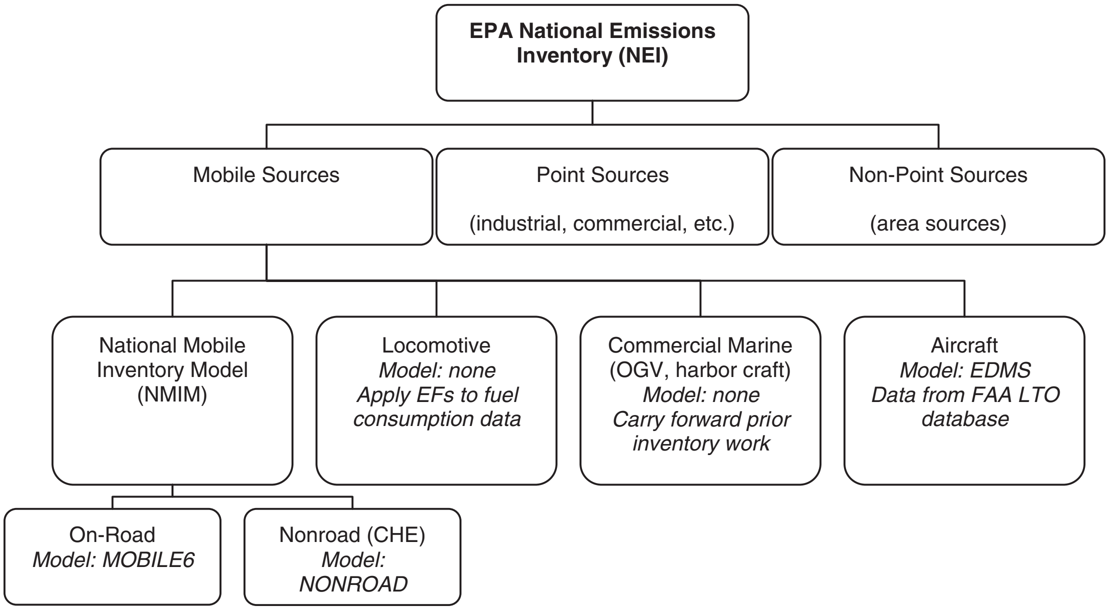
NEI Structure and Methodologies

The NEI is a comprehensive nationwide inventory from all stationary and mobile emission sources (see Exhibit 3-5). The breadth of data collection and modeling require unique methodological approaches for many emission sources, leading to a tiered or bottom-up structure for assembling the inventory. NEI calculations are separated into three components: point sources, non-point sources, and mobile sources. This section focuses on the mobile source component, because it includes all emissions from freight transportation. However, a brief discussion of point and non-point sources is included here in order to illuminate the scope of the NEI.

Mobile Source Emissions

All transportation-related emissions are captured within the mobile source component of the NEI. This category includes emissions from on-road vehicles, nonroad vehicles (cargo handling equipment), locomotives, commercial marine vessels, and aircraft. Each mode has a different approach to measuring emissions and apportioning the national inventory to states and counties. Although the inventory for each mode is calculated independently, emissions from on-road and nonroad sources are grouped within the National Mobile Inventory Model (NMIM), a meta-model that collects input data and processes results for the two modes.

Exhibit 3-5. Structure of NEI methodology for mobile source emissions.



The methodological approach for each mode varies depending on the quality of data and tools available. Depending on the mode, emissions are calculated by applying analytical models, combining activity data with emission factors, or applying a growth factor to the results of prior inventories. As a result, the strengths, weaknesses, and uncertainties in the NEI mobile source inventory vary by mode. A summary of the methodologies is as follows:

- On-road emissions, which include all heavy-duty trucks, are calculated using EPA's MOBILE6 model, combined with nationwide data on vehicle activity from FHWA. When states provided alternate activity or other model inputs, the state-level data were used in place of EPA inputs. Emissions are allocated to the county level using NMIM.
- The inventory for nonroad emissions, which include cargo handling equipment, is calculated using EPA's NMIM, which calculates emissions through the NONROAD model. When states provided alternate model inputs, the state-level data were used in place of EPA inputs. Emissions are allocated to the county level using NMIM.
- The locomotive emissions inventory is developed by combining locomotive fuel-use data from DOE with published criteria pollutant emission factors (EFs). HAP emissions are calculated by applying speciation profiles to VOC and PM estimates. Emissions are allocated to the county level using rail network data from U.S.DOT.
- The 2002 NEI inventory for commercial marine vessels (harbor craft, inland vessels, and ocean-going vessels) was based on emissions estimations produced for "marine diesel regulations for 2000." Port emissions were disaggregated based on cargo volume, and underway emissions were disaggregated based on United States Army Corps of Engineers (U.S. ACE) waterway data. When state data were available, they were used in place of EPA inputs. HAP emissions were calculated by applying speciation profiles to VOC and PM estimates.
- Emissions from commercial aircraft are calculated by applying airport activity data to FAA's Emissions Dispersion Modeling System (EDMS) model. HAP emissions are calculated by applying speciation profiles to VOC and PM estimates. The EDMS inventory is measured on the county-level scale; state and national emissions are calculated by aggregating project-level emissions.
- The mobile component of the NEI does not include emissions from pipelines.

NEI On-Road Methodology

The NEI mobile source component includes a methodology for calculating criteria pollutant and HAP emissions associated with on-road vehicles, including heavy-duty vehicles. The methodology collects county-level vehicle data, calculates emissions using the MOBILE6 model, and allocates the resulting emissions inventory to the state and county level.

The process is achieved using the National Mobile Inventory Model (NMIM), which operates above MOBILE6, preprocessing input data and postprocessing emission results. NMIM contains a database of all county-level information required to run the emissions model. The NMIM County Database, used for both on-road modeling with MOBILE6 and nonroad modeling with NONROAD, contains detailed information on vehicle activity, fleet mix, and infrastructure. This information, in addition to county-level meteorological and fuel data, comprises a complete set of data inputs for MOBILE6. In the postprocessing phase, NMIM combines emissions results from MOBILE6 with nonroad emissions, and reallocates the resulting inventory to the state and county level in a form consistent with other components of the NEI. Where states provide alternate inputs into NONROAD, these values are used in place of the default NMIM inputs.

Although the general approach used in this methodology has remained consistent since 1990, details of its application continue to evolve. In December 2008, EPA issued updated guidance for the on-road methodology used for the 2005 NEI. The new methodology is more consistent than in prior years, and relies on the MOBILE6 model to compute on-road emissions throughout the United States, Puerto Rico, and the Virgin Islands. In past years, when state emissions inventories were available, notably in California, Colorado, and Oregon, the state inventories were used in place of EPA emissions calculations. However, the 2005 NEI methodology still gives precedence to state-level VMT and activity data when available. More information about the development and validation of the NEI can be found in the *2002 National Emission Inventory (NEI) Preparation Plan—Final.* (46)

Summary of Strengths and Weaknesses. A summary of NEI on-road methodology strengths and weaknesses is provided in Exhibit 3-6.

Sources of Uncertainty. The NEI on-road methodology introduces uncertainty into several aspects of the approach, from data collection to inventory assessment. This section focuses on uncertainties unique to the NEI method, including uncertainties in allocating emissions across geographic scales and uncertainties in disaggregating emissions into freight and non-freight inventories. Uncertainties associated with MOBILE6 and estimation of truck VMT are discussed in Section 3.3.

Uncertainty also exists in the way that NMIM aggregates emissions results from the project-level level. The approach used in NMIM introduces uncertainties about the accuracy of state and national emissions. NMIM uses county-level data

Exhibit 3-6. Summary of strengths and weaknesses—NEI on-road methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Method represents physical processes through MOBILE6 model.	
Sensitivity to input parameters	Method utilizes detailed facility-level and meteorological data to account for operational fluctuations in emissions.	Method has significant data reporting requirements at the county level; relies on state and local agencies for accurate input.
Flexibility	Method is flexible enough to be applicable to all counties.	Data reporting requirements are high, in fixed format.
Ability to incorporate effects of emission reduction strategies	Method can include county-level emission inspection and maintenance programs.	
Representation of future emissions		Method does not predict future emissions.
Consideration of alternative vehicle/fuel technologies	Method can incorporate alternative fuels, low emission vehicles.	
Data quality	EPA performs data checks and follows up with states and local agencies regarding discrepancies.	
Spatial variability	Method incorporates variations in altitude and meteorology by county.	
Temporal variability		Method only calculates annual emissions. It does not evaluate emissions or fluctuations on seasonal or monthly scales.
Review process	Draft NEI made available for public and peer review, comment, revisions.	
Endorsements	EPA.	

sets to calculate local emissions inventories; as such, the accuracy of state and national emissions results depends on the accuracy of county data. Although EPA maintains default data sets on each county, local agencies have the opportunity to supplement or replace EPA values with more accurate county-specific data. Since the accuracy of emissions inventories varies by county, any county-level errors will propagate upward when local results are aggregated to the state and national level.

Using data outputs from NMIM, the NEI methodology allows users to disaggregate freight emissions at a high degree of detail. NMIM reports annual emissions by pollutant and by vehicle category. The specified vehicle types are referenced from the MOBILE6 model, and include light-duty vehicles (passenger cars), light-duty trucks, medium-duty trucks, and heavy-duty trucks. Data are further allocated to gasoline and diesel categories. For example, freight emissions can be determined by selecting emissions from certain vehicle classes, such as Class 8B heavy-heavy-duty trucks. Because county-level data are typically not reported with the same level of detail, the NEI relies on MOBILE6's default VMT distribution among truck classes, which is based on national default parameters. National parameters are a poor surrogate for local parameters since the distribution of VMT by truck classes should not be consistent across different counties. As a result, there are uncertainties associated with disaggregating county data to a level that is more detailed than was originally reported.

NEI Rail Methodology

In the NEI, EPA divides rail transportation into the following five categories:

- Line-haul service (Class I),
- Regional and local service (Class II/III),
- Railyard,
- Passenger, and
- Commuter.

Freight transportation is represented in the first three categories, with the majority of emissions generated by line-haul transportation.

Unlike the methodologies for on-road, nonroad, and aircraft emissions, the NEI rail methodology does not rely on analytical models to calculate an emissions inventory. Instead, emissions are calculated directly from industry-wide fuel usage data, and combined with fuel-based emissions factors. Data on rail fuel consumption, reported by EIA, are allocated to individual rail categories according to established category ratios developed for the NEI; this fuel allocation is examined more closely in Section 3.4.4. Since California requires low-sulfur fuel for in-state locomotives, the emissions calculations are performed separately, although the same methodology is employed.

Since the emissions inventory is created using national data, it must be distributed to the state and county level using a top-down approach. Emissions are allocated to counties based on county-level rail activity data, which is provided by the Bureau of Transportation Statistics (BTS). A GIS analysis allocates traffic on rail segments to each county. The inventory of railyard emissions is allocated spatially using a separate approach, in which emissions are allocated to urban counties containing Class I railyards.

Summary of Strengths and Weaknesses. A summary of NEI rail methodology strengths and weaknesses is provided in Exhibit 3-7.

Sources of Uncertainty. The most accurate data for rail emission calculations are where fuel is purchased and added to locomotives, as well as rail activity (in ton-miles) at the state level. The burn ratio in gallons per ton-mile, and the allocation of rail activity to regions are the least known parameters. The NEI rail methodology introduces two principal sources of uncertainty into emissions calculations. One instance, discussed in this section, occurs when the NEI distributes rail consumption data to each rail category (i.e., line-haul, Class II/III). Additional sources of uncertainty, including the challenges of allocating emissions to the county level using BTS activity data, are not unique to the NEI and are examined more fully in Section 3.4.

This methodology relies on fuel sales data to estimate rail emissions, which—while simplifying the analysis—adds challenges in data collection. Fuel consumption data are most readily available at the national level for the entire rail industry and are reported annually by EIA. However, an accurate representation of rail emissions requires more detailed fuel consumption data for each rail company. Although aggregated fuel consumption information is available from the Surface Transportation Board, more detailed data are often unavailable, because many companies view fuel consumption as proprietary information. To distribute fuel consumption among each rail category, EPA devised Source Classification Code (SCC) Ratios, or activity correction factors that express the ratio of fuel usage attributable to each rail class. For example, EPA determined through an analysis outside the NEI that Class I line-haul rail accounts for 85% of rail fuel consumption, and allocates fuel use to Class I according to this ratio. However, EPA's methodology for developing these SCC Ratios is poorly documented, and it is difficult to evaluate their accuracy. If the values were developed using a limited data set, then they may introduce considerable uncertainty into the analysis.

NEI Commercial Marine Vessel Methodology

The commercial marine vessel (CMV) methodology accounts for emissions from marine transportation. It is broken

Exhibit 3-7. Summary of strengths and weaknesses—NEI rail methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes		Does not address physical processes; applies average EF to fuel consumption.
Sensitivity to input parameters		Insensitive to all parameters aside from fuel consumption and freight volume.
Flexibility		Method has little flexibility in data sources and parameters.
Ability to incorporate effects of emission reduction strategies		None.
Representation of future emissions		Method does not forecast future emissions.
Consideration of alternative vehicle/fuel technologies	Uses California-specific data to account for cleaner fuel.	
Data quality		Emission factors based on EPA locomotive standards. (*47*)
Spatial variability		Does not account for geographic variations in terrain, speeds.
Temporal variability		Method only calculates annual emissions. It does not evaluate emissions or fluctuations on seasonal or monthly scales.
Review process	Draft NEI made available for public and peer review, comment, revisions. (*46*)	
Endorsements	EPA.	

Exhibit 3-8. EPA marine compression-ignition engine categories.

Category	Specification	Use	Approximate Power Ratings
1	Gross Engine Power ≥ 37 kW* Displacement < 5 liters per cylinder	Small harbor craft and recreational propulsion	< 1,000 kW
2	Displacement ≥ 5 and < 30 liters per cylinder	OGV auxiliary engines, harbor craft, and smaller OGV propulsion	1,000 – 3,000 kW
3	Displacement ≥ 30 liters per cylinder	OGV propulsion	> 3,000 kW

* EPA assumes that all engines with a gross power below 37 kW are used for recreational applications and are treated separatelyfrom the commercial marine category.

down into different categories based upon engine size as shown in Exhibit 3-8.

Category 1 and 2 CMVs include "all boats and ships used either directly or indirectly in the conduct of commerce or military activity." (*48*) CMVs can range from 20-ft charter boats to 1,000-ft tankers and military vessels. Although the majority of marine vessels are included in this source category, recreational marine vessels are classified as nonroad vehicles and included in the nonroad category.

Category 1 and 2 CMV emissions inventories for years 2005 and 2002 are based on emission estimates EPA performed for the *Draft Regulatory Impact Analysis Control of Emissions from Compression-Ignition Marine Engines.* (*49*) This document uses a bottom-up approach to quantify total marine emissions. First, an engine inventory is built using data on engine sales and scrappage, to which annual load factors are applied in order to calculate total marine engine activity. Total CMV emissions are calculated by combining activity levels with emission factor standards set in the RIA. This emission inventory was carried forward to NEI 2002 and 2005.

Before allocating the inventory to the county level, the NEI methodology divides emissions by mode of operation: in/near port and underway operation. The disaggregation follows EPA SIP guidance that 75% of distillate fuel and 25% of residual fuel is consumed while in/near port. (*50*) This separation into port emissions and underway emissions allows a more precise geographic allocation. The method for allocating emissions geographically is more complex than with on-road or nonroad vehicles, since CMV emissions impact only selected counties. The port emissions are allocated among the 150 largest U.S. ports, based on total port traffic. Underway emissions are allocated through a GIS-based approach that overlays shipping lanes and waterways with county borders. Based on this analysis, emissions are allocated to counties based on ton-miles of cargo in adjacent waterways. Port and waterway data were supplied by the Army Corps of Engineers, and GIS data were supplied by BTS.

Category 3 NEI inventory includes emissions from both propulsion and auxiliary engines. The inventories include both near-port emissions as well as the inter-port (underway) emissions from these vessels when operating away from port in U.S. waters. The boundaries for vessels operating in the oceans generally extend from the U.S. coastline to the 200 nautical mile limit of the Exclusive Economic Zone (EEZ). For ships operating in the Great Lakes, the boundary extends out to the international boundary with Canada.

Emissions were developed separately for near-port and underway emissions. For near-port emissions, inventories for 2002 were developed for 89 deep water and 28 Great Lakes ports in the United States. The Waterway Network Ship Traffic, Energy, and Environmental Model (STEEM) provides emissions from ships traveling in shipping lanes between and near individual ports. (*51*) Near-port inventories were performed in a manner similar to the mid-tier methodology discussed in Section 3.5.2. These emissions were married with the STEEM data, and replaced the less accurate near-port estimates in STEEM. Port call data came from the Army Corps of Engineers' entrances and clearances data set, which is also discussed in Section 3.5.2.

Where state agencies had developed a state-wide CMV emissions inventory, these values were given precedence over EPA calculations. As more states perform their own inventories, this inclusion leads to a less consistent overall methodology. In the 2002 NEI, 26 states submitted statewide inventories, and the NEI methodology was applied to emissions in the remaining states and territories.

Summary of Strengths and Weaknesses. A summary of NEI (*46*) marine methodology strengths and weaknesses is provided in Exhibit 3-9.

Sources of Uncertainty. Category 1 and 2 inventories rely on engine counts determined from Power Systems Research. This database does not determine how many engines are on each vessel or accurately determine usage or load factors as discussed in Section 3.5.3. Category 3 data rely on foreign cargo movements and a somewhat streamlined methodology that uses detailed data from typical ports to estimate emissions at other ports. This is discussed in detail in Section 3.5.2.

Exhibit 3-9. Summary of strengths and weaknesses—NEI marine methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Relies on port call activity for Category 3.	None. Methodology does not include physical processes in inventory for Category 1 and 2.
Sensitivity to input parameters		None. Methodology based on estimate of engine inventory for Category 1 and 2. Relies on port call data from U.S. ACE and STEEM for Category 3.
Flexibility		None. Methodology relies on inventory constructed for year 2000 for Category 1 and 2. Relies on top 117 ports for Category 3.
Ability to incorporate effects of emission reduction strategies		None.
Representation of future emissions		None.
Consideration of alternative vehicle/fuel technologies		None. Does not consider benefits from new fuels.
Data quality		Emissions calculations rely on assumptions related to equipment inventory.
Spatial variability	Allocates emissions locally according to county-level marine activity.	
Temporal variability		None.
Review process	Draft NEI made available for public and peer review, comment, revisions.	
Endorsements	EPA.	

NEI Nonroad Methodology

The NEI nonroad category encompasses a wide array of vehicles—essentially all motorized vehicles and equipment that are not normally operated on public roads. This category also excludes locomotives, commercial marine vessels, and aircraft, which are analyzed separately. The nonroad category extends to a variety of fuel types, including diesel, gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG). The following types of vehicles are included in the nonroad analysis:

- Freight cargo handling equipment (CHE);
- Airport ground support equipment (GSE);
- Recreational vehicles and equipment (marine and land based);
- Farm and construction machinery; and
- Industrial, commercial, and lawn and garden equipment.

The approach employed in this methodology is similar to the approach in the on-road methodology: activity, engine mix, and fuel data are collected at the county level, emissions are calculated using EPA's NONROAD model, and the resulting national inventory is apportioned to the state and county levels. As in the on-road inventory, data collection and disaggregation is handled by NMIM, which operates above NONROAD. NMIM formats county data into input files for NONROAD, runs the model, and processes the results to be consistent with other components of the NEI. Where states provide alternate inputs into NONROAD, these values are used in place of the default NMIM inputs.

The nonroad methodology has evolved as better tools and data have emerged. The NONROAD model was first applied to this category in 2001 for the 1996 inventory. In past years, state emissions inventories were used in place of EPA calculations, notably in California, Pennsylvania, and Texas. Inventories for years prior to 1996 were developed retroactively using NONROAD.

Summary of Strengths and Weaknesses. A summary of NEI (*46*) nonroad methodology strengths and weaknesses is provided in Exhibit 3-10.

Sources of Uncertainty. There are sources of uncertainty in all nonroad methodologies in terms of data collection, equipment emission factors, and other factors. These topics are discussed in more detail in Section 3.6.

NEI Aircraft Methodology

The NEI aircraft methodology captures emissions from all domestic and international aircraft operating within the United States. Aircraft are classified by EPA into four categories: commercial, air taxi, general aviation, and military. This analysis focuses on emissions from commercial aircraft used to carry freight, passengers, or both. Commercial aircraft tend to be large, powered by jet engines, and operate at large

Exhibit 3-10. Summary of strengths and weaknesses—NEI nonroad methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes		Does not address physical processes; applies average EF to equipment inventory.
Sensitivity to input parameters		
Flexibility	Although the NONROAD model has default equipment distributions, local agencies can submit county-specific data.	
Ability to incorporate effects of emission reduction strategies		Does not incorporate inspection/maintenance profiles or other strategies.
Representation of future emissions		Does not forecast future emissions.
Consideration of alternative vehicle/fuel technologies	Can incorporate alternative fuels such as LPG and CNG/LNG.	
Data quality	Can incorporate county-level data submitted by local agencies.	Quality of data will vary depending on locality. Default parameters may not capture spatial variations.
Spatial variability		Does not account for the effect of geography on emissions estimates.
Temporal variability		Method only calculates annual emissions. It does not evaluate emissions or fluctuations on seasonal or monthly scales.
Review process	Draft NEI made available for public and peer review, comment, revisions.	
Endorsements	EPA.	

airports. Emissions from these aircraft are calculated by combining airport activity data with FAA's EDMS emissions model. Since the inventory is estimated independently for each airport, emissions are allocated to the county level by default. State and national emissions are calculated by aggregating county-level emissions.

Data on airport activity is measured in terms of the Landing and Takeoff (LTO) cycle, a five-mode approach consisting of the following:

- Approach: period beginning when aircraft enters the pollutant "mixing zone," typically at an altitude of 3,000 ft, until landing;
- Taxi/idle-in: time spent after landing until aircraft is parked at the gate and engines turned off;
- Taxi/idle-out: period from engine startup to takeoff;
- Takeoff: time spent after takeoff that lasts until the aircraft reaches 500 to 1,000 ft;
- Climbout: period following takeoff that concludes when aircraft passes out of mixing zone.

LTO data is collected in *Airport Activity Statistics of Certificated Air Carriers,* (*52*) which captures statistics for all domestic carriers. Each LTO cycle is correlated with an airport location, carrier, and aircraft type.

Airport statistics are input into the EDMS model, which combines LTO data with emissions factors that are specific to each type of aircraft and each phase of the LTO cycle. EDMS uses default time-in-mode (TIM) values to determine total time spent by aircraft in each LTO mode, and calculates emissions using measured emissions factors. See Section 3.7 for more information on EDMS.

Summary of Strengths and Weaknesses. A summary of NEI (*46*) aircraft methodology strengths and weaknesses is provided in Exhibit 3-11.

Sources of Uncertainty. Sources of uncertainty are discussed in Section 3.8.

3.2.4 Evaluation of Parameters

The GHG Inventory and NEI methodologies include an analysis of all transportation modes; as such, many data inputs required for these analyses are the same as inputs required for each modal methodology, as discussed in subsequent chapters. This section focuses on parameters that are unique to the EPA national methodologies. These parameters are all unique to the process of measuring and allocating fuel consumption at the national level.

Exhibit 3-11. Summary of strengths and weaknesses—NEI aircraft methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Accounts for variations in emissions between aircraft engines, between LTO modes.	
Sensitivity to input parameters	Sensitive to activity by type of aircraft	
Flexibility	Can include changes in activity at any airport	
Ability to incorporate effects of emission reduction strategies		None.
Representation of future emissions		None.
Consideration of alternative vehicle/fuel technologies		None.
Data quality	FAA maintains detailed activity (LTO) records.	
Spatial variability	Accounts for activity and fleet mix at each airport.	Does not incorporate local meteorology.
Temporal variability		None. Emissions reported annually.
Review process	Draft NEI made available for public and peer review, comment, revisions.	
Endorsements	EPA.	

The parameters discussed in this section are used in allocating fuel consumption to the transportation sector and to individual modes, and are used in one or both of the EPA national methods. A summary of parameters is presented in Exhibit 3-12, and more detailed information is provided in the pedigree matrix (Exhibit 3-13) and the subsequent qualitative discussion.

Pedigree Matrix

A pedigree matrix, provided in Exhibit 3-13, for data quality assessment assigns quantitative scores to all parameters included in Exhibit 3-12. The criteria to assign scores in the pedigree matrix are included in Appendix A.

Parameters Used in Fuel Consumption Calculations

Since transportation emissions in the EPA GHG Inventory are due to the combustion of fossil fuels, the primary input into the inventory is data on fuel consumption within each mode. Although some data sources capture fuel use in individual modes (e.g., rail), EPA chooses a methodology that measures nationwide fuel consumption and allocates fuel use to economic sectors such as industrial, residential, and transportation. This approach has several benefits: it relies on comprehensive fuel data available from EIA, and it accurately measures GHG emissions due to fuel use for the nation as a whole. However, the process introduces uncertainties when fuel use and GHG emissions are assigned to the transportation

Exhibit 3-12. Parameters for the national inventories.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Fuel Supply Data	GHG Inventory	National	✓	✓	×
Economic Sector Activity Data	GHG Inventory	National	✓	✓	×
Modal Activity Data	GHG Inventory, NEI	National	✓	✓	×
Fuel Carbon Content	GHG Inventory	National	✓	×	×
Modal Emissions Factors	NEI	National	✓	×	×
Marine Equipment Inventory	NEI	National	✓	×	×
Rail GIS Data	NEI	National	✓	×	×
Local Nonroad Equipment Inventory	NEI	National	✓	×	×
On-Road Fleet Mix	NEI	National	✓	×	×

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

Exhibit 3-13. Pedigree matrix—national parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Fuel Supply Data	5	1	1	1	1	1	N/A	1
Economic Sector Activity Data	4	3	Varies	2	Varies	1	N/A	5
Modal Activity Data	4	3	Varies	2	1	1	N/A	5
Fuel Carbon Content	5	1	1	1	1	1	1	1
Modal Emissions Factors	4	2	3	2	3	2	2	Varies
Marine Equipment Inventory	2	3	3	4	3	2	N/A	5
Rail GIS Data	2	2	1	1	2	1	1	2
Local Nonroad Equipment Inventory	2	3	3	2	3	5	N/A	Varies
On-Road Fleet Mix	2	2	2	2	1	2	N/A	2

sector and to individual modes. This section qualitatively analyzes the assumptions made when estimating modal fuel consumption.

Measuring Nationwide Fuel Use—Fuel Supply Data. The combustion of fossil fuels accounted for 83% of nationwide GHG emissions in 2007. (*53*) Since emissions from fuel combustion constitute the vast majority of the inventory, the need to accurately measure nationwide fuel use is paramount. EPA measures total fuel consumption in the United States using data from EIA, primarily the agency's Monthly Energy Review, and additional petroleum product detail. The Monthly Energy Review reports data on both fuel production (petroleum imports, domestic production, and refining) as well as consumption (by fuel and end-use sector). The fuel production data conforms to a reporting convention promulgated by IPCC and the International Energy Agency (IEA), in which data are presented in a top-down format. This structure aggregates data on fuel production and distribution to assess fuel use, referred to as "apparent consumption." These data are used by the GHG Inventory as the first step in allocating fuel consumption.

This step in the process contains few uncertainties compared to subsequent steps. The collection of national fuel data contains few assumptions, since EIA has comprehensive access to primary sources of information. Larger uncertainties occur in the following steps in which national data are allocated to the transportation sector and individual modes.

Assigning Fuel Use to the Transportation Sector—Economic Sector Activity Data. After collecting national fuel consumption data, the EPA methodology distributes fuel use among economic sectors, to determine the GHG emissions attributable to each sector. As part of this step, EPA reconciles the results of a top-down approach, based on EIA data, with the results of a bottom-up approach, based on industry activity measurements. Consistent with IPCC guidelines, the bottom-up (or *sectorial approach*) relies on several data points, including consumption data by EIA and end-use energy consumption surveys such as the Manufacturing Energy Consumption Survey, which is conducted every four years. Additional information is used to adjust fuel consumption for the transportation sector: EPA builds an activity-based estimate of fuel consumption from modal data, including FHWA statistics for on-road activity and AAR statistics for rail activity.

Several potential sources for error exist in applying this method to allocate fuel consumption to the transportation sector. These include

- Consumption data, often collected in the form of fuel expenditures, may distort true fuel usage. For example, collection methods may focus on large, more efficient consumers, and bypass smaller entities that may use comparatively more fuel. In addition, data based on fuel prices may be biased as larger consumers can often leverage lower prices due to high purchasing volume.
- Transportation activity data, collected for each mode independently by separate agencies, may contain different biases and errors due to differing methodologies. Further, activity sets may be incomplete for modes with limited information such as commercial vessels and nonroad equipment.

Assigning Fuel Use to Vehicle Types—Modal Activity Data. This stage of distribution allocates total transportation fuel consumption to individual modes and sub-allocates to vehicle types. The modal distribution is completed using a combination of data from the activity analysis conducted in the prior step and EIA data on individual fuel types. These two data sources serve to confirm or reconcile differences in reporting. For example, rail fuel statistics are reported by AAR based on company surveys, while the same data are reported by EIA based on responses from fuel distributors. Similar comparisons can be conducted for aviation fuel and marine bunker fuel. The distribution of gasoline and diesel fuel is more complex, as the fuels are used in several modes, but is conducted using activity data. However, the distribution of fuel within vehicle types requires additional data and assumptions. For on-road vehicles, the distribution among passenger cars, light-duty trucks, and medium- and heavy-duty trucks is completed using detailed VMT data from FHWA. Similarly, aircraft consumption can be separated into commercial and other sources using FAA flight records. However, there is no comparable detailed source of information for distributing fuel use among categories of marine vessels.

To the extent that GHG inventories by vehicle subcategory can be used to inform an analysis of an individual vehicle type, this step in the methodology can introduce additional uncertainties into future analyses. Sources of error include

- For on-road vehicles, this step requires data on vehicle fuel types (gasoline versus diesel) as well as activity by vehicle type. Since these two data sources are maintained by separate agencies, EIA and FHWA, respectively, their category definitions and relationships may not align. This issue is magnified when considering alternative fuels with a small vehicle share, such as CNG and LPG. The GHG Inventory does not disaggregate alternative fuel usage to vehicle categories.
- Uncertainty exists in activity data in the nonroad category, including the comparative activity of mobile nonroad vehicles versus stationary nonroad equipment. This creates added challenges in correctly allocating fuel use and emissions to the nonroad mobile category. The GHG Inventory does not distinguish between emissions from construction equipment and agricultural machinery, and emissions from nonroad trucks.

3.3 Heavy-Duty Trucks

This section includes (1) a brief documentation of the current practice and methodologies for calculating emissions from heavy-duty trucks, (2) a summary of the strengths and weaknesses of such methods, and (3) an analysis of uncertainty associated with these methods, as well as with the parameters used in the emission calculations. Although the estimation of truck emissions is conceptually simple (i.e., emissions are the product of freight activity and emission factors), the analytical procedures for emission estimation can be quite complex depending on the goals of the analysis and the level of data and resource availability. Exhibit 3-14 summarizes the main methods and models to estimate truck emissions.

3.3.1 Evaluation of Emission Models

Despite the high number of existing emission models, this section focuses on the four most widely used models. EPA's MOBILE6 and CARB's EMFAC2007 are the two approved models for State Implementation Plan (SIPs), conformity analyses, and project-level analyses under NEPA and CEQA, respectively. EPA's MOVES2009, which brings many methodological improvements over MOBILE6, is currently in draft form, but will eventually replace MOBILE6. The Comprehensive Modal Emissions Model (CMEM), developed by UC Riverside, is the most established micro-scale emissions model.

MOBILE6

MOBILE6 is an emission factor model designed by EPA to produce motor vehicle emission factors for use in transportation analyses, including SIP development, transportation

Exhibit 3-14. List of truck methods and models.

Method/Model	Type	Geographic Scale	Pollutants	Freight/Passenger
MOBILE6	Model	All	All	Both
MOVES2009	Model	All	All	Both
EMFAC2007	Model	All	All	Both
CMEM	Model	Local	All	Both
Regional Method	Method	Regional	All	Both
Local Method	Method	Local	All	Both

conformity, and project-level analysis required under NEPA. It can be used at any geographic level within the United States.

With the release of MOBILE6 in 2001 came several improvements regarding heavy-duty vehicles (HDVs) over its previous version, MOBILE5: (1) increase in the number of HDV categories, (2) addition of off-cycle NO_x impacts as a result of control strategies that optimize fuel economy over emissions (i.e., defeat device issue), and (3) incorporation of 2004 and 2007 HDV emission standards, including the use of low-sulfur fuel starting in 2006. (*54*)

Summary of Strengths and Weaknesses. A summary of MOBILE6 strengths and weaknesses is provided in Exhibit 3-15.

Analysis of Process Uncertainty. The emissions rates generated by MOBILE6 require a multitude of input assumptions that can either be MOBILE6's national defaults or user-specified parameters. MOBILE6 is particularly sensitive to assumptions regarding vehicle age, VMT by vehicle class, average speeds, and temperature. (*55*) This discussion focuses on the following key issues: (1) emission factors, (2) truck age distri-

Exhibit 3-15. Strengths and weaknesses—MOBILE6.

Criteria	Strengths	Weaknesses
Representation of physical processes	EFs incorporate effects of vehicle average speeds.	EFs are based on engine testing (rather than chassis dynamometer testing). EFs are based on a single driving cycle. Model assumes that brake and tire EFs, which are based on passenger cars, are the same for HDVs. PM EFs are based solely on heavier truck classes; therefore PM emissions from the lighter classes of HDVs might be overestimated. There are concerns about how speed correction factors capture speed/congestion effects on emissions. Data on age distribution, mileage accumulation rates, and fuel ratios are not available for all truck categories. Model does not consider high emitters or mal maintenance and tampering for HDVs. Model does not consider start emissions for diesel vehicles.
Model sensitivity to input parameters		Number of engine starts and soak time cannot be modified by user. Other than HC, CO, and NO_x, emissions of other pollutants are not sensitive to vehicle average speed or facility type. EFs do not take air conditioning effects into account. Model does not consider effects of road grade or pavement quality.
Model flexibility	Few inputs are required. National default parameters (VMT mix by vehicle class, vehicle age distribution) can be overridden by local estimates.	
Ability to incorporate effects of emission reduction strategies	Model is able to capture the effects of strategies that change truck VMT, vehicle average speed (for HC, CO, NO_x), fleet average age.	Model is not able to capture the effects of strategies that affect pavement quality or congestion level.
Representation of future emissions	EFs can be estimated up to 2050.	There are concerns as to whether the assumptions used to estimate future EFs are still in line with latest vehicle technology trends.
Data quality		Data based upon engine testing and conversion factors are applied to calculate grams per mile. These conversion factors are fixed by weight class and may not be representative of heavy-duty freight trucks.
Spatial variability		There are concerns as to whether national defaults are representative of regional and local parameters.
Temporal variability		
Review process	There have been many independent analyses and reviews of MOBILE6.	
Endorsements	MOBILE6 is the required model for SIPs and conformity analyses.	

bution and mileage accumulation, (3) how truck speeds affect truck emissions, (4) high emitters, (5) diesel fraction, (6) start emissions and soak time, and (7) classification of trucks.

Emission Factors—General. The emission factors in MOBILE6 were based on engine test data submitted by manufacturers as part of the certification process (in g/bhp-hr). (*54*) As a result, emission factors needed to be converted (to grams/mile) based on fuel density, brake-specific fuel consumption (BSFC), and fuel economy. Because of the wide variation in gross vehicle weight, fuel economy, horsepower ratings, and transmission types, the gram/mile emission factors derived from engine test data had much higher uncertainties than those calculated by vehicle dynamometer testing.

This report (*54*) also compared MOBILE6 emission factors for HDVs with chassis dynamometer data. Results indicated that HC and CO emissions in MOBILE6 matched well with available test data, while NO_x emissions seem to be overestimated for older models (before 1979) and underestimated for newer models (1994 and later).

MOBILE6 is not designed to measure second-by-second emission rates, but it relies on specific driving cycles to generate emission rates. For light-duty vehicles, there are different driving cycles assumed for each of the four facility types. For heavy-duty trucks however, all vehicle categories are based on the same driving cycle—the Federal Test Procedure (FTP) transient cycle—independently of the facility type. Additionally, MOBILE6 does not incorporate the effects of road grade, actual vehicle weight, or vehicle aerodynamics, all of which have a strong effect on emission factors.

Emission Factors—PM. Previous research indicated several deficiencies in the estimation of PM emission factors in MOBILE6, mainly from carrying over the algorithms from PART5, the previous model for PM emission factors. (*56*) PART5 is believed to underestimate emissions from real vehicles, primarily because it is based on low-mileage, proper functioning vehicles, and does not consider high emitters to the same degree. (*57*)

MOBILE6 accounts for the implementation of the 2007 PM emission standards for HDVs, which require the implementation of low-sulfur diesel fuel (15 ppm limit) and a 90% reduction in exhaust PM emission standards for HDVs. (*58*) The assumptions associated with brake and tire PM emissions were not affected. A significant shortcoming of MOBILE6 is that it assumes the same brake and tire PM emission factors (in grams/mile) for all vehicle classes. Because these factors were developed from passenger car testing, brake and tire PM emissions from HDVs are likely underestimated. This is the case because brake and tire wear should be proportional to the energy required to stop a vehicle, which, in turn, is a function of vehicle weight and speed.

PM idling emission rates in MOBILE6 (reported in grams/hour) are based on the heavier classes of HDVs, so MOBILE6 likely overestimates idle PM rates from lighter classes of HDVs. Additionally, these rates are not corrected for diesel sulfur content, nor do they account for more stringent PM standards in the 2007 rule.

Emission Factors—Air Toxics. Data on air toxics emissions from HDVs are very sparse, and emission factors used in MOBILE6 are based on very few data points. (*58*) The implementation of the 2007 standards, which are likely to require particulate filters, will certainly increase the margin of error of current air toxic emission factors for HDVs in MOBILE6.

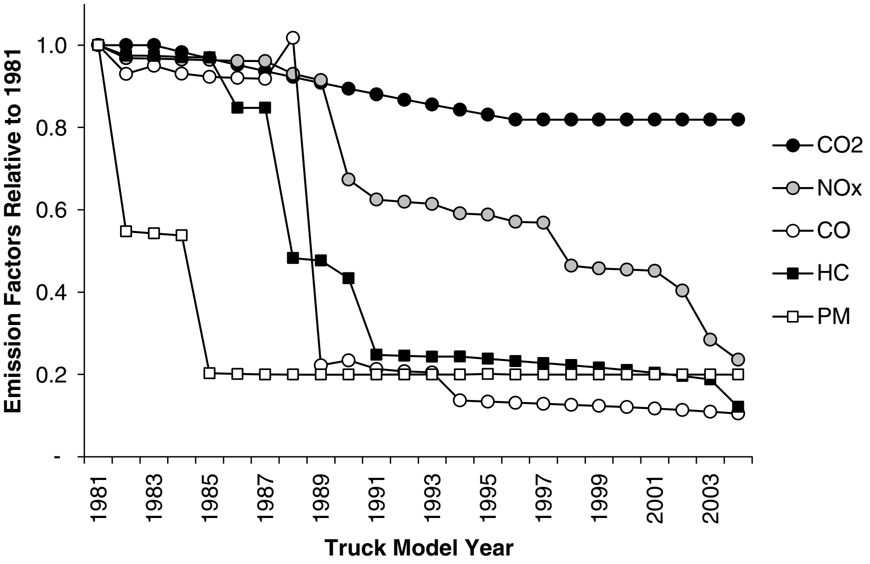
Truck Age Distribution and Mileage Accumulation. The default truck age distribution and mileage accumulation in MOBILE6 were developed based on a report that estimated truck age distribution in 1996 from vehicle registration data. (*59*) Mileage accumulation was estimated from the 1992 TIUS. EPA developed exponential fit curves to convert the 1996 truck age distribution to other years, but the mileage accumulation rates in 1996 were used for the remaining years. This adds a degree of uncertainty in the analysis of emissions, because mileage accumulation rates are likely to evolve over time.

The default parameters for truck age distribution and mileage accumulation are important to the extent that emission factors vary by truck model year. Exhibit 3-16 illustrates the relative difference in emission factors of CO_2, NO_x, CO, HC, and PM_{10} relative to a 1981 HDV8b truck. In comparison to other pollutants, CO_2 emission factors are not very sensitive to truck model year and remain constant after 1996. Other pollutants' emission factors are very sensitive to truck model year. As a result, assumptions regarding truck age distribution and mileage age distribution have a large impact on fleet-average emission factors and on total emissions.

Average Speed. Although MOBILE6 does not enable user-customized driving cycles, speed correction factors are used to differentiate emissions of HC, CO, and NO_x by vehicle average speed. For heavy-duty trucks, MOBILE6 inherited the same speed correction factors from MOBILE5, as opposed to light-duty vehicles, for which adjusted speed correction factors were developed. The uncertainties associated with the use of speed correction factors to adjust emission factors by vehicle average speed are discussed in Section 3.3.4.

High Emitters. Having been identified as one of the main issues in MOBILE6, correctly representing the share of high emitters is challenging for many reasons, including (1) the number of high emitters is relatively small, (2) the range in emissions is quite large, and (3) owners of high emitters are typically reluctant to submit their vehicles to testing. (*55*)

Exhibit 3-16. MOBILE6's sensitivity to truck model year (HDV8b).



MOBILE6 incorporates correction factors to account for high emitters, and despite many criticisms about the underlying methodology, it is a step in the right direction. However, such correction factors are applied to light-duty vehicles only, so high emitter heavy-duty trucks are not considered. The effects of tampering and mal maintenance in heavy-duty vehicles also are disregarded.

Diesel Fraction. Diesel fraction, defined as the share of diesel vehicles in a particular vehicle category, is important since emission rates are different for diesel and gasoline-powered vehicles. Although users can input specific diesel fractions for each model year within each vehicle category, this is rarely done due to a lack of project-specific information. As a result, most analyses rely on default values provided in MOBILE6. The main source of uncertainty relates to the fact that MOBILE6 assumes that diesel fractions for vehicles of model years later than 1996 have the same diesel fraction as a 1996 model year. (*60*) Although this is not an issue for Class 8 trucks, which are virtually all diesel powered, diesel fraction for Classes 2b through 7 have varied quite substantially from 1972 to 1996.

Start Emissions and Soak Time. Start emissions are those that occur immediately after a cold engine start; soak time represents the time between when the engine is turned off and the next time it is restarted. Emission rates for heavy-duty gasoline vehicles include engine starts, and the number of engine starts and the soak time distribution cannot be adjusted by the user (such adjustment is possible for light-duty vehicles). (*60*) Because the trip length can be quite different for different truck trips, the inability to customize start emissions can add uncertainty to emission rates. MOBILE6 does not consider start emissions for any diesel vehicles, thus adding another set of uncertainties to the emission calculations.

Classification of Trucks. Although MOBILE6 includes 16 categories of heavy-duty trucks, data on age distribution, mileage accumulation rates, and fuel ratios are not available for all truck categories. (*59*) There are only 7 categories for registration distributions by age and only 18 categories for average annual mileage accumulation rates by age. As a result, some weight classes were combined (Classes 4 and 5 as well as Classes 6 and 7), and it was assumed that such classes had the same age distribution.

EMFAC2007

Developed by the California Air Resources Board (ARB), EMFAC is the approved emissions model in California, and it is used for SIP development, conformity analysis, and other analyses that are typically conducted using MOBILE6 in other states. The model produces emission rates and inventories for criteria air pollutants, CO_2, and CH_4. Air toxics can be speciated using CARB factors. EMFAC2007 produces emission calculations at the county, regional, and state levels, for past, current, and future years.

The overall approach for emission calculations in EMFAC and MOBILE6 is very similar, where regression analyses of primary data sets are used to calculate emission rates and correction factors. Because the approaches are very similar, the main potential limitations in accuracy are the same as those described in the discussion of MOBILE6. One main difference is the way that EMFAC2007 handles off-cycle emissions due to the defeat device. MOBILE6 allows the user to specify how fast the device will be removed, while EMFAC2007 makes assumptions that the device will not be removed in 1994 to 1998 trucks.

At its core, the development of EMFAC2007 was based on the inclusion of area-specific activity data for various regions within California, including vehicle registration, mileage accumulation, vehicle age distributions, and VMT, as well as temperature and humidity profiles.

Summary of Strengths and Weaknesses. A summary of EMFAC2007 strengths and weaknesses is provided in Exhibit 3-17.

Analysis of Process Uncertainty.

Development of Heavy-Duty Truck Emission Factors. EMFAC2007 updated heavy-duty truck emission factors and speed correction factors based on new data obtained through the CRC E55/E59 Project, whose objective was to reduce the uncertainty of heavy-duty truck emission factors by quantifying PM emissions in the South Coast Air Basin to support emission inventory development and to quantify the influence of tampering and mal maintenance (T&M) on heavy-duty emissions. (*61*)

The update of heavy-duty emission factors was a significant improvement. In EMFAC's previous version, heavy-duty truck emission factors were developed from testing of various engines on an engine dynamometer rather than of the entire vehicle on a chassis dynamometer. (*55*) As a result, emission factors needed to be converted (to grams/mile) based on fuel density, BSFC, and fuel economy. Because of the wide variation in gross vehicle weight, fuel economy, horsepower ratings, and transmission types, the gram/mile emission factors derived from engine test data had much higher uncertainties than those calculated by vehicle dynamometer testing.

Although the resulting database is the largest available, the fleet is still too small to accurately characterize changes between model years. Another source of uncertainty in this method is that all emissions were measured on a very limited number of driving cycles.

Exhibit 3-17. Analysis of strengths and weaknesses—EMFAC2007.

Criteria	Strengths	Weaknesses
Representation of physical processes	Updated EFs based on chassis dynamometer testing from CRC E55/E59 project. EFs incorporate effects of average trip speeds.	Emission factors are based on a very limited number of driving cycles. Not enough data on EF to accurately differentiate among different truck model years. There are concerns about how speed correction factors capture speed/congestion effects on emissions. Relies on "average trip" drive cycle, rather than facility-specific information.
Model sensitivity to input parameters		Model does not consider effects of road grade or pavement quality.
Model flexibility	Few inputs are required. County-based default parameters (VMT mix by vehicle class, vehicle age distribution) are included in the model, but can be overridden by local estimates.	
Ability to incorporate effects of emission reduction strategies	Model is able to capture the effects of strategies that change truck VMT, vehicle average speed (for HC, CO, NO_x), fleet average age.	Model is not able to capture the effects of strategies that affect pavement quality.
Representation of future emissions	EFs can be estimated up to 2050.	There are concerns as to whether the assumptions used to estimate future EFs are still in line with latest vehicle technology trends.
Consideration of alternative vehicle/fuel technologies		Only indirectly through input of different EFs.
Data quality	California-specific default data. Other regions can tailor EMFAC using other values.	
Spatial variability	County-based input parameters differentiate results.	Cannot be applied to facility level. Valid only at county and state level.
Temporal variability		Truck VMT distribution based on outdated data.
Review process		There have not been many independent analyses and reviews of EMFAC.
Endorsements	EMFAC is the required model for SIPs and conformity analyses within California.	

Characterization of Congestion and Modal Emissions. EMFAC2007 uses trip-based speed correction factors (rather than facility-based correction factors in MOBILE6). Trip-based speed correction factors can be appropriate for the development of regional emission inventories, but they fall short when the objective is to estimate local or project-level emissions. This is the case since the outputs from travel demand models include speed at the link level and not at the trip level. Therefore, adjusting emissions at the link level with speed correction factors at the trip level is not consistent, and is an important source of uncertainty. Additionally, EMFAC2007 does not incorporate the effects of road grade, actual equipment weight, or equipment aerodynamics, all of which have a strong effect on emission factors.

In order to assess the degree of uncertainty associated with the use of speed correction factors in the development of emission factors in EMFAC2007, a comparison was done with emission factors generated by a modal approach (i.e., second-by-second approach) where the driving cycles developed by Sierra Research were adapted for heavy-duty trucks. (*62*) In Exhibit 3-18, the black line represents EMFAC2007 emission factors, while the other lines represent modal emission factors on freeways and arterials, respectively. Both approaches provide comparable results for uncongested freeways at high speeds, but very different results for congested freeways and arterials. Unlike MOVES, EMFAC2007 differentiates GHG emissions based on average trip speed but does not consider congestion explicitly. Additionally, EMFAC2007 does not differentiate among different roadway types. For instance, a vehicle with an average speed of 30 mph could be traveling along an uncongested arterial, or along a congested freeway. Although the emission factors under these two scenarios are very different, EMFAC2007 cannot differentiate between them. The modal approach however, has the ability to differentiate these two scenarios, thus creating the differences between the two models.

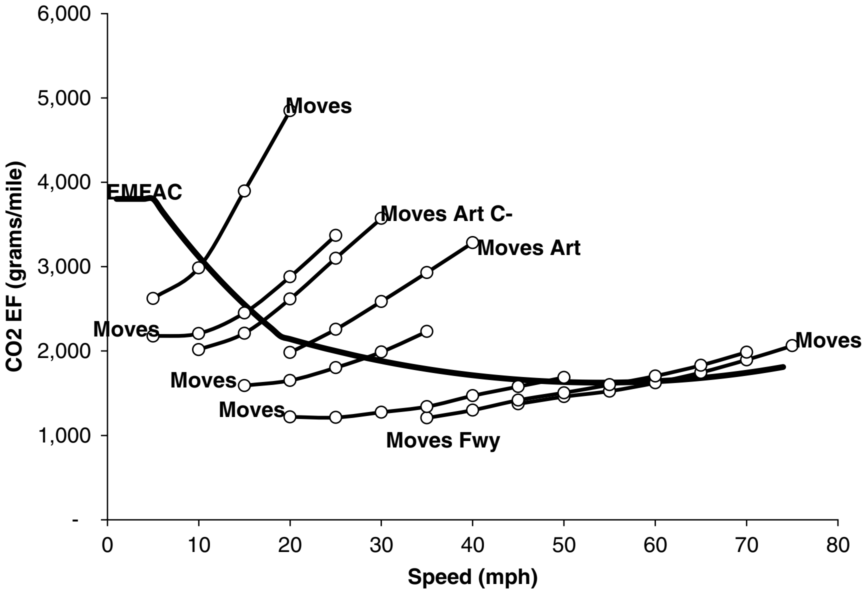
Truck VMT Distribution. Because EMFAC2007 is also intended to estimate emissions inventories at the county level, it relies on a methodology to allocate VMT information (reported by Council of Governments [COGs] and MPOs) to specific vehicle categories. VMT estimates are provided by travel demand models and validated by traffic count data. VMT estimates are generated at different levels of resolution, and heavy-duty truck VMT is typically not provided separately.

In contrast to its previous version, which allocated VMT to each vehicle category based on registration data, EMFAC2007 allocates VMT based on (estimated) travel data. (*63*) The primary data source was a 1999 Caltrans heavy-duty truck survey, which was used to estimate the fraction of heavy-duty truck VMT traveled in each county in California, as well as mileage accumulation rates and truck age distribution.

The survey included origin and destination information but not route, so the latter had to be estimated based on shortest-path algorithms. To reduce the uncertainty in this method, these routes were validated with actual truck routes collected by GPS data. A second source of validation included other annual publications by Caltrans.

A statistical comparison of these two data sources indicated that results were consistent for one year. In order to es-

Exhibit 3-18. Emission factor comparison for heavy-duty trucks: EMFAC2007 vs. modal approach.



timate truck VMT distribution for earlier and later years, only one of the data sources was used, which accounted for different growth rates in different counties. MVSTAFF, which is maintained by Caltrans, predicts statewide VMT based on a variety of model inputs including socioeconomic parameters (e.g., population, income, economic growth rates), as well as the past 25 years of vehicle registration information. Naturally, there are uncertainties associated with such estimates, given that vehicle registration and socioeconomic patterns might not be the best indicators of heavy-duty truck patterns in the state.

The truck VMT in each area was calculated by taking the product of the registered truck population (by model year), out of state fraction, and accumulation mileage rates. Truck VMT was then redistributed to specific counties based on the methodology previously described. There are a few sources of uncertainty associated with the process of estimating truck VMT, as follow:

- Based on a 1998 study (*64*), it is assumed that 25% of trucks are out-of-state trucks, and a factor of 1.33 is applied to total state VMT. There are two main issues with this method:
    - It assumes that accumulation mileage rates for in-state trucks are the same for out-of-state trucks. This issue might be resolved with the Interstate Registration Program, which will reevaluate accumulation mileage rates for in-state and out-of-state trucks.
    - It assumes a percentage of out-of-state trucks based on a single study at a given point in time.
- Accrual rates by truck age are based on the 1992 Truck Inventory and Use Survey, again another snapshot in time.

Other sources of uncertainty relate to the way VMT information is provided by COGs and MPOs. Although some jurisdictions provide explicit VMT estimates for heavy-duty trucks (e.g., SCAG), the majority of organizations provide total VMT unclassified by vehicle type. So the allocation of VMT to the specific categories of heavy-duty trucks is uncertain.

Truck Age Distribution. EMFAC2007 relies on a statewide model year distribution for heavy-duty trucks, which is generated based on registration data that CARB receives annually from the DMV. Although this method is likely to be reasonable for statewide analyses, the model year distribution could diverge from the state average in isolated counties. For example, there is a significant amount of drayage traffic, which is typically moved by an older fleet, in proximity to the Ports of Los Angeles and Long Beach. Therefore, the use of a statewide model year distribution would not be representative of the actual fleet.

Another source of uncertainty is that the gross vehicle weight (GVW) assignment to each truck is not based on DMV registration information (because such information is often not available), but through cross-checking vehicle identification number with and vehicle reference books, which only indicates the manufacturer-specified GVW, and not the actual average GVW.

MOVES2009

MOVES is EPA's most recent emission model, which will eventually replace MOBILE6 and NONROAD when fully implemented. Its most current version—MOVES2009—has recently been released. It calculates emissions of GHGs, criteria air pollutants, and some air toxics from highway vehicles, and it allows multiple scale analysis—from modal emission analyses to NEI estimation.

An uncertainty analysis of MOVES is challenging since it is still in draft version, and it is not yet approved for official use. As a result, there have not been many studies or analyses related to MOVES. Because MOVES is still under development, it is important to define whether one should analyze MOVES in its current form or the version of MOVES when fully implemented. Such distinction will be present throughout the analysis.

The main improvements MOVES offers in comparison to MOBILE6 can be summarized as follows:

- Employs a "modal" emission rate approach "as a prelude to finer-scale modeling"; (*65*)
- Relies primarily on second-by-second data to develop emissions rates, which better represents the physical processes from heavy-duty vehicles, including the ability to model cold starts and extended idling;
- Is designed to work with transparent databases, which can be modified and updated depending on the user's needs;
- Includes energy consumption, N_2O, and CH_4 explicitly;
- Uses a graphical user interface.

Summary of Strengths and Weaknesses. MOBILE6 has been highly scrutinized, and many of its pitfalls are tentatively addressed in the development of MOVES. At the same time, MOVES is still under development, and the lack of available studies prevents a more comprehensive uncertainty analysis. As a result, the analysis of strengths and weaknesses of MOVES will be based on the main differences over MOBILE6 that relate to the representation of heavy-duty truck emissions (see Exhibit 3-19).

Analysis of Process Uncertainty.

Binning Approach. MOVES uses a binning approach to calculate modal emissions, and unique source bins are

Exhibit 3-19. Comparison of MOVES and MOBILE6.

Criteria		MOBILE6	MOVES	Comment
Geographic Scale	Micro-scale analysis	×	✓	When fully implemented
	Macro-scale analysis	✓	✓	Both models enable the estimation of regional and national emission inventories.
Air Pollutants	Criteria air pollutants	✓	✓	Both models include all criteria air pollutants.
	Greenhouse gases	Incomplete	✓	MOVES adds energy consumption, N_2O, and CH_4 explicitly.
	Air toxics	✓	✓	When fully implemented.
	Life-cycle emissions	×	✓	When fully implemented, MOVES will integrate with GREET to provide well-to-wheels emissions.
Representation of physical processes	Ability to consider user-specified driving cycles	×	✓	MOVES employs a “modal” emission rate approach that will allow users to model emissions on a second-by-second basis based on user-specified driving cycles.
	Emission factors based on actual in-use emissions	×	✓	MOBILE6 uses engine certification data while MOVES uses second-by second vehicle emission rates.
	Extended idling	×	✓	
	Cold starts	×	×	
	Vehicle Weight	✓	✓	
	Ability to consider different HDT categories	✓	✓	Because MOVES classifies heavy-duty vehicles based on how VMT/fuel data are reported, it provides fewer HDT categories than MOBILE does.
	Ability to consider different facility types	✓	✓	MOVES expands the number of available facility types.
Representation of future emissions	Estimation of Future Calendar Years	✓	✓	
	Consideration of alternative vehicle/fuel technologies	Incomplete	✓	
Model flexibility	Relationship Database	×	✓	MOVES is designed to work with transparent databases, which can be modified and updated depending on the user’s needs.
	Ability to incorporate effects of emission reduction strategies	✓	✓	Because MOVES is based on a modal approach, it is more capable of capturing the effects of many emission reduction strategies, such as improvements in pavement quality, reduction in congestion, etc.
	Graphical user interface	×	✓	
	Uncertainty assessment	×	✓	When fully implemented, MOVES will enable the assessment of uncertainty based on the uncertainty of some inputs.
Review process		✓	×	Although MOBILE6 has been highly scrutinized, the final version of MOVES has not been released yet.

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

differentiated by characteristics that significantly influence fuel/energy consumption and emissions. (66) At its most disaggregated level, emissions can be calculated by

- **Geography:** the entire United States, at the county level;
- **Facility Types:** including off-network roads, rural and urban restricted access roadways (i.e., freeways and interstates), and rural and urban roads with unrestricted access;
- **Time Spans:** energy/emission output by hour of the day for calendar years 1990 and 1999 through 2050, with options to run at more aggregate month or year levels;
- **Vehicle Types:** all highway vehicle sources, including six heavy-duty truck categories (i.e., refuse, single-unit short-haul, single-unit long-haul, combination short-haul, combination long-haul, mobile home). All vehicle types are further subdivided according to fuel type, engine technology, loaded weight, and engine size.
- **Energy/Emission Outputs:** energy consumption (e.g., total energy, petroleum-based energy, and fossil fuel-based energy), N_2O, CH_4, atmospheric CO_2, CO_2 equivalent, total gaseous hydrocarbons, CO, NO_x, and PM;
- **Emissions Processes:** running, start, extended idle (e.g., heavy-duty truck "hotelling"), well-to-pump, brake wear, tire wear, evaporative permeation, evaporative fuel vapor venting, and evaporative fuel leaks. Running emissions are further subdivided in vehicle-specific power and instantaneous speed bins. This method produces 15 bins defined by combinations of speed and vehicle-specific power. Idle and decelerations are considered separately, resulting in 17 total bins.

Development of Emission Factors. MOVES provides methodological improvements over MOBILE6 as it relates to the development of emission factors for heavy-duty trucks. The emission factors in MOVES rely upon second-by-second emission data, which allows a much broader range of data to be used in the development of emission rates. Emissions data were compiled from previous EPA test programs and from several external sources, including the Coordinating Research Council (CRC), UC Riverside, Texas Department of Transportation, University of Texas, and West Virginia University. EPA contracted with Eastern Research Group (ERG) to assist in the acquisition, quality checks, and compilation of data collected by outside parties.

The information included in the second-by-second emission data was used to develop energy rates for each vehicle type. Each data point was allocated to a bin, which was characterized by vehicle type, instantaneous speed, and vehicle-specific power. All measurements falling into each bin were then averaged. The end result of this process was a table containing energy rates (in kJ per hour) and coefficients of variation by bin.

The strengths of this approach included the use on real trucks (as opposed to engine testing), driving cycles based on real-world conditions over a wide range of operating conditions, and the inclusion of actual deterioration and maintenance. The sample, which was of relatively small size (100 trucks of 30 model years), was biased to older (and potentially dirtier) trucks with unknown maintenance history (or degree of tampering). Additionally, driving cycles were not randomly sampled.

Because there were some bins without data, supplemental methods were used to "fill the holes." After an evaluation of different methods for hole filling, two methods were selected: (1) the use of PERE (Physical Emission Rate Estimator), which models fuel consumption on a second-by-second basis according to a power demand equation, and (2) interpolation of neighboring cells populated with data.

Although light-duty vehicles were well covered (i.e., over 90% of bins were filled with primary data), there were relatively more holes in bins associated with heavy-duty trucks. Single-unit trucks had 65% of bins filled, and combination trucks had less than 36% of bins filled. In particular, the heaviest truck classes (over 60,000 lbs) were very poorly represented, so there are concerns related to the validity of such factors.

Relational Database. MOVES relies on a relational database that contains default information for the entire United States. The data for this database come from many sources including EPA, Census Bureau vehicle surveys, FHWA travel data, as well as other federal, state, local, industry, and academic sources. The database is transparent, so users can modify the data with updated local inputs, which might be more appropriate for analyses at the project or regional level.

CMEM

UC Riverside's Comprehensive Modal Emissions Model (CMEM) estimates vehicle emissions at the micro-scale level. It uses a parameterized physical approach that breaks down the entire combustion process into different components that correspond to physical phenomena associated with vehicle operation. Particular emphasis was taken to model the effects of road grade, variable ignition timing, and truck platoon scenarios, where aerodynamic effects can provide a significant benefit in terms of fuel savings. The UC Riverside team also simulated instantaneous fuel consumption in a number of actual heavy-duty trucks to calibrate their model.

CMEM relies on second-by-second input data including instantaneous speed and road grade, as well as on detailed vehicle configuration (e.g., engine power rating, aerodynamic coefficient, rolling resistance coefficient, transmission, weight). As a result, CMEM is generally used for project-level analyses where a high degree of confidence is needed for a particular scenario.

Summary of Strengths and Weaknesses. A summary of CMEM strengths and weaknesses is provided in Exhibit 3-20.

Analysis of Process Uncertainty. CMEM's analysis of model uncertainty developed by UC Riverside was divided into the following three areas:

- **Emissions Measurement Variability:** although measurement instruments were calibrated prior to each HDDV test, a certain degree of inherent emission measurement variability always exists. The instrument precision varied from less than 0.5% for CO_2 to just under 11% for NO_x;
- **Vehicle Operation Variability:** it was found that small differences in driving the specified driving cycles accounted for 5% to 10% variability in emissions. Following specified driving cycles is typically impacted by other vehicles on the road, road grade, wind conditions, and safety concerns;
- **Vehicle Sampling Variability:** although there is little data to estimate vehicle-to-vehicle variability, data from CARB indicate that there is considerable variability in emissions across different model years and equipment manufacturers.

3.3.2 Evaluation of Regional Methods

On-road vehicle emission inventories developed by MPOs and state air quality agencies are the most detailed when compared to other transportation modes. Trucking emissions are typically calculated as part of the total on-road vehicle emissions estimation process. Because on-road vehicles are one of the largest sources of pollutant emissions, and because of Transportation Conformity determination requirements, the process used for estimating on-road vehicle activity and emissions is often more complex than for other transportation

Exhibit 3-20. Analysis of strengths and weaknesses—CMEM.

Criteria	Strengths	Weaknesses
Representation of physical processes	CMEM measures fuel and emissions rates on a second-by-second basis according to a set of input parameters that describe the vehicle, driving cycle, and road facility. CMEM's main advantage over MOVES/PERE is that it considers vehicle operational history effects (i.e., how the last seconds of operations affect fuel consumption/emissions). Model development was not dependent on pre-specified driving cycles.	
Model sensitivity to input parameters	The model outputs are sensitive to all parameters that have a strong effect on fuel consumption and emissions (e.g., vehicle characteristics, fuel characteristics, engine specifications, road grade, second-by-second driving cycle).	
Model flexibility		A driving cycle might not be representative of average traffic mix. If the goal of the analysis is to represent a mix of vehicles and traffic conditions, computation requirements can be heavy.
Ability to incorporate effects of emission reduction strategies	Model can measure individual project-level impacts, such as changes in congestion levels, use of HOV lanes, incident management programs, traffic signal coordination.	
Representation of future emissions		Modeler needs to know exactly the effects of future scenarios on all input parameters to the model.
Consideration of alternative vehicle/fuel technologies		
Spatial variability	Because CMEM is a micro-scale emissions model, it is well set up to capture the variability of emissions based on local conditions (e.g., road grade, pavement quality, ambient temperature).	
Review process	Uncertainty analysis is performed specifically for heavy-duty truck module.	
Endorsements		"Research grade" model—not established for industry use.

sources. All large metropolitan areas develop detailed estimates of VMT and on-road emissions by vehicle class and roadway functional class. For emission inventory purposes, some regions rely on the MPO travel demand forecasting model to determine VMT and vehicle speeds, calibrating the model to observed traffic counts. Other regions estimate VMT directly from traffic counts.

Emission factors are developed using EPA's MOBILE6 model or, in California, CARB's EMFAC model. Development of emission factors requires regionally specific information on inspection and maintenance (I/M) programs, fuel characteristics, temperature information, vehicle age distribution, and vehicle mileage accumulation by model year.

A previous report has summarized the methods to estimate freight emissions at six metropolitan areas, namely Baltimore, Chicago, Dallas-Fort Worth, Detroit, Houston, and Los Angeles. (*67*) All six study regions use a similar methodology to estimate on-road vehicle emissions, which can be summarized in the following steps:

1. The region's MPO uses a four-step travel demand model to estimate base year and future year traffic volumes by link. In some cases, the model estimates truck trips independent of passenger vehicle trips (i.e., independent truck trip generation and trip distribution modules). In other cases, the models estimate only passenger vehicle trips, and truck volumes are calculated as a percentage of passenger vehicle volumes.
2. As required by EPA, the MPO adjusts the travel model traffic volumes based on observed traffic counts. In this way, the model is calibrated to reflect base year conditions as accurately as possible.
3. The MPO estimates traffic volumes on local roads that are not represented in a travel model. Some MPOs do this estimation themselves (e.g., the Baltimore MPO); others rely on local roadway VMT provided by the state DOT (e.g., the Detroit MPO).
4. Daily traffic volumes by link are disaggregated to hourly volumes, using observed traffic counts.
5. Model traffic volumes at the link level are allocated to major vehicle types, based on traffic count information.
6. VMT is summed by vehicle type and facility type.
7. The MOBILE6 model requires VMT by 16 different vehicle types. Most regions do not have VMT or traffic count information at this level of detail, so they rely on the MOBILE6 defaults to apportion VMT into these 16 vehicle types.
8. Hourly speeds are estimated for each link. Because emission factors vary with vehicle speed, the distribution of VMT by speed can have an important effect on emissions. MPOs use equations that compare link-level volume and capacity to estimate speed.
9. MOBILE6 input scripts are developed for information such as fuel Reid vapor pressure (RVP), engine tampering levels, inspection and maintenance programs, and vehicle emission standards. If emissions are being calculated for a specific day or month, MOBILE also requires input information for factors such as maximum and minimum temperature and sunrise and sunset times.
10. MOBILE6 produces emission factors and VMT weighting factors, typically for each county, urban/rural area, and roadway functional type. VMT is multiplied by the appropriate emission factors to determine emissions. In California, emissions are estimated using the EMFAC model developed by CARB.

It is typically assumed that any heavy-duty truck (i.e., any truck over 8,500 lbs GVW) is a "freight truck." In reality, there are heavy-duty trucks that do not move freight. Some examples of non-freight heavy-duty trucks are utility trucks used for service and repair of utility infrastructure, construction trucks (e.g., winches, concrete mixers and equipment transport vehicles), urban garbage haulers, tow trucks, service industry trucks used primarily to transport equipment, and daily rental trucks. Because it is virtually impossible to separate the activity and emissions of non-freight heavy-duty trucks from freight trucks, and because non-freight heavy-duty trucks are relatively insignificant compared to freight trucks, generally no attempt is made to distinguish between the two.

Summary of Strengths and Weaknesses. A summary of strengths and weaknesses of regional MPO methods is provided in Exhibit 3-21.

Analysis of Process Uncertainty. The analysis of process uncertainty of this regional method is captured within the discussion of parameter uncertainty, including the following:

- Estimation of truck VMT by travel demand models;
- Use of average speed information;
- Use of emission factors; because the emission factors are estimated with either EMFAC (for California) or MOBILE (for the remaining states), the analysis of uncertainty associated with the estimation of emission factors is included in the discussion of these two models.

3.3.3 Evaluation of Local/Project Methods

Typically, the calculation of freight emissions at the local or project level can rely on more accurate estimates of freight activity, which is generally estimated in VMT. The emission factors are generally extracted from the same models used in national or regional approaches, but they are commensurate with the level of detail included in activity data. For example,

Exhibit 3-21. Analysis of strengths and weaknesses—regional MPO method.

Criteria	Strengths	Weaknesses
Representation of physical processes	Travel demand models are calibrated by current traffic counts.	Overall, there are many concerns related to the accuracy of travel demand models in estimating truck VMT. Truck VMT data are not disaggregated into all truck categories in MOBILE6. There are concerns about whether MOBILE6 and EMFAC can accurately capture congestion effects through average speed. Travel demand models do not calculate average speed directly, but rather estimate it through traffic volume and road capacity.
Model sensitivity to input parameters		The level of detail associated with truck travel activity from travel demand models is not commensurate with the level of detail required by emissions models.
Ability to incorporate effects of emission reduction strategies	Model is able to capture the effects of strategies that change truck VMT, vehicle average speed (for HC, CO, NO_x), fleet average age.	
Representation of future emissions	Future emissions can be represented to the extent that travel demand models can forecast truck VMT.	
Consideration of alternative vehicle/fuel technologies		Typically, there are none.
Data quality		Depending on the region, truck VMT are estimated as a share of passenger vehicle VMT, otherwise they are estimated through land-use categories as a function of employment.
Spatial variability	Travel demand models are specific to a given region of interest.	
Temporal variability	Some regions have travel demand models that have the ability to model traffic in different periods throughout the day.	Most regions have travel demand models that are based on a 24-h period. This method does not typically capture speed variations within the hour.
Endorsements	This is the method that most MPOs rely on to calculate regional emissions.	

if activity data includes traffic volumes at different speed bins, then emission factors can be estimated based on these same speed bins.

The approach used to calculate freight emissions at the local level can be summarized in five steps:

1. **Configuration of vehicle types**
   Because emission models have their own vehicle classification system, agencies need to understand which specific vehicle types should be considered in an estimation of emissions from heavy-duty trucks. Exhibit 3-22 includes the vehicle types that are considered in the three main emission models.
2. **Determination of vehicle activity**
   Truck activity is characterized in terms of VMT and idling hours. For analyses that do not include the effects of speed and congestion on emissions, aggregate measures of VMT by vehicle type in the study area are sufficient for the calculation of emissions. If VMT for each vehicle type is not available, the state or county average VMT distribution (i.e., travel fractions) can be used as a surrogate method.

   More sophisticated analyses include speed and congestion effects on emissions. In those cases, VMT by vehicle type and average speed are determined for each roadway link in the study area. Because congestion levels can vary quite rapidly, the definition of time periods is important. To properly evaluate the effects of congestion on GHG emissions, VMT should be determined at different time periods during the day. There is no standard method to determine truck idling hours and, ideally, project-level data are collected.
3. **Determination of road level of service and driving cycles**
   For those analyses that include the effects of congestion on emissions, congestion levels are characterized for each roadway segment in all project scenarios. Level of service (LOS) characterizes congestion levels and is the primary

Exhibit 3-22. Heavy-duty truck types.

MOBILE6	EMFAC2007	MOVES2009
Class 2b HDV (8,501-10,000 lbs GVWR)	LHDT Light heavy-duty trucks (8,501-14,000 lbs GVWR)	Single-Unit Short-Haul Trucks
Class 3 HDV (10,001-14,000 lbs GVWR)		
Class 4 HDV (14,001-16,000 lbs GVWR)	MHDT Medium heavy-duty trucks (14,001-33,000 lbs GVWR)	Single-Unit Long-Haul Trucks
Class 5 HDV (16,001-19,500 lbs GVWR)		
Class 6 HDV (19,501-26,000 lbs GVWR)		
Class 7 HDV (26,001-33,000 lbs GVWR)		Combination Short-Haul Trucks
Class 8a HDV (33,001-60,000 lbs GVWR)	HHDT Heavy heavy-duty trucks (> 33,000 lbs GVWR)	
Class 8b HDV (>60,000 lbs GVWR)		Combination Long-Haul Trucks

measurement used to determine the operating quality of a roadway segment or intersection. Methods applied to calculate LOS are provided in the *Highway Capacity Manual* (*68*), which is the industry standard that guides roadway operational analyses.

The derivation of emission factors that take road LOS into account depends on the development of customized driving cycles, which consist of a series of data points representing the speed of a vehicle versus time, usually on a second-by-second basis. Because the development of project-specific driving cycles is time and resource intensive, standard driving cycles can be used as a surrogate method. An EPA research project developed a set of driving cycles under a variety of congestion levels for different road types. (*62*)

The representation of congestion and LOS by a driving cycle is often criticized, since traffic patterns and delay can vary substantially within the same LOS. Additional research could indicate alternative methods to consider congestion in the evaluation of emissions from on-road sources. There also has been criticism against the methodology used by Sierra Research in the development of their driving cycles.

4. **Calculation of emission factors**
   One of two models is generally used to calculate emission factors, namely EMFAC in California, and MOBILE6 elsewhere. Depending on the analysis, the emission factors extracted by these models can represent specific truck types, model years, fuel types, and engine technologies. For more sophisticated analyses that include the effects of congestion, emission factors also can depend on average speed. In order to consider customized driving cycles in the estimation of emission factors, a modal emission model needs to be used. CMEM, which was developed by UC Riverside under an EPA contract, is arguably the most established modal emission model. However, MOVES was designed to enable micro-scale emissions analyses, and also can be used in analyses that consider customized driving cycles. MOBILE6 and EMFAC do not consider different driving cycles explicitly (GHG emissions in MOBILE6 are insensitive to speed).

   Idling emission factors are generally calculated for the lowest possible speed in grams of pollutant per mile, and multiplied by that speed to estimate an emission factor in grams per hour.
5. **Calculation of emissions**
   Emissions are calculated by multiplying freight activity by the appropriate emission factors.

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses for local methods will vary significantly depending on the method utilized for truck activity estimation. If a travel demand model is used, then the strengths and weaknesses will be similar to those described in the regional model. The following section describes the strengths and weaknesses when other methods are applied.

Analysis of Process Uncertainty.

Estimation of Truck VMT. Some project-level analyses estimate truck VMT based on regional travel demand models, whose uncertainties are discussed in the regional method. However, many local/project level analyses rely on project-specific data, which is more accurate than data estimated by models. Even though there will be variation between estimated and actual truck traffic, this is a source of uncertainty inherit to project-level analysis, and it is beyond the scope of this analysis to provide methods to more accurately estimate truck VMT at the project level. However, other sources of uncertainty that could be improved are

- Estimation of truck weight: this is key since emissions are highly dependent on truck weight.
- Determination of truck specifications: if project-level analyses rely on more specific truck configurations, the emission factors need to be consistent with the modeled truck. The most important elements to characterize trucks involve truck class, engine power, gross weight, and fuel type.

Truck Age Distribution. Many project-level analyses still rely on the national average vehicle age distribution, which sometimes is not a good proxy for local vehicle age distributions. For example, if a project is associated with a specific type of traffic, it will more likely focus on a group of carriers that will tend to use a fleet of trucks whose age range is narrower. For example, long-distance trucks that transport time-sensitive cargo tend to be newer, while drayage fleets that transport international cargo between port terminals and local facilities tend to be older than the national average fleet.

Determination of Driving Patterns. Project-level analyses that still rely on average emission factors are implicitly assuming average driving patterns that might be representative of national patterns, but not necessarily of local driving conditions. For example, if project-related traffic occurs solely at night, when traffic flows are generally smooth, or solely during peak times, when traffic flows are usually interrupted, average traffic patterns will probably not provide a good representation of actual driving patterns.

For those projects that do estimate project-specific driving patterns, the following issues might arise:

- There is usually a high degree of variation in traffic patterns, so considerable resources need to be spent in order to develop a mix of driving patterns that provide a good representation of actual driving conditions.
- Modal emission models rely on entire driving cycles to estimate emission factors, and it is very rare that project-level analyses have the resources to develop a number of driving cycles that will provide a good representation of project-related driving patterns. More typically, project-level analyses rely on traffic volumes and road capacity information to determine average speed and road LOS.
- The representation of road LOS and average speeds by specific driving cycles is often criticized because there can be a high degree of variation in driving patterns even within the same LOS, especially for the more congested levels of service;
- The emission analyses that rely on the standard definitions of road LOS require the use of driving cycles that represent such levels of service. To date, the driving cycles from Sierra Research (*62*) are the only ones that were developed with the aim of representing the standard levels of service defined by the *Highway Capacity Manual.* There are criticisms of the validity of the statistical methods used by Sierra Research in the development of those cycles. Further, these cycles were developed for light-duty vehicles, not heavy-duty trucks. To date, there are no driving cycles developed for heavy-duty trucks that aim to characterize different road levels of service.
- Another issue is the time resolution of the analysis. For congestion patterns to be properly characterized, time resolution needs to be evaluated in shorter time periods, usually less than one hour, and ideally less than 30 minutes.

Determination of Emission Factors. Emission models such as MOBILE6 and EMFAC are not able to generate emission factors that rely on customized driving cycles. For project-level analyses that characterize congestion by developing a customized driving cycle, a modal emission model is necessary. Two examples are CMEM and MOVES, whose uncertainties are discussed in Section 3.3.2.

The development of composite emission factors, which depend on the distributions of truck model year, engine technology, fuel type, and vehicle weight to characterize the project truck fleet average, is generally impacted by the fact that the development of such distributions often relies on very limited information. The use of default distributions included in emissions models brings the issue of whether such distributions are representative of local scenarios.

3.3.4 Evaluation of Parameters

Exhibit 3-23 includes a list of parameters used in the methods and models previously described.

Pedigree Matrix

A pedigree matrix (see Exhibit 3-24) for data quality assessment assigns quantitative scores to most of the parameters included in Exhibit 3-23. The criteria to assign scores in the pedigree matrix are included in Appendix A.

Truck VMT

In addition to emission factors, a total measure of truck VMT is the parameter with the biggest impact on emissions. It is recognized that current methodologies do not provide estimates of truck VMT with a reasonable degree of accuracy for emission calculation purposes. The main issues relate to (1) how truck movements are represented in travel demand models, (2) how truck trip generation data are developed, and (3) the level of detail included with truck VMT.

Estimation of Truck VMT in Travel Demand Models. All large metropolitan areas develop detailed estimates of VMT by vehicle class and roadway functional class. For emission inventory purposes, some regions rely on the MPO travel demand forecasting model to determine VMT and vehicle speeds, calibrating the model to observed traffic counts. Other regions estimate VMT based directly on traffic counts.

Many MPOs use a four-step travel demand model to estimate base year and future year traffic volumes by link. In some cases, the model estimates truck trips independent of passenger vehicle trips (i.e., independent truck trip generation and trip distribution modules). In other cases, the models estimate only passenger vehicle trips, and truck volumes

Exhibit 3-23. Parameters.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Truck VMT	All	All	✓	✓	×
VMT Share by Truck Type	All	All	✓	✓	×
VMT Share by Time of Day	All	Regional/Local	✓	✓	×
Truck Age Distribution	All	All	✓	✓	×
Mileage Accumulation	All	All	✓	×	×
Distribution of Emission Control Technology	All	All	×	✓	×
Truck Fuel Type Distribution	All	All	✓	×	×
Average Speed	MOBILE6, EMFAC2007	Regional/Local	✓	✓	×
Driving Cycles	CMEM	Local	✓	✓	×
Emission Factors	All	All	✓	✓	✓
Classification of Truck Types	All	All	✓	✓	×
Road Grade	CMEM	Local	×	✓	✓
Empty Miles	All	All	✓	✓	✓

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

Exhibit 3-24. Pedigree matrix—truck parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Truck VMT	5	2	1	Varies	1	1	1	4
VMT Share by Truck Type	4	3	3	5	3	2	1	4
VMT Share by Time of Day	2	3	1	5	Varies	2	1	4
Truck Age Distribution	4	2	3	Varies	3	1-2	1	3
Mileage Accumulation	3	2	3	5	3	2	1	3
Truck Fuel Type Distribution	3	3	3	N/A	N/A	N/A	1	2
Average Speed	3	3	1	1	1	1	1	3
Driving Cycles	3	2	1	4	3	2	1	5
Emission Factors	5	2	1	Varies	3	2	1	5
Classification of Truck Types	3	1	1	N/A	N/A	N/A	1	3
Empty Miles	3	3	3	5	3	2	1	5

are calculated as a percentage of passenger vehicle volumes. In both cases, many MPOs recognize that the methods to estimate truck VMT are less sophisticated than those used for passenger VMT. Thus, the uncertainties associated with truck VMT are higher when compared to passenger VMT.

Travel demand models use a computerized representation of the regional roadway system that includes all freeways and arterials but typically few or no local streets. This is probably not a big concern for heavy-duty trucks, since just a small share of truck miles are traveled on local roads.

Truck Trip Generation Data. Truck trip generation data are used to estimate truck traffic patterns and, consequently, truck VMT. A previous NCHRP report summarized the current state of practice on the development of truck trip generation data. (*69*) Conclusions point out that the state of the practice in truck trip generation data are primitive when compared to passenger trip generation data. Therefore, new truck trip data collection methods, capable of better characterizing truck flows at the metropolitan level, need to be developed. (*70*)

Most states and MPOs have not developed truck travel demand models, and most often truck traffic is estimated as a fixed percentage of total vehicle flows. There currently are no well-accepted methods of estimating truck trip generation rates, and those models that do utilize some type of methodology typically estimate truck trip generation rates through land-use categories as a function of employment. Land uses are generally collected by surveys. Sources of errors include the following:

- Land-use categories are very broad, and there is a high degree of variability of trip rates within these categories, as well as from region to region;
- Land-use categories were originally developed to correlate with the movement of people not freight;
- Inaccuracy of self-administered travel diary surveys (respondents can be concerned about revealing confidential information and distrusting of government) and small travel survey samples due to low response rates;
- Inappropriateness of employment as an explanatory variable—many experts indicate that industrial output is a better indicator of truck trip generation rates than employment, since labor productivity varies widely within industry category (within the same land-use category), from firm to firm, and over time;
- Lack of a consistent truck classification system—typical approaches include GVW, configuration (e.g., single-unit, combination), and number of axles, but there is no accepted methodology, which makes it difficult to compare trip generation rates; and
- A high degree of variability in the underlying economic activities that generate truck activity, which makes it challenging to apply truck trip generation rates outside of the local area where the data collection took place.

When truck trip generation data are obtained from traffic counts, the accuracy of the equipment and the selection of count locations are the most important parameters to determine data uncertainty. Most studies in the literature estimate rates based on small samples (fewer than 10 observations), with high variability from site to site.

For projects where truck VMT is estimated from commodity-based models, the number of truck trips is usually calculated by converting total tonnage transported by truck into truck trips by a payload conversion factor. These methods tend to underestimate urban trips, since they do not account for trip chaining nor local and delivery activity. They also exclude construction, service, and utility-related truck trips, which are not captured in commodity flows. Using commodity-based models in regional applications generates challenges because flows are generally allocated to traffic analysis zones (TAZ) using employment shares by industry, and employment data by industry at the TAZ level is difficult to obtain.

Level of Activity Detail. The level of detail associated with truck travel activity from current travel demand models is not commensurate with the level of detail required by emissions models, which ideally require detailed activity information disaggregated by truck type, truck weight, model year, fuel type, engine technology, ambient temperature, road type, average speed, and fuel type, among others. If only aggregate estimates of truck VMT are available, average distributions, which might not be representative of regional or local conditions, must be used to estimate an average emission factor.

Truck VMT data generally used in emission analyses at the national level rely on information from FHWA's Highway Statistics, which in turn is based on data obtained by the Highway Performance Monitoring System (HPMS). The HPMS provides data that characterize the extent, condition, performance, use, and operating characteristics of the nation's highways. States are required to report annually to FHWA aggregate estimates of VMT in collector and local roads, which account for over 15% of total highway VMT in the United States. Current practices used by the states to report local VMT estimates vary significantly and are not typically documented properly. However, because the vast majority of heavy-duty truck traffic occurs along arterials and larger facilities, the uncertainty associated with freight VMT should be smaller than for passenger VMT.

Truck VMT Share by Truck Type

Another source of uncertainty is that truck VMT needs to be disaggregated into the different truck categories in emission models. For example, with MOBILE6, truck VMT data need to be disaggregated into eight classes. If only total VMT is estimated, then the data need to be disaggregated into 16 vehicle classes. Because most regions do not have VMT or traffic count information at this level of detail, they rely on the MOBILE6 defaults to apportion VMT into these vehicle classes. Because there is a wide variation in VMT distribution across vehicle categories, the use of national average travel fractions to apportion VMT to specific vehicle categories is certainly a weak method that could add significant uncertainty to emissions estimates.

Truck VMT Share by Time of Day

The estimation of truck VMT by time of day is important for emission analysis because average speed and congestion levels, which can be important inputs, can be very different in peak versus off-peak periods. Additionally, ambient temperature is also an important input for some pollutants, especially for NO_x, which has a strong impact on ground ozone levels. In most current truck travel demand models, 24-h trip generation rates are disaggregated into time periods based on traffic counts from different time periods. Because of the limited number of traffic counts, there is uncertainty in the algorithms used to apply the share determined by each count location to those links where traffic counts are not available.

Truck Age Distribution

Because emission factors vary by model year, a composite emission factor needs to be developed based on truck age distribution. As previously mentioned, project-level and regional analyses typically rely on national age distributions, which bring uncertainty into emissions analyses since the accuracy of these analyses depends on how well national age distributions reflect local and regional fleets. The variability in truck age distribution nationwide is important to the extent that emission factors vary by truck model year. The discussion of MOBILE6 includes how emission factors vary by model year. Although emissions of CO_2 are not very sensitive to truck model year, the emissions of criteria air pollutants are generally very sensitive to truck model year.

Distribution of Emission Control Technology

Diesel emission control technology is broken down into the following four categories:

- **Uncontrolled:** generally trucks built prior to 1990 would be considered uncontrolled because no federal heavy-duty emission standard existed before 1990. Emission standards started in California for heavy-duty engines in 1987.
- **Moderate:** those trucks with engines meeting standards starting in 1990 and continuing on through 2003. This is because emission control in these engines was mostly due to engine modifications such as better fuel injection, turbocharger improvements, combustion cylinder geometry improvements, and use of after coolers.
- **Advanced:** in 2004 most engines required exhaust gas recirculation to control NO_x emissions.
- **After treatment:** for trucks with engines built in 2007 and later, these will require catalyzed diesel particulate filters and other catalytic devices to reduce NO_x emissions.

The distribution of emission control technology is usually built into the emission factors and takes into account engines in a given model year that meet future or prior emission standards due to averaging, banking, and trading. Areas with significant amounts of engines that meet future emission standards can provide errors in the emission factors.

Average Speed

The most common method used to represent congestion or driving patterns in emission models is by assuming an average speed at each roadway link. The implicit assumption is that average speed is a good proxy for congestion. Both MOBILE6 and EMFAC develop base emission rates for various truck classes using standard driving cycles. These base rates are then adjusted to a particular average speed and road type by using speed correction factors. There are four important sources of uncertainty with this method:

- The use of average speed is not the best method to represent driving patterns. The development of MOVES, which relies on a modal approach, is an indication of the shortcomings associated with the characterization of driving patterns by a single estimate of average speed.
- Travel demand models do not calculate average speed directly, but use estimates of traffic volume and road capacity to estimate average speed. Speed/volume relationships are not always very accurate, and are sometimes adjusted so that modeled traffic volumes match observed volumes. (*55*)
- Average speeds are estimated at an hourly basis, so this method does not capture speed variations within the hour, which can be quite significant especially during peak times.
- In the case of MOBILE6, emission factors only vary by speed for HC, CO and NO_x emissions. Other pollutants are insensitive to speed variations and do not represent real world conditions.

More accurate methods of characterizing driving patterns are the use of emission factors that are based on specific road levels of service, or on a combination of vehicle-specific power and instantaneous speed.

Driving Cycles

Emission factors for MOBILE6 and EMFAC2007 are developed based on emissions testing on a standardized driving cycle such as FTP. A great amount of research has been devoted to the development of driving cycles that reflect actual driving and, as a result, the Heavy-Duty Diesel Test Cycle (HDDTC) was developed by the California Air Resources Board. However, the question still remains as to whether a single driving cycle is able to provide enough information for the development of accurate speed correction factors.

Modal emissions models such as MOVES and CMEM also rely on prespecified driving cycles, but the development of emission factors does not depend on speed correction factors, but on a combination of vehicle-specific power and instantaneous speed. The use of different driving cycles also can reduce the uncertainty associated with the development of emission factors.

Emission Factors

The analysis of emission factors is discussed under each specific emission model.

Classification of Truck Types

The classification of trucks is important because (1) truck trip generation rates depend on how trucks are defined and (2) emission rates have a strong dependence on equipment type. Depending on the study, trucks might be classified based on their gross weight, number of axles, or configuration (single-unit, combination). Such variance in classification systems prevents the development of trip generation rate averages across studies. As a result, the number of sample studies for a given classification system is small, which increases the uncertainties associated with trip generation rates.

Another issue is that the heavy-duty truck categories in MOBILE6 and EMFAC2007 do not match the categories reported under HPMS. As a result, the process of mapping truck categories between these systems is not always straightforward. For example, HPMS currently characterizes heavy-duty trucks in two categories, namely single-unit trucks and combination trucks, as opposed to eight categories in MOBILE6, and three categories in EMFAC2007, in both cases according to gross vehicle weight. This issue is being resolved in MOVES since it categorizes heavy-duty trucks according to the same classification system used by HPMS.

Road Grade

The effects of road grade are not incorporated into MOBILE6 or EMFAC2007. Although this is not a freight-related issue per se, the effects of road grade on emissions are more pronounced on heavy-duty trucks than on light-duty vehicles. The importance of road grade on heavy-duty emissions can be evaluated from current modal emissions models. A previous study that evaluated truck movements over 23 different corridors concluded that fuel consumption increased by 10% to 35% as a result of grades. (*71*) Assuming that fuel consumption is a good proxy for emissions, the impacts of road grade are significant on emissions as well.

Empty Miles

Empty miles refer to the need for empty equipment to be relocated to places where it is required. Because additional fuel is consumed (and emissions generated) in the movement of empty truck equipment, ideally, empty miles should be considered in emission analyses.

In national analyses, where truck VMT is estimated based on HPMS data, empty movements are captured as well as loaded movements, since traffic measurements do not differentiate trucks based on their cargo. In regional and project-level analyses however, empty movements need to be considered separately. The incorporation of empty miles is very challenging because of a lack of data. Public data sources with aggregate information about empty miles exist. For example, VIUS provides data on empty mileage for different truck types. (Other than a truck's home-base state and the share of miles driven within and outside of the home-base state, there is no information in VIUS that could indicate empty mileage in specific corridors.) More accurate empty factors for specific lanes and commodities could be obtained directly from trucking companies, but that is generally unlikely due to confidentiality issues. It is possible that transportation rates could reflect empty miles, but it is difficult to disaggregate the impacts of empty miles from other factors such as supply and demand, labor markets, and equipment availability. Due to these challenges, many analyses simply disregard empty movements. A recent study from FRA (*71*) estimated the impacts of empty miles on fuel consumed in different truck movements, with a fuel penalty between 9% and 21% in fuel efficiency.

3.4 Rail

This section includes (1) a brief documentation of the current practice and methodologies for calculating emissions from freight rail, (2) a summary of the strengths and weaknesses of such methods, and (3) an analysis of uncertainty associated with these methods, as well as with the parameters used in the emission calculations. Topics covered include streamlined and detailed methods of estimating rail activity, emission factors, and total emissions at the national, regional, and project-level geographic scales. Most rail emission methodologies combine fuel-based emission factors with measured or calculated fuel consumption to determine total emissions. However, as data availability varies over different geographic scales, different methodologies are required.

Independently of the geographic scale, rail operations are typically categorized in switch and line-haul due to different activity patterns and equipment configurations. Line-haul operations refer to the movement over long distances, generally with newer and more powerful locomotives than switch operations, and tend to idle less. Switch activities refer to the assembling and disassembling of trains at railyards, sorting of rail cars, and delivery of empty rail cars to terminals. Switch operations involve short-distance movements, significant idling, and older equipment.

Most rail methodologies rely on fuel consumption data to determine emissions. Detailed fuel consumption data are typically considered sensitive information by railroads. However, nationwide aggregate fuel consumption data, which are based on 100% reporting for Class I railroads, are available from industry or government agencies (i.e., Association of American Railroads, Energy Information Administration, state agencies, private companies via surveys). When fuel consumption data are not available for the region of interest, it must be estimated either by apportioning fuel consumption from a larger geographic area (top-down) or by aggregating fuel consumption from individual rail movements (bottom-up). Both methods require measurements of rail activity.

Because the rail sector has fewer metrics of activity when compared to other modes, methods for calculating emissions tend to be overly simplified or overly complex, with the attendant uncertainties and inaccuracy. Streamlined, or top-down, methods determine emissions based on publicly available data on fuel consumption at the state or national level, and apportion emissions to the state or county level using an available activity metric, such as traffic density or mileage of active track. Detailed, or bottom-up, methods calculate fuel consumption either by measuring freight movements or surveying individual railroad companies. Both approaches are discussed in this section. Exhibit 3-25 includes the summary of methods to calculate rail emissions.

3.4.1 Evaluation of Emission Models

The calculation of rail emissions does not typically rely on a specific emission model. In some isolated cases, train simulation software also can be used to estimate fuel consumption on a given rail line. The best well-known train simulation software in the United States is possibly the Train Energy Model (TEM) developed by the Transportation Technology Center for the Association of American Railroads. It is a single train simulator for long-haul trains along specific routes, and was designed to calculate journey time and fuel use. Simulation model outputs are typically compared against real-world scenarios in order to calibrate the model and adjust the coefficients. Like most train simulation models, TEM relies on a set of train resistance equations originally developed by W. J. Davis in 1926. (*72*) These equations quantify train resistance based on train weight, speed, number of axles, train composition, track curvature, and grade. Fuel consumption can be derived from train resistance. Since then, the equations have been adapted to more recent standards, accounting for updated rail equipment and operational requirements. The use of train simulation software enables the most accurate results, but requires activity data at a level that is not typically available to most agencies.

3.4.2 Evaluation of Regional Methods

Typically, there is little or no published information on railroad activity available for a specific region. Thus, state and regional air quality agencies must obtain railroad activity data directly from the railroad companies. Railroad companies often are reluctant to provide detailed fuel consumption or activity data due to concerns over distributing sensitive information. Even when these data are provided, they often are not reported with a high level of detail, due in part to the railroad company procedures for maintaining such data.

Exhibit 3-25. Rail methods.

Method	Geographic Scale	Pollutants
EPA GHG Inventory	National	GHG
Locomotive National Emissions Inventory (NEI)	National	CAP and toxics
Line-Haul Emissions by Traffic Density	Regional/Local	All
Line-Haul Emissions by Active Track	Regional/Local	All
Switch Emissions by Number of Switchers or Hours	Regional/Local	All
Line-Haul/Switch Emissions by Employees	Regional/Local	All
Line-Haul/Switch Emissions by Time in Mode	Local	All
Line-Haul Emissions at Marine Terminals	Local	All

Methods to quantify regional rail emissions can be divided in the following types: (1) line-haul emissions by traffic density, (2) line-haul emissions by active track, (3) switch emissions by number of switchers or hours of operation, and (4) line-haul/switch emissions by number of employees.

Line-Haul Emissions by Traffic Density

EPA's guidance for regional inventory preparation provides an approach that estimates line-haul rail fuel consumption by means of traffic density. (*73*) In the National Emission Inventory (NEI), previously described in Section 3.2.3, EIA's estimates of national rail fuel consumption are multiplied by EPA's national locomotive emission factors. (*74–75*) National rail emissions can be apportioned to individual counties based on their share of traffic density (gross ton-miles). County traffic density is obtained from the National Transportation Atlas Database (NTAD), which includes traffic density data for each track in the United States. (*76*) To maintain the confidentiality of railroad data, the NTAD does not contain actual traffic density, but six ranges of traffic density, of which the medians are used for emission calculations. (*77*)

A similar method relies on statewide data, which can be used in place of national data. Each freight railroad that operates in a state/region is asked to report gross ton-miles (GTM) by county, as well as total fuel consumption in the state. If a railroad is able to provide this information, the statewide line-haul fuel use is apportioned to counties in direct proportion to the GTM. Sometimes the railroads perform this fuel use allocation using their own estimate of fuel use per GTM.

Another variation of the same method relies on more project-level data. According to the formula in Equation 4, fuel consumption is determined by dividing traffic density (in GTV) by the systemwide fuel consumption index, measured in gross ton-miles per gallon.

$$\begin{array}{c}\text{Fuel}\\ \text{Consumption}\\ (\text{gallons})\end{array} = \frac{\begin{array}{c}\text{Rail Traffic Density}\\ (\text{gross ton-miles})\end{array}}{\begin{array}{c}\text{Fuel Consumption Index}\\ (\text{gross ton-miles per gallon})\end{array}} \qquad \text{(Equation 4)}$$

A systemwide fuel consumption index can be determined for each individual railroad by dividing its annual traffic density by its annual fuel consumption, and these two parameters can be obtained from published Surface Transportation Board (STB) data. This method also is based on the apportionment of fuel use by GTM, but it relies on more specific data, which can be obtained from each of the participating railroads.

The fuel use estimates for each railroad are summed, with the result being an estimate of total railroad fuel use by county. Emission factors (in grams/gallon) are applied to the fuel use figures to estimate annual emissions.

Using a constant fuel consumption index, which is equivalent to apportioning fuel use by GTM, is an inaccurate method for most regional and project-level emission applications because it ignores key local factors such as grade, equipment type (which influences aerodynamic coefficients, and payload to tare ratios), and possibly congestion. All of these factors can have a substantial effect on fuel consumption per ton-mile, as indicated in a recent study from FRA. (*71*) Correction factors for grade and commodity group can be used to minimize the uncertainty associated with the use of a single measure of fuel efficiency. There have also been questions about the accuracy of county-level GTM data reported by railroads.

As indicated by a previous study, a good example of the potential shortcomings of such an approach is its application in California. (*77*) The two Class I railroads that operate in California, Union Pacific and Burlington Northern Santa Fe, primarily offer intermodal service over relatively hilly terrain in the Sierra Nevada Mountains. Their national operations however, are dominated by coal trains operating at relatively level terrain. Because coal trains are much more fuel efficient than intermodal trains, system fuel consumption index is a very poor indicator of regional fuel consumption index in California.

The FRA study and other analyses have estimated measures of rail fuel efficiency for different types of trains, lanes, and commodities, so it is possible to determine a range of variation in terms of fuel consumption index (Exhibit 3-26).

Correction factors to adjust the systemwide fuel consumption index in EPA's guidance were developed by Sierra Research. (*78*) Such correction factors adjust for the steepness of terrain as well as the proportion of bulk rail traffic. Although these factors account for the effects of the most important parameters on rail fuel efficiency, there are concerns about the validity of such factors given that they were estimated based on outdated data from a single study. Additionally, it is uncertain to what extent such correction factors are used in emissions studies.

The use of fuel consumption indexes that are specific to a given lane, train type, and commodity, such as those included in the FRA study, provide a more accurate measure of train fuel efficiency.

Exhibit 3-26. Range of rail fuel efficiency (gross ton-miles/gallon).

Rail Equipment	Min	Max
Double-Stack	523	849
Mixed	367	691
Auto Rack	542	620

Exhibit 3-27. Analysis of strengths and weaknesses—comparison of methods.

Criteria	Emissions by Traffic Density	Emissions by Active Track	Emissions by Number of Switch Locomotives or Hours	Emissions by Employee
Representation of physical processes	**Weakness:** Depending on the quality of input data, this method can provide an inaccurate estimate of regional emissions if it assumes that emissions are proportional to gross ton-miles. This assumption ignores the fact that emissions also depend on type of rail equipment, commodity, terrain level, and logistics requirements.	**Weakness:** This method provides a very inaccurate estimate of regional emissions because it assumes that emissions are proportional to active track. This ignores the dependence of emissions on track utilization, rail equipment, commodity, terrain level, and logistics requirements.	**Weakness:** This method assumes no variation in terms of the number of operating hours per switch locomotive (if that information is not provided by the railroads). It also assumes the same duty cycle across different yards.	**Weakness:** This method is very inaccurate because it does not consider differences in duty cycles, operating hours, commodity carried, equipment types, terrain, and labor productivity.
Method sensitivity to input parameters	**Weakness:** These methods are only dependent on one input.			
Method flexibility	**Strength:** This method can be used with either national or statewide data.		**Strength:** If local data are not available by the participating railroads, surrogate data from average estimates can be used.	
Representation of future emissions	**Strength:** Because this method relies on data that is published annually and that can be forecasted based on economic projections, emissions can also be forecasted.			
Data quality	**Weakness:** Because of railroad confidentiality, the NTAD only provides ranges of traffic density. There have also been concerns about the accuracy of county-level GTM data reported by railroads.		**Strength:** If number of switch locomotives is used, the process of data collection should be straightforward and accurate. **Weakness:** If number of hours is used, data quality can vary widely because there are no standards related to data collection.	
Spatial variability	**Weakness:** These two methods do not provide a good representation of the differences across geographies because they ignore the impacts of terrain grade on emissions.		**Weakness:** This method does not provide a good representation of the differences across railyards because it assumes the same duty cycle and, sometimes, the same number of hours per switch locomotive.	
Temporal variability	**Weakness:** Because these methods rely on aggregate data, they do not provide any indication on how emissions are distributed across different months, weeks, or days. The only exception is if the number of hours of operation is collected at different time periods.			
Review process	**Weakness:** There have not been any studies comparing regional/local emissions from these two methods versus other methods.		**Weakness:** Recent emission inventories completed by railroads show large differences in operating hours and fuel use by switch locomotive. The difference in operating hours is between 0% to110%, and the difference in fuel use per locomotive is between -32 to +41%.	**Weakness:** There have not been any studies comparing regional/local emissions from this method to those of other methods.
Endorsements		**Strength:** Based on EPA guidance	**Strength:** Based on EPA and CARB guidance.	

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses is provided in Exhibit 3-27.

Line-Haul Emissions by Active Track

For railroads that are not able to report GTM, mileage of active track is used as a proxy. If the railroad is able to report statewide line-haul fuel use, fuel use is apportioned to counties in direct proportion to the railroad's track mileage by county. If the railroad cannot report statewide fuel use, national-level fuel use (as reported by the Association of American Railroads) is apportioned to state and county based on track mileage. Like the previous method, fuel use estimates for each railroad are summed, resulting in an estimate of total fuel use by county. Emission factors (in grams/gallon) are applied to the fuel use to estimate annual emissions.

The main shortfall to this methodology is that active track is almost certainly not an accurate proxy for fuel use. In most regions, some rail lines are used much more heavily than others. Thus, using track length to apportion fuel consumption to the county level probably results in significant inaccuracies.

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses is provided in Exhibit 3-27.

Switch Emissions by Number of Switchers or Hours

EPA and CARB utilize a simplified approach to estimate emissions at individual railyards, whose emissions are added in regional studies. Each freight railroad that operates in a region is asked to report the number of switch yard locomotives they operate, by county or by individual yard. Some railroads also are able to provide hours of switch locomotive use by county or yard. Railroads are asked to report the average annual fuel consumption rate (in gallons per locomotive per year) of their switch yard locomotives. If railroads cannot provide this rate, a rate is assumed based on EPA guidance or on information from other railroads. Switch yard locomotive fuel use is then calculated by applying a fuel consumption rate to the number of switch yard locomotives, assuming an average locomotive duty cycle. Fuel use estimates are summed, and emission factors (in grams/gallon) are applied to the fuel use to estimate annual emissions from switch locomotives.

This method assumes no variation in terms of the number of operating hours per switch locomotive (if that information is not provided by the railroads) or the locomotive duty cycle across different yards. As indicated by a recent study, recent emission inventories completed by railroads to support CARB's railyard health risk assessment show large differences in operating hours and fuel use by switch locomotive. As for operating hours, the difference between the detailed studies and those utilizing the standard methodology ranged from 0% to almost 110%, while the difference in fuel use per locomotive ranged from –32% to 41%. (*77*)

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses is included in Exhibit 3-27.

Line-Haul/Switch Emissions by Employees

Class II and III railroads (short line and switch railroads) are often unable to provide the information described above (e.g., number of switch locomotives, hours of operation). In some regions (such as Chicago), the number of Class II/III railroads in operation is considered too large to make surveys of individual companies practical. In these cases, fuel consumption can be estimated by obtaining the number of employees of the railroad by county (using a commercial employment database such as Dun & Bradstreet) and a ratio of fuel consumption per employee.

This method does not take into consideration that different railroads carry different commodities on different types of trains over varying terrain—all of which are factors that have a strong effect on fuel efficiency. Additionally, this method also assumes that labor productivity is the same among railroads, which is also a questionable assumption.

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses is provided in Exhibit 3-27.

3.4.3 Evaluation of Local/Project-Level Methods

The previous section included methods that could estimate emissions at the regional and local level but that generally do not rely on specific project-level data. This section includes those methods that are based on local inputs. Local/project-level analyses that rely on detailed activity data from participating railroads result in more accurate rail emissions than regional analyses do.

Line-Haul/Switch Emissions by Time in Mode

Rail activity can be measured in number of operating hours in each notch for each type of train traveling on each route or operating at each railyard. Railroads can obtain such information from locomotive event recorders, which record time spent on each throttle notch, and train performance modeling software (e.g., Train Energy Model). This is by far the most accurate method, but it relies on detailed information from railroads, which do not always have the resources to collect (or are willing to share) such information.

Studies that rely on this type of methodology are generally performed very sporadically due to the intense resource requirements—an example is the Booz-Allen study (*79*) in California. Updates to such studies, like those done by CARB, typically are based on growth factors that are applied equally to all routes. (*80*) The use of growth factors is related to several shortcomings: (1) some growth factors are based on U.S. economic growth and are not specific to California, (2) growth factors will not reflect changes in train and commodity mix, train length, and locomotive power, all of which have a strong effect on locomotive duty cycles and the time spent on each throttle notch. (*77*) In particular, intermodal traffic has increased at an annualized rate of 3.9% from 1990 to 2005, well above the 3.1% annual increase in rail on average. (*81*) Therefore, it is highly unlikely that the train or commodity mix will remain constant over time. The use of event recorder data to get time-in-notch and fuel consumption can be done to extrapolate data from a few trains to the line average.

Summary of Strengths and Weaknesses. An analysis of strengths and weaknesses is provided in Exhibit 3-28.

Line-Haul Emissions at Marine Terminals

Although EPA guidelines (*82*) recommend that line-haul locomotive activity be measured in terms of fuel consumption, the estimation of rail-related emissions at port emission inventories typically take an alternative approach to better reflect line-haul operations within marine terminals. Since line-haul locomotives move over very short distances within marine terminals, rail activity is measured in hours of operation. Because line-haul emission factors can be expressed in terms of horsepower-hour, rail activity can be calculated in the same unit, as shown in Equation 5.

$$\begin{matrix}\text{Line-Haul}\\\text{Rail Activity}\\(\text{bhp-hr})\end{matrix} = \begin{matrix}\text{Number}\\\text{of}\\\text{Trains}\end{matrix} \times \begin{matrix}\text{Locomotives}\\\text{per Train}\end{matrix} \times \begin{matrix}\text{Hours}\\\text{at}\\\text{Port}\end{matrix} \times \begin{matrix}\text{Average}\\\text{Load}\\\text{Factor}\end{matrix} \times \begin{matrix}\text{Average}\\\text{Locomotive}\\\text{Horsepower}\end{matrix} \qquad \text{(Equation 5)}$$

In a detailed inventory, all inputs to this equation are obtained from the participating railroads, which otherwise need to be estimated. If local estimates are not available, the number of containerized trains can be calculated based on the number of TEUs, train capacity, an average utilization rate,

Exhibit 3-28. Analysis of strengths and weaknesses—emissions by time in mode.

Criteria	Strengths	Weaknesses
Representation of physical processes	Provided that data are available to represent the local conditions (grade, equipment type, duty cycles), this is the most accurate method to estimate rail emissions.	
Method sensitivity to input parameters		
Method flexibility		This method relies on very detailed data requirements.
Ability to incorporate effects of emission reduction strategies	Because key input parameters are captured in this method, it is generally possible to analyze the effects of emission reduction strategies.	
Representation of future emissions		
Consideration of alternative vehicle/fuel technologies	This method can capture the effects of the use of hybrid switch locomotives.	
Data quality		Data quality can vary significantly depending on the specific data collection process.
Spatial variability	If detailed local data are provided, this method gives a good degree of spatial variability.	
Temporal variability		This method does not provide any indication on how emissions are distributed across different months, weeks, or days.
Review process		
Endorsements		

plus a ratio of empty miles. EPA's best practices guidance for port-related emission inventories provides default assumptions for the other inputs based on previous inventories, but relying on average inputs ignores the operational differences among different ports. As a result, the difference between using default assumptions and using local assumptions could be a factor of up to three times, based on a comparison with emission inventories done by the ports of Los Angeles, (*83*) Long Beach, (*84*) and Seattle and Tacoma. (*85*)

A more accurate method to quantify line-haul rail activity at marine terminals is to use event recorders to measure fuel burnt per train mile within a port.

Summary of Strengths and Weaknesses. An analysis of strengths and weaknesses is provided in Exhibit 3-29.

3.4.4 Evaluation of Parameters

Exhibit 3-30 includes a list of parameters used in the methods and models. These parameters are described throughout this section.

Pedigree Matrix. Exhibit 3-31 provides a pedigree matrix for data quality assessment that assigns quantitative scores to all parameters included in Exhibit 3-30. The criteria to assign scores in the pedigree matrix are included in Appendix A.

Fuel Consumption

Class I railroads are required to report fuel use to the Surface Transportation Board (STB) via Schedule 700 of the R1 Annual Report. As a result, the fuel use data published by the Association of American Railroads (AAR) is based on 100% reporting. Even then, there have been questions about the accuracy of fuel consumption data reported by railroads. For example, the fuel use in Texas reported by railroads for 2001 (220 million gallons) is less than half the locomotive fuel sales for the state as reported by DOE (504 million gallons) for that year. Some of this discrepancy can be explained by the fact that railroads often purchase fuel in one state and then consume that fuel in another. Unfortunately, there are no mechanisms to verify the fuel consumption data reported by railroads. Additionally, there is little correlation between fuel purchases and fuel consumption in a state because locomotives can travel long distances between fuel purchases. Note that Class II and III railroads are not required to report fuel use.

Exhibit 3-29. Analysis of strengths and weaknesses—emissions at marine terminals.

Criteria	Strengths	Weaknesses
Representation of physical processes		If local estimates of rail activity are not available, the use of default assumptions could result in large uncertainties due to operational differences across different marine terminals.
Method sensitivity to input parameters		
Method flexibility	This method can be used with either local estimates or national default assumptions.	
Ability to incorporate effects of emission reduction strategies		
Representation of future emissions	Because this method relies on cargo data to estimate rail activity, economic indicators can be used to forecast emissions.	
Consideration of alternative vehicle/fuel technologies		
Data quality		
Spatial variability	If detailed local data are provided, this method provides a good degree of spatial variability.	
Temporal variability		This method does not provide any indication on how emissions are distributed across different months, weeks, or days.
Review process		
Endorsements		

Exhibit 3-30. Rail parameters.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Fuel Consumption	National	National	✓	✓	×
Locomotive Duty Cycles	All (explicit in regional/local)	Regional/Local	✓	✓	✓
Emission Factors	All	All	✓	✓	✓
Locomotive Type	All (explicit in local)	All	✓	✓	✓
Locomotive Tier Distribution	All	All	✓	✓	×
Empty Miles	All	Local	✓	✓	✓
Traffic Density	Emissions by Traffic Density	Regional/Local	✓	×	×
Miles of Active Track	Emissions by Active Track	Regional/Local	✓	×	×
Number of Switch Locomotives	Emissions by Switchers	Regional/Local	✓	×	×
Hours by Switch Locomotive	Emissions by Hours	Regional/Local	✓	×	×
Number of employees	Emissions by Employees	Regional/Local	✓	×	×

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

Exhibit 3-31. Pedigree matrix—rail parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Fuel Consumption	5	1	3	1	1	1		5
Locomotive Duty Cycles	4	Varies	3-4	Varies	4	5		5
Emission Factors	5	2	3	3-4	4	5		5
Locomotive Type	3	Varies	4	3-4	4	5		4
Locomotive Tier Distribution	4	Varies	4	Varies	1	5		3
Equipment Type	4	1	4	Varies	1	Varies		4
Empty Miles	3	4	3	1	1	2		5
Traffic Density	5	1-2	3-4	1	1	1		Varies
Miles of Active Track	5	1	3	1	1	1		1
Number of Switch Locomotives	5	1	4	1	1	1		1
Hours by Switch Locomotive	5	2-3	4	1	1	1		3
Number of employees	5	1	3	1	1	1		1

Although self-reported fuel consumption estimates are considered the most accurate data source available, this accuracy could be improved by reconciling top-down (i.e., fuel consumption through fuel sales data) and bottom-up (i.e., fuel consumption through activity data) approaches.

Rail Activity

Rail fuel use needs to be estimated based on rail activity if accurate fuel sales data are not available or are not representative of fuel burned in a geographic area. The estimation of rail activity in gross ton-miles or number of hours is examined in the previous discussion of methods.

Locomotive Duty Cycles

A locomotive duty cycle is a usage pattern expressed as the percentage of time spent in each of the throttle notches. The 1998 rulemaking was based on two duty cycles—one for line-haul and one for switch—which were development based on industry data. (*86*) Line-haul data were based on 2,475 hours operated by 63 trains from five Class I railroads across many regions in the country. Without more information about the process of sampling and development of an average cycle, it is reasonable to assume that there were enough data points to provide a good representation of an average duty cycle. Switch duty cycle data came from two local railroads with over 300 hours of operation by eight trains. The relatively small number of switch locomotives and railroads brings concerns about the statistical representation of an average switch duty cycle. Additionally, the variation of the percentage of time in each throttle notch was very high for both line-haul and switch cycles, as illustrated in Exhibit 3-32. Such high variation is the main reason why the use of an average duty-cycle is a poor substitute for regional or local data. These cycles were developed before the widespread use of idle control devices in locomotives, so updated cycles should incorporate those effects.

Emission Factors

Generally, locomotive emission factors are based on EPA's 1992 emission inventory guidance. (*87*) Documentation since then has provided updated rail emission factors based on more recent emission standards for locomotives, including EPA's 1998 Regulatory Support Document, and the Sierra Research work published in 2004. (*86, 88*) The most recent emission factors for locomotives are included in EPA's 2008 Regulatory Impact Assessment, (*89*) which includes new emission standards for Tier III and Tier IV locomotives. The RIA documentation also provides baseline emission rates for NO_x, PM, HC, and CO in 2008, which are based on average duty

Exhibit 3-32. Duty cycle variation (% time in throttle notch).

	Line-Haul Duty Cycle			Switch Duty Cycle		
Throttle Notch	Average	Lowest	Highest	Average	Lowest	Highest
Idle	38.0	77	1	59.8	82	23
Dynamic Brake	12.5	41	0	N/A	N/A	N/A
1	6.5	23	0	12.4	18	7
2	6.5	23	0	12.3	18	7
3	5.2	13	2	5.8	20	1
4	4.4	11	1	3.6	17	1
5	3.8	12	0	3.6	15	0
6	3.9	11	0	1.5	10	0
7	3.0	18	0	0.2	1	0
8	16.2	39	0	0.8	4	0

Source: U.S. Environmental Protection Agency (1998): Locomotive Emission Standards, Regulatory Support Document.

cycles for switch and line-haul locomotives. (*90*) However, the emission rates for Tier II and older locomotives are still based on the previous rulemaking document.

Baseline emission rates (NO_x, PM_{10}, HC, and CO) by locomotive type and throttle notch were developed based on data provided by locomotive manufacturers (GM and EMD), and EPA weighted these data by the average duty cycles to estimate average baseline emission rates. Exhibit 3-33 summarizes the variation in emission rates for NO_x and PM. For the line-haul cycle, the highest emission rates were roughly twice the lowest rate, while for the switch cycle the highest rates were about four times higher than the lowest rate. This wide discrepancy is strictly related to the measurement of emission rates and is not influenced by the variation in duty cycles that was previously examined. Therefore, the errors embedded in both parameters will be added and propagated through the calculation of rail emissions at the regional or local level.

The emission rates for different locomotive tiers were based on the expected emission reduction compared to the baseline rates. Tier III will need electronic common rail fuel injection systems as well as better oil control. These electronic systems should reduce the amount of uncertainty in emissions factors for these engines. Tier IV will most likely need selective catalytic reduction (SCR). Additional complexities exist in tampering and mal maintenance as well as whether the urea tanks are filled. Significant swings in emissions can occur if tampering or mal maintenance occurs.

In most analyses of rail emissions, emission factors are converted from g/bhp-hr to g/gal by applying a factor of 20.8 bhp-hr/gal for line haul, and 18.5 bhp-hr/gallon for switchers. This assumes a constant brake-specific fuel consumption (BSFC) of 0.341 lb/bhp-hr for line-haul and 0.383 lb/bhp-hr for switchers. These average BSFCs were determined through certification test data, but BSFC tends to vary depending on engine size as well as notch setting. Errors in emission factors can result if the locomotives have different duty cycles than those included in the certification tests. However, significant changes to emission factors typically occur when there are high variations in the share of time spent in notches 5 through 8 versus time in idle.

The emission factor for CO_2 tends to be the most accurate because CO_2 emissions are proportional to fuel consumption. $PM_{2.5}$ emission factors can be calculated by assuming that they represent a fixed percentage of PM_{10} emissions. EPA recommends the use of 97% based upon an analysis done for the NONROAD model. This was based upon engines using 500 ppm sulfur diesel fuel and may be different for engines using higher sulfur content. PM_{10} emission factors reflect the emission rates expected from locomotives operating on fuel with sulfur levels at 3,000 ppm, so it is important that regional and local analyses obtain information about the sulfur content of diesel fuel used in locomotives. EPA estimates that the PM_{10} emission rate for locomotives operating on nominally 500 and 15 ppm sulfur fuel will be 0.05 and 0.06 g/bhp-hr

Exhibit 3-33. Baseline emission rates (g/bhp-hr).

	Line-Haul Duty Cycle			Switch Duty Cycle		
Pollutant	Average	Lowest	Highest	Average	Lowest	Highest
PM	0.32	0.22	0.41	0.44	0.22	0.86
NO_x	13.0	10.3	18.2	17.4	9.2	33.1

Source: U.S. Environmental Protection Agency (1998): Locomotive Emission Standards, Regulatory Support Document.

lower than the PM_{10} emission rate for locomotives operating on 3,000 ppm sulfur fuel, respectively. (*89*)

Emissions of SO_2 are relatively accurate, and can be calculated through a mass balance approach, since it can be reasonably assumed that most of the sulfur in the fuel will be converted to SO_2 (the rest will be emitted as particulate matter).

Locomotive Type

Most analyses of rail emissions depend on emission rates developed by EPA as part of the rulemaking. As previously indicated, these emission rates were based on measurements from 63 locomotives of three types, and a large variation was observed between the highest and lowest emission measurements of the same locomotive type. However, the variation of the minimum measurements across the three locomotive types was not as high, with measurements of NO_x for the line-haul cycle ranging from 10.3 to 11.5 g/bhp-hr, and from 0.22 to 0.25 for PM. Similar variations were observed for maximum measurements. The variations across locomotive types for the switch cycle were higher, especially for the maximum measurements, which ranged from 15.8 to 33.1 for NO_x, and from 0.39 to 0.86 for PM.

These differences are not an issue for analyses where fuel consumption data can be obtained directly. However, for those analyses where fuel use is estimated based on activity data rather than fuel consumption data, variations in locomotive type can increase the difference between actual and modeled emission factors.

Locomotive Tier Distribution

Locomotive tier distribution is certainly an important factor when deriving a composite emission factor, since emission rates are widely different across locomotive tiers (with the exception of CO), as shown in Exhibit 3-34. Therefore, it is important to obtain the correct locomotive tier distribution from participating railroads when estimating regional and local emissions.

Equipment Type

Train type has a strong effect on fuel consumption and, consequently, on emissions. Two factors influence this correlation, namely the ratio between payload and total car weight (payload plus tare weight), and train aerodynamic resistance.

Rail cars with a low ratio between payload and total car weight will have lower fuel efficiency when measured in terms of revenue ton-miles/gallon. A study from FRA evaluated (*71*) the differences in fuel efficiency among different types of rail cars. For example, auto haulers, with ratios between payload and total car weight ranging between 25% and 30%, have relatively poor fuel efficiency in comparison to other equipment types. In contrast, tank cars and covered hoppers have ratios above 75%, which explains higher fuel efficiencies in comparison to other equipment types.

Empty Miles

More sophisticated analyses also can account for fuel consumed in empty movements by applying an empty factor to Equation 5. If local estimates are not available, data from the R1 report can be used to estimate empty ratios by rail car type. (*91*)

Empty miles refer to the miles spent to get empty equipment to places where it is needed. Because additional fuel is consumed (and emissions generated) in the movement of empty rail cars, ideally, empty miles should be considered in emission analyses.

In national analyses, where fuel use is estimated based on information reported by Class I railroads, empty movements are captured as loaded movements. In regional and local analyses however, empty movements need to be considered separately since fuel use is estimated from rail activity. The incorporation of empty miles is very challenging due to lack of data and the complexity of the logistics of empty movements. Public data sources with aggregate information about empty miles exist. For example, data from the R1 report can be used to estimate empty ratios by rail car type. However, due to these challenges, many analyses simply disregard empty movements. A recent study from FRA estimated the

Exhibit 3-34. Emission rates for line-haul and switch locomotives (g/bhp-hr).

	Line-Haul Locomotives			Switch Locomotives		
Tier	PM_{10}	NO_x	HC	PM_{10}	NO_x	HC
Remanufactured Tier 0	0.20	6.70	0.29	0.23	10.62	0.57
Remanufactured Tier I	0.20	6.70	0.29	0.23	9.90	0.57
Remanufactured Tier II	0.08	4.95	0.13	0.11	7.30	0.26
Tier III	0.08	4.95	0.13	0.08	5.40	0.26
Tier IV	0.015	1.00	0.04	0.015	1.00	0.08

Source: EPA (2008).

impacts of empty miles on fuel consumed in different rail movements, with a fuel penalty between 4% and 29% in fuel efficiency. (*71*)

3.5 Waterborne/Ocean-Going Vessels

Cargo movements by marine vessels include ocean-going vessels (OGVs) and barge movements pushed by tugs or tows. OGVs are discussed in this section, followed by a discussion of tug/tow movements at ports and inland rivers in Section 3.6.

Emissions from OGVs are usually determined at and around ports because these are the entrances and clearances of cargo into the regions of modeling interest. They are estimated using information on number of calls at a particular port, engine power, load factors, emission factors, and time in like modes.

The current practice to calculate emissions from OGVs is to use energy-based emission factors together with activity profiles for each vessel. The bulk of the work involves determining representative engine power ratings for each vessel and the development of activity profiles for each ship call. Using this information, emissions per ship call mode can be determined using Equation 6.

$$E = P \times LF \times A \times EF \qquad \text{(Equation 6)}$$

Where

E = Emissions (grams [g]),
P = Maximum Continuous Rating Power (kilowatts [kW]),
LF = Load Factor (percent of vessel's total power),
A = Activity (hours [h]), and
EF = Emission Factor (grams per kilowatt-hour [g/kWh]).

3.5.1 Summary of Methods and Models

There are three basic methods for calculating emissions from OGVs at ports, namely (1) detailed methodology where considerable information is gathered regarding ships entering and leaving a given port, (2) a mid-tier method that uses some detailed information and some information from surrogate ports, and (3) a more streamlined method in which detailed information from a surrogate port is used to estimate emissions at a "like" port. The detailed methodology requires significant amounts of data and resources and produces the most accurate results. The mid-tier and streamlined methods require less data and resources but produce less accurate results. (*9*) Exhibit 3-35 lists these three methods.

There are no current publicly available models for calculating OGV emissions at ports. Most researchers use one of the three methods described here to estimate emissions at ports. A list of recent mid-tier and detailed inventories is provided in Exhibit 3-36.

3.5.2 Evaluation of Methods and Models

Since all of the current methods and models estimate emissions at ports, the geographic distinctions (i.e., national, regional, and local/project scale analyses) are less meaningful than in other sectors. Generally, to estimate national OGV emissions, all major ports are modeled and emissions added together. For a regional approach, such as that done by CARB for estimating California marine vessel emissions, a similar approach is taken where emissions at the major California ports are estimated and then added together. The difference really relies upon whether a detailed or streamlined method is used for the individual ports and the data that are collected.

Detailed Methodology

In the detailed methodology, emissions from OGVs are estimated from detailed information on ship calls at a given port together with detailed ship characteristics, time and speed in each mode, load factors, and emission factors. The more detailed the information collected, the more accurate the results. Each parameter, as well as its potential biases and errors, is discussed in the following subsections.

Calls. The most accurate information for the number of calls comes from the local port Marine Exchange or Port Authority (MEPA). MEPAs generally record vessel name, IMO number, date and time of arrival, and date and time of departure. Larger MEPAs also record flag of registry; ship type; pier/wharf/dock (PWD) names; dates and times of arrival and departure from various PWDs, anchorages, next ports; cargo type; cargo tonnage; activity description; draft; vessel

Exhibit 3-35. OGV methods.

Method	Geographic Scale	Pollutants	Freight/Passenger
Detailed Methodology	All	All	Both
Mid-Tier Methodology	All	All	Both
Streamlined Methodology	All	All	Both

Exhibit 3-36. Recent port inventories.

Port	Year Published	Data Year	Method	Pollutants	Contractor*
Selected Alaska Ports (*92*)	2006	2002	Mid-Tier	SO_2, NO_x, PM_{10}, $PM_{2.5}$, CO, NH_3, VOC	Pechan
Beaumont/Port Arthur (*93*)	2004	2000	Detailed	NO_x, CO, HC, PM_{10}, SO_2	Starcrest
Charleston (*94*)	2008	2005	Detailed	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2	Moffatt & Nichol
Corpus Christi (*95*)	2003	1999	Detailed	NO_x, VOC, CO	ACES
Houston (*96*)	2009	2007	Detailed	NO_x, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2, CO_2	Starcrest
Great Lakes (Ports of Cleveland, OH and Duluth, MN) (*97*)	2006	2004	Detailed	HC, NO_x, CO, PM_{10}, $PM_{2.5}$, SO_2	Lake Carriers Assoc.
Lake Michigan Ports (*98*)	2007	2005	Mid-Tier	NO_x, PM_{10}, $PM_{2.5}$, HC, CO, SO_x	Environ
Los Angeles (*99*)	2008	2007	Detailed	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
Long Beach (*100*)	2009	2007	Detailed	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
New York/New Jersey (*101*)	2008	2006	Detailed	NO_x, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2, CO_2, N_2O, CH_4	Starcrest
Oakland (*102*)	2008	2005	Detailed	NO_x, ROG, CO, PM, SOx	Environ
Portland (*103*)	2005	2004	Mid-Tier	NO_x, HC, CO, SOx, PM_{10}, $PM_{2.5}$, CO_2, 9 Air Toxics	Bridgewater Consulting
Puget Sound** (*104*)	2007	2005	Detailed	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
San Diego (*105*)	2008	2006	Detailed	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest

Notes:

* Starcrest = Starcrest Consulting Group LLC, ACES = Air Consulting and Engineering Solutions; Environ = Environ International Corp.

** Includes the Ports of Anacortes, Everett, Olympia, Port Angeles, Seattle, and Tacoma.

dimensions; and other information. Generally MEPAs record every ship that enters or leaves a port but do not record those that stop at private terminals outside the port authority jurisdiction. On a national or regional level, not counting these calls can lead to underestimation of emissions related to OGVs for the area.

A second source of call data is U.S. ACE entrances and clearances data. The Maritime Administration (MARAD) maintains the Foreign Traffic Vessel Entrances and Clearances Database, which contains statistics on U.S. foreign maritime trade. Data are compiled during the regular processing of statistics on foreign imports and exports. The database contains information on the type of vessel, commodities, weight, customs districts and ports, and origins and destinations of goods.

There are several drawbacks to using U.S. ACE entrances and clearances data. First, it does not contain any call TIM information. Average TIM and speeds need to be used with the U.S. ACE data to perform a mid-tier or streamlined analysis. Second, it only represents foreign cargo movements. Thus domestic traffic, defined in the Jones Act (*106*) as U.S. ships delivering cargo from one U.S. port to another U.S. port, is not accounted for in the database. Ship calls where no cargo is loaded or unloaded are also excluded. However, U.S. flagged ships carrying cargo from a foreign port to a U.S. port or from a U.S. port to a foreign port are accounted for in the U.S. ACE entrances and clearances database since these are considered foreign cargo movements. Although at most ports domestic commerce is carried out by Category 2 ships, there are a few exceptions, particularly on the West Coast. Unfortunately, there is little or no readily available information on domestic trips, so determining this without direct port input is difficult. Third, the entrances and clearances data does not always match MEPA data because it does not differentiate between public and private terminals at a port. This is important because a port authority may not have jurisdiction over private terminals. A recent study found that the U.S. ACE entrances and clearances data accounted for over 90% of the emissions from Category 3 ships calling on U.S. ports. (*107*) For a national or regional level analysis, not counting U.S. Jones Act ships could result in an large underestimation of emissions if the region is on the West Coast. From a local level, including ship calls that are not part of a port authority jurisdiction could result in an overestimation of emissions for that port.

Power. Determination of ship propulsion power is fairly straightforward using Lloyd's Ship Register data. Lloyd's data are produced by Lloyd's Register-Fairplay Ltd., headquartered in Surrey, England. (*108*) Lloyd's data contains information on ship characteristics that are important for preparing detailed marine vessel inventories. These data include the following:

- Name,
- Ship Type,
- Build Date,
- Flag,
- Dead weight tonnage (DWT),
- Vessel service speed, and
- Engine power plant configuration and power.

All data are referenced to both ship name and IMO number. Only the IMO number is a unique identifier for each ship because the name of a ship can change. Lloyd's insures many of the OGVs on an international basis and, for these vessels, the data are quite complete. For other ships using a different insurance certification authority, the data are less robust. Using Lloyd's data to determine propulsion power should lead to fairly accurate emissions calculations.

Auxiliary engine power also can be determined from Lloyd's data, but many records are missing this information. Best practices dictate using ratios of auxiliary to propulsion power from a CARB survey (*109*) based upon ship type to determine total ship auxiliary power. Although on a large scale this will lead to fairly accurate emission determinations, on a local level, ship auxiliary power to propulsion power ratios may vary by ship size and thus be less accurate for a smaller port.

Load Factor. Load factors are expressed as a percent of the vessel's total propulsion or auxiliary power. At service or cruise speed, the propulsion load factor is assumed to be 83%. At lower speeds, the Propeller Law should be used to estimate ship propulsion loads, based on the theory that propulsion power varies by the cube of speed as shown in Equation 7.

$$LF = \left(AS/MS\right)^3 \qquad \text{(Equation 7)}$$

Where

LF = Load Factor (percent),
AS = Actual Speed (knots), and
MS= Maximum Speed (knots).

When ships move against significant river currents, the actual speed in Equation 7 should be calculated based upon the following: for vessels traveling with the river current, the actual speed should be the vessel speed minus the river speed; for vessels traveling against the river current, the actual speed should be the vessel speed plus the river speed. Because of the stall speed of a ship, load factors are assumed not to fall below 2%. There are several assumptions made here. First, the cruise speeds listed in Lloyd's data are 94% of maximum speed used in Equation 7. Starcrest, in their 2001 Port of Los Angeles inventory (*110*) determined that service speed varied from 83.3% to 100% of maximum speed for 28 ships surveyed. The average of those surveyed was 94%. Thus, propulsion cruise load factors could vary from 57.8% to 100% resulting in a possible over- or underestimation of emissions.

The second assumption is that the Propeller Law holds true for all conditions and propeller designs. The basic Propeller Law assumes a fixed pitch propeller and free sailing in calm waters. Wind and water currents, heavy seas, fouling, and other factors can increase the amount of load necessary, while improved propellers, ship hull design and other factors can reduce the power required to move at a given speed. Thus, propulsion load factors calculated using the Propeller Law can result in potential errors in emission calculations. Since the Propeller Law is used to derive main engine load factors for cruise, RSZ and maneuvering modes, uncertainty in this approach propagates to emissions calculations in those OGV activity modes.

Current auxiliary engine load factors came from interviews conducted with ship captains, chief engineers, and pilots during Starcrest's vessel boarding programs. (*83*) Auxiliary load factors are specified by ship type and time in mode. Because ships vary in generating needs, auxiliary load factors can vary from ship to ship. Overstating the auxiliary load factor can result in an overestimation of emissions, while understating the auxiliary load factor can result in an underestimation of emissions. In a large inventory (or several inventories to comprise a regional or national analysis) it is likely that these factors balance out.

Activity. OGV activity is usually broken into like modes that have similar speed and load characteristics. Vessel movements for each call are described by using four distinct TIM calculations. A call combines all four modes, while a shift normally occurs as maneuvering. Each TIM is associated with a speed and, therefore, an engine load that has unique emission characteristics. Although there will be variability in each vessel's movements within a call, these TIMs allow an average description of vessel movements at each port. TIMs should be calculated for each vessel call occurring in the analysis year over the waterway area covered by the corresponding MEPA. TIMs are described in Exhibit 3-37.

Cruise speed (also called service speed) is listed in Lloyd's data and generally taken as 94% of the maximum service speed. Distances from the maximum port boundary to either the

Exhibit 3-37. Vessel movements and TIM descriptions within MEPA areas.

Summary Table Field	Description
Call	A call is one entrance and one clearance from the MEPA area.
Shift	A shift is a vessel movement within the MEPA area. Shifts are contained in calls. Although many vessels shift at least once, greater than 95% of vessels shift three times or less within most MEPA areas. Not all MEPAs record shifts.
Cruise (h/call)	Time at service speed (also called sea speed or normal cruising speed) usually is considered to be 94% of maximum speed and 83% of maximum continuous rating (MCR). This is calculated for each MEPA area from the port boundary to the breakwater or reduced speed zone. The breakwater is the geographic marker for the change from open ocean to inland waterway (usually a bay, river, or channel).
Reduced Speed Zone* (RSZ) (h/call)	Time in the MEPA area at a speed less than cruise and greater than maneuvering. This is the maximum safe speed the vessel uses to traverse distances within a waterway leading to a port. Reduced speeds can be as high as 15 knots in the open water of the Chesapeake Bay, but tend to be about 9 to 12 knots in most other areas. Some ports are instituting RSZs to reduce emissions from OGVs as they enter the port.
Maneuver (h/call)	Time in the MEPA area between the port entrance and the pier/wharf/dock (PWD). Maneuvering within a port generally occurs at 5 to 8 knots on average, with slower speeds maintained as the ship reaches its PWD or anchorage. Even with tug assist, the propulsion engines are still in operation.
Hotelling (h/call)	Hotelling is the time at PWD or anchorage when the vessel is operating auxiliary engines only or is cold ironing. Auxiliary engines are operating at some load conditions the entire time the vessel is manned, but peak loads will occur after the propulsion engines are shut down. The auxiliary engines are then responsible for all onboard power or are used to power off-loading equipment, or both. Cold ironing uses shore power to provide electricity to the ship instead of using the auxiliary engines. Hotelling needs to be divided into cold ironing and active to accurately account for reduced emissions from cold ironing.

*Referred to as the transit zone in many inventory documents.

RSZ or the breakwater are used with the cruise speed to determine cruise times into and out of the port (however, not all ports have a physical breakwater, and for those without, an imaginary breakwater needs to be defined). Some MEPAs record which route was used to enter and leave the port, and this information can be used to determine the actual distances the ships travel. Determining the actual distance and speed during cruise mode is the most accurate method. Speeds and locations can be determined using the Automatic Identification System (AIS), which at least two services track. (Lloyd's AISLive and VesselTracker.com). Less accurate methods include assuming the ship travels at service speed during the cruise portion and estimating the distance the vessel travels in that mode.

Reduced speed zone TIM also is an estimation based on average ship speed and distance. Starcrest refers to this TIM as "transit" in their inventory documents. Generally, the RSZ starts when a ship enters the U.S. coastline such as a shipping channel, river, or bay where speeds need to be reduced for navigational purposes. The RSZ ends at the port entrance. Pilots can provide average ship speeds for a precautionary or reduced speed zone. Again, such speeds are estimates and more accurate results can be gained from using AIS.

Maneuvering time in mode is estimated based on the distance a ship travels from the port entrance to the PWD. Average maneuvering speeds vary from 3 to 8 knots depending on direction and ship type. Outbound speeds are usually greater than inbound speeds because the ship does not need to dock. Ships go from half speed to dead slow to stop during maneuvering. Time in mode varies depending on the location of, and the approach to, the destination terminal and turning requirements of the vessel. Best practice is to determine maneuvering times from conversations with pilots. Again, the maneuvering time will vary by ship size, currents, traffic, and other factors. Accuracy in determining maneuvering times can affect calculations of hotelling time as discussed in the next paragraph.

Hotelling can be calculated by subtracting time spent maneuvering into and out of a PWD from the departure time minus the arrival time into a port. If possible, anchorage time (time at anchorage within the port but not at a PWD) should be broken out from time at a PWD. Some MEPAs record shifts as well and this will allow for further refinements in maneuvering time. Other methods to determine hotelling include conversations with pilots. During hotelling, the main propulsion engines are off, and only the auxiliary engines are operating, unless the ship is cold ironing. Hotelling times also can be determined from pilot records of vessel arrival and departure times when other data are not available. Actual hotelling times should be calculated for each individual port because hotelling is generally a large portion of the emissions at a port. Hotelling times should be separated for those ships that use cold ironing at a port and those that do not. It is important to also look for outliers (ships with extremely long hotelling times) to eliminate those in the average since they may represent ships at a PWD but not with auxiliary engines on. Miscalculation of hotelling time can directly affect emission calculations. Hotelling emissions are generally a significant part of ship emissions near ports.

Emission Factors. The current set of marine engine emission factors come from ENTEC (*111*), which were derived from emissions data from 142 propulsion engines and 2 of the most recent research programs: Lloyd's Register Engineering Services in 1995 and IVL Swedish Environmental Research Institute in 2002. ENTEC estimated uncertainties at the 95% confidence interval, presented in Exhibit 3-38 for the ENTEC emission factors.

New work by IVL (*112*) shows major reductions in CO and HC emissions in comparisons with the previous ENTEC study. CO emissions for slow-speed diesel engines (SSDs) are about one-third of previous values, while the new study shows HC emissions at approximately half of prior values. In addition, PM emissions seem to vary significantly from ship to ship. Because of these observed differences, it is likely that the actual uncertainty (within the given confidence intervals) on PM, CO, and HC emissions are much higher than those specified in Exhibit 3-38.

Another assumption made in using emission factors is that they are constant down to about 20% load. Below that threshold, emission factors tend to increase as the load decreases. This trend results because diesel engines are less efficient at low loads and BSFC tends to increase. Thus, while mass emissions (grams per hour) decrease with low loads, the engine power tends to decrease more quickly, thereby increasing the emission factor (grams per engine power) as load decreases. Energy and Environmental Analysis Inc. (EEA) demonstrated this effect in a study prepared for EPA in 2000. (*113*) This study defined low-load adjustment factors that should be multiplied by the propulsion engine emission factors when the load factor is below 20%. These factors can be large at very low loads.

Exhibit 3-38. Estimated uncertainties at 95% confidence interval.

Pollutant	Estimated Uncertainty
NO_x	± 20%
SO_2	± 10%
CO_2	± 10%
HC	± 25%
PM	± 25%
BSFC	± 10%

Exhibit 3-39. Low-load adjustment factor derivation information.

Pollutant	Observations	R^2
NO_x	291	0.57
SO_2	239	0.78
CO_2	291	0.65
CO	291	0.52
HC	291	0.52
PM	31	0.95

Although these low-load adjustment factors are used in most of the recent port inventory analyses and are recommended in the EPA guidance (*114*), they were derived mostly on distillate fuels, and much of the data came from Coast Guard cutters and ferries. Exhibit 3-39 shows the observations and R^2 values from the curve fits for the various emissions. As can be seen from Exhibit 3-39, the curve fits have relatively low R^2 values.

These low correlation coefficients and the small sample of ship types imply highly uncertain low-load adjustment factors. It also should be noted that the PM adjustment factors are particularly suspect because they were only estimated based on smaller engines operating on distillate fuel. Although errors can occur in the determination of the low-load adjustment factor, the loads at which these adjustments are applied are very low, and the overall impact of these uncertainties is probably small.

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses is included in Exhibit 3-40.

Mid-Tier Methodology

Some mid-size ports, or those preparing emission inventories with mid-sized resources, could prepare a simplified, mid-tier version of the inventory. This differs from the detailed methodology by averaging vessel characteristics and operational data by ship type. Even better resolution can be gained if the average information also is broken down by ship size (DWT range). Load factors and emission factors for each ship type and DWT range can be calculated using a method similar to that in the detailed methodology. Annual vessel calls for each ship type and DWT range should be determined at the port. Each call should be divided into the various modes

Exhibit 3-40. Summary of strengths and weaknesses—comparison among methodologies.

Criteria	Detailed	Mid-Tier	Streamlined
Representation of physical processes	**Strength:** Dominant physical processes included.		
Sensitivity to input parameters	**Strength:** Method relies on detailed user inputs that may not be readily available, but should produce best results **Weakness:** General, overall uncertainty unknown	**Weakness:** Method relies on surrogates for missing inputs; results highly sensitive to quality of inputs	
Flexibility	**Weakness:** Requires detailed data collection	**Strength:** Customizable to data limitations	
Ability to incorporate effects of emission reduction strategies	**Strength:** Best information available; effects may be included in use of different EFs	**Strength:** Highly customizable	
Representation of future emissions	**Strength:** Projections available in the model and customizable to local information		
Consideration of alternative vehicle/fuel technologies	**Strength:** May be achieved in methodology by using appropriate EFs		**Weakness**: Does not consider alternative vehicle/fuel technologies
Data quality	**Strength:** Structured from best available information	**Weakness:** Structured from available information	
Spatial variability	**Strength:** Applicable to any location, but data requirements likely limit to smaller spatial scales	**Strength:** Applicable to any location; data flexibility allows multiple spatial scales	
Temporal variability	**Weakness:** Most likely limited to annual inventories	**Strength:** Designed for annual inventories, but scalable with appropriate information	
Review process	**Strength:** Documented in EPA Methodology Guidance		
Endorsements	**Strength**: EPA endorsed		

of operation and each mode also should be averaged for the vessel type and DWT range.

The mid-tier approach is detailed in *Commercial Marine Port Inventory Development.* (*115*) In this report, U.S. ACE entrances and clearances data are married with Lloyd's data. Emissions for the modeled port were then determined by mode, ship type, engine type, and DWT range from similar categories at the paired typical port for which a detailed inventory was done.

The same baseline errors and parameter uncertainties discussed in the detailed methodology exist in this method. Additional uncertainties arise from the selection of the like port and the implications of that choice on the various activity modes.

Like-Port Selection. This process involves determining a port for which a detailed inventory has been prepared (typical port) that is similar to the port to be modeled (i.e., like or modeled port). The more similar the port chosen as the typical port is to the modeled port, the more accurate the results. For large ports, the errors are probably small because most of the detailed inventories done to date were for large ports. However, if modeling a small port and using a large port as the typical port, the error margins could be large as different ship sizes service smaller ports and the port efficiency is usually lower. Additional issues in port selection are discussed in each of the time-in-mode calculations discussed below.

Cruise Mode. Cruise mode emissions are calculated by determining ratios of number of calls, average propulsion and auxiliary engine power, and vessel service speed between the modeled port and the typical port. Because this information is used, uncertainties in the cruise mode emissions for the modeled port are related to uncertainties in the detailed port analysis, the similarities between distances traveled at the two ports, and the vessel, engine, and fuel similarity at the two ports. The bias due to distance may be quantifiable and correctable.

RSZ Mode. In the transit, or RSZ, mode, the average distance and average speed is specified for both the typical and modeled port. In addition to ratios of number of calls and propulsion and auxiliary engine power, ratios of propulsion load factors and TIM are also calculated and used in determining emissions. This should provide results similar in accuracy to the detailed port analysis as long as the average speeds are fairly representative of the ships that call on both ports. If there is a disparity of speeds among the ships at the two ports, errors can result in the emission calculation.

Maneuvering Mode. For the maneuvering mode, only ratios of number of calls and propulsion and auxiliary engine power are used. It is assumed that the modeled port and the typical port have the same maneuvering time and load factors. If the two ports are different in distances from the port entrance to the PWD or in the number of shifts that occur, errors in maneuvering emissions will result. However, since maneuvering emissions are small compared to the other activity modes, the contribution to overall error will probably be small.

Hotelling Mode. For the hotelling mode, only ratios of number of calls and auxiliary engine power are used. It is assumed that the average hotelling time for each ship type is the same between the typical port and the modeled port. This can lead to errors if the efficiency at the typical port is different than at the modeled port. Since hotelling emissions are significant, the resulting error could be significant as well.

Summary of Strengths and Weaknesses. The analysis of strengths and weaknesses is included in Exhibit 3-40.

Streamlined Methodology

A streamlined methodology can be applied if those preparing port inventories do not have sufficient resources to follow the mid-tier approach described. In this approach, those preparing port inventories should use an existing emission inventory from another similar port, scaling the emissions up or down based on the ratio of vessel operation data between the two ports. Two EPA activity guidance documents provide details on estimating emission inventories from other ports. (*116–117*) These documents use U.S. ACE data to scale emissions based on the ratio of ship trips from a like port that has an existing inventory compared to the port in question. No adjustments are made, however, for average propulsion and auxiliary power or vessel speed. This can result in significant error if the typical port selected is different from the modeled port as discussed in the mid-tier methodology subsection.

Summary of Strengths and Weaknesses. Exhibit 3-40 includes the analysis of strengths and weaknesses for the detailed, mid-tier, and streamlined methodologies.

3.5.3 Evaluation of Parameters

Exhibit 3-41 summarizes all parameters relevant for calculating emissions from OGVs calling at ports. Each of these has been detailed under the discussion of the appropriate model or method in Section 3.5.2. Also as discussed above, no quantitative assessments are provided, because the range of parameters is essentially unknown.

Exhibit 3-41. Parameters.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Calls	All	All	✓	✓	×
Engine Power	Detailed and mid-tier	All	✓	✓	×
Load Factor	Detailed and mid-tier	All	✓	✓	×
Activity	Detailed	All	✓	✓	×
Emission Factors	Detailed	All	✓	✓	×
Port Selection	Mid-tier and streamlined	All	✓	✓	×
Fuel Type	Secondary; used to determine emission factors	All	×	×	×
Growth Factor	Optional and secondary; needed for future year projections	All	×	×	×
Engine Age Distribution	Optional and secondary; needed to determine average emission factors	All	×	×	×

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

Exhibit 3-42. Pedigree matrix—OGV parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Calls	4	1-2	1-2	1-2	1	1	Varies	3
Engine Power	4	2	1	1	1	Varies	2	2
Load Factor	4	3-4	3	2	1	Varies	3	4
Activity	4	2-4	3	3	1	Varies	1	3
Emission Factors	4	2-3	1-2	4-5	3	Varies	3	4
Port Selection	4	4	3	N/A	N/A	Varies	N/A	N/A

Pedigree Matrix. Exhibit 3-42 shows the pedigree matrix for the six primary parameters for determining emissions from OGVs. Criteria to assign scores in the pedigree matrix are included in Appendix A.

Calls. Emissions are linearly related to the number of calls. Call data should be determined for each ship type and DWT range. Thus, while accurate assessment of the number of ship calls is critical, in many cases there can be errors depending upon the source of the data and the geographic boundaries of the analysis.

Engine Power. In the detailed and mid-tier approaches, propulsion power is determined directly from Lloyd's data. Conversely, auxiliary power is estimated from surveys that produce ratios of auxiliary power to propulsion power by ship type. More accurate determination of auxiliary power would improve emission calculations.

Load Factor. In the detailed approach, propulsion load factors are calculated using the Propeller Law. There are inherent errors in applying that law to all ships and speed ranges. Currently the Propeller Law is universally accepted as the method to use to determine propulsion load factors. It is doubtful that significant errors would result from these calculations.

Auxiliary load factors, however, have been determined from surveys and tend to change with each new Starcrest inventory. More precise determination of auxiliary engine load factors, particularly during hotelling, would provide more accurate results.

Emission Factors. Emission factors for ships were determined for a small subset of engines. Although most ships use similar engines, this set does not represent a large enough sample to be accurate. This is particularly true of PM emissions. Measurement techniques of PM emissions vary and there is sensitivity to sampling methodology (e.g., tunnel length). PM emission factors need a more robust data set to determine them more accurately. In addition, current thinking is to estimate $PM_{2.5}$ emission factors as 92% of PM_{10} emission factors for OGVs. Various studies have estimated $PM_{2.5}$ emissions from 80% to 100% of PM_{10} emissions. Therefore, a more accurate determination of $PM_{2.5}$ emission factors is needed.

Low-load adjustment factors also need reviewing. The current methodology is based upon limited data and rough curve fits. Improvement of the low-load adjustment factors can result in more accurate emission calculations.

Furthermore, the current emission factors were determined for engines built before year 2000 when IMO set NO_x emission standards on OGV engines. More testing is needed to determine the emission factors for engines built after 2000 as well as for future IMO Tier II and Tier III NO_x emission standards.

Port Selection. In the mid-tier and streamlined methodologies, selecting a typical port that is like the port to be modeled is of utmost importance. EPA has provided some guidance on how to select the typical port and a list (*118*) based upon detailed inventories prepared at the time. As more ports prepare detailed inventories, this list should be expanded.

3.6 Waterborne/Harbor Craft

A wide range of commercial harbor craft (H/C) is in operation at or near ports, including assist tugboats, towboats/pushboats/tugboats, ferries and excursion vessels, crew boats, work boats, government vessels, dredges and dredging support vessels, commercial fishing vessels, and recreational vessels. These vessels serve many purposes other than just direct goods movement. From a freight perspective, it is worthwhile to focus only on those commercial H/C (SCC 2280002000) directly involved in goods movement, such as tug and towboat operations that move freight barges. Emissions and parameters relative to other commercial H/C are not considered here.

There are no common models with the capability to estimate emissions from these vessels; neither CARB's NONROAD nor EPA's OFFROAD model considers commercial H/C. Instead, estimates of emissions for tug and towboats and other commercial H/C may be made through other methodologies, such as the best practice or streamlined approaches discussed in EPA's *Current Methodologies* document. (*9*) These general approaches rely on various sources for the necessary parameters and generally draw on the methodologies of the NONROAD or OFFROAD models, or other published studies. They assemble parameters including a survey or estimate of the vessel and/or engine counts and engine activity and merge this information with emission and load factor data from the technical literature. For example, H/C emission inventories are commonly calculated using an equipment power methodology, as shown in Equation 8.

$$\mathrm{EMIS}_{\mathrm{Pollutant}} = \sum_{\mathrm{Main+Auxiliary}} \mathrm{EF}_{\mathrm{Pollutant}}(\mathrm{Tier}) \cdot \mathrm{LF} \cdot \mathrm{A} \cdot \mathrm{HP} \cdot \mathrm{CF} \qquad \text{(Equation 8)}$$

Where the sum is over the population of all main and auxiliary engines active in the fleet and the input parameters are as follow:

EF = the emission factor for a given pollutant species and engine,
HP = the engine horsepower,
LF = the load factor,
A = the annual activity,
CF = the appropriate emission control factor.

Any deterioration, low-load, transient, or other adjustment effects (if able to be characterized) are considered in the age- or tier-distributed EF. Both main and auxiliary engines are included. Differences in the best practices and streamlined methodologies are chiefly dependent on the amount of data directly collected rather than derived through surrogates. For the purposes of uncertainty assessment, they will be treated as the same methodology.

Two specific H/C methodologies are EPA's national scale Regulatory Impact Analysis (RIA) done in support of the 2008 rulemaking (*119*) and CARB's analysis of statewide H/C emissions analysis in support of its rulemaking. (*120*) Although constrained by the same limitations discussed previously, these analyses are both sufficiently developed and tailored to be discussed separately. A third, general methodology is discussed for local scale analysis based on available guidance and previous project analyses. The following sections discuss these national, regional, and project-scale methodologies.

Uncertainty in the resulting H/C emissions from these methodologies can then be attributed to either process uncertainty (that is, the degree to which Equation 8, or similar formulations, represent the actual processes causing emissions) or parameter uncertainty (that is, the uncertainty in the individual elements of Equation 8). Evaluation of process uncertainty is presented in the following three sections by domain; discussion of parameter uncertainty also appears for each methodology and is then summarized in Section 3.7.5.

In both cases, any known biases should be corrected during the analysis. The effects of quantifiable residual uncertainty in input parameters on total calculated uncertainty may be made using standard error propagation methods, discussed in Section 4.3.4. If no covariance is assumed for the parameters in Equation 8 the net error in total emissions would be given by Equation 9.

$$\sigma^2\mathrm{Emis} = \sum_{\mathrm{Main+Auxiliary}} \left[\begin{array}{l} (\mathrm{HP} \cdot \mathrm{LF} \cdot \mathrm{A})^2\, \sigma^2\mathrm{EF} \\ +(\mathrm{EF} \cdot \mathrm{LF} \cdot \mathrm{A})^2\, \sigma^2\mathrm{HP} \\ +(\mathrm{EF} \cdot \mathrm{HP} \cdot \mathrm{A})^2\, \sigma^2\mathrm{LF} \\ +(\mathrm{EF} \cdot \mathrm{HP} \cdot \mathrm{LF})^2\, \sigma^2\mathrm{A} \end{array} \right] \qquad \text{(Equation 9)}$$

Where

σ^2 indicates the variance.

Note, however, that Equation 9 assumes the number of engines is sufficiently well known to complete the sum. More likely, the estimates and uncertainties are made by calculations discussed in Section 3.6.2, which would allow inclusion of uncertainty in number as well.

3.6.1 Summary of Methods and Models

As stated previously, the discussion here will focus on elements of potential methods to estimate H/C emissions generally, since few studies focus only on H/C directly involved in goods movement (i.e., ocean and line-haul tug and tow vessels). Since no models may be used to calculate H/C emissions directly, Exhibit 3-43 lists only methods. Two specific and one general method are listed, although the structure of each is very similar. The specific methods were developed by

Exhibit 3-43. Harbor craft inventory methods.

Method/Model	Type	Geographic Scale	Pollutants	Freight/Passenger
EPA RIA Methodology	Method	National	NOx, HC, PM, toxics	Both
ARB H/C Methodology	Method	Regional	NOx, PM, ROG, CO	Both
Local H/C Method	Method	Local/Project	All	Both

regulatory agencies to detail H/C emissions within a set geographic range. The general method, which is labeled here as "the Local H/C Method," is an aggregate of several studies that have been conducted at the project level. Neither of the specific methodologies, and most of the studies that form the basis of the general method, were applied solely to freight-moving H/C, although all could be modified to exclude other H/C types.

3.6.2 Evaluation of National Methods and Models

The most current, national scale inventory of H/C emissions is related to EPA's 2008 locomotive and marine engine rulemaking. (*119*) The Regulatory Impact Analysis (RIA) developed includes a baseline national emission inventory for Category 1 and 2 commercial marine vessels, including freight-related, commercial H/C. (*89*)

EPA RIA Methodology

In this case, separate inventories were developed for commercial marine diesel engines in the following three principal categories:

- Category 1 propulsion engines,
- Category 1 auxiliary engines, and
- Category 2 propulsion engines.

Propulsion and auxiliary engines less than 37 kW (50 hp) were also considered. Category 2 auxiliary engines were not considered, however, as these are only used on Category 3 vessels. These inventories include all commercial harbor craft, however, not only those directly involved in goods movement. Exhibit 3-44 shows the current definitions of marine compression-ignition engine categories. Exhibit 3-45 shows the strengths and weaknesses of the EPA RIA Methodology.

Calculation Method. Commercial marine diesel engine inventories for HC, CO, NO_x, and PM were estimated using spreadsheet calculations using the formula shown in Equation 10.

$$E = N \times P \times L \times A \times EF \qquad \text{(Equation 10)}$$

Where

E is the 50-state emission inventory (tons per year) for commercial marine vessels,
N is engine population (units),
P is the average rated power (kW),
L is the load factor,
A is the engine activity (operating hours/year), and
EF is the emission factor (gram/kW-hr).

Average rated power, load factor, and activity parameters are assumed constant across all simulation years but populations and emission factors were considered to vary by year and age. Populations and the corresponding age distribution

Exhibit 3-44. EPA marine compression ignition engine categories.

Category	Specification	Use	Approximate Power Ratings
1	Gross engine power ≥ 37 kW* displacement < 5 liters per cylinder	Small harbor craft and recreational propulsion	< 1,000 kW
2	Displacement ≥ 5 and < 30 liters per cylinder	OGV auxiliary engines, harbor craft, and smaller OGV propulsion	1,000–3,000 kW
3	Displacement ≥ 30 liters per cylinder	OGV propulsion	> 3,000 kW

* EPA treats all engines with gross power below 37 kW (50 hp) separately.

Exhibit 3-45. Summary of strengths and weaknesses—EPA RIA methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Overall average emissions processes included from all Category 1 and 2 H/C	Variety of methods used to account for different input data
Sensitivity to input parameters	Method relies on documented inputs and discusses necessary choices	Some inputs show significant differences from other studies; resulting overall uncertainty uncharacterized
Flexibility	Tailored methodology	Not directly applicable to H/C subcategories or smaller spatial domains
Ability to incorporate effects of emission reduction strategies	Designed to model effects of future regulations	
Representation of future emissions	Designed to model effects of future regulations	
Consideration of alternative vehicle/fuel technologies		
Data quality	Information included and documented from testing and other authorities.	Unknown uncertainty or bias
Spatial variability		No spatial analysis included
Temporal variability		Produces only annual inventories
Review process		Unclear from documentation
Endorsements	EPA	

are calculated for the baseline year (generally 2002) and then projected. Emission factors vary with age to account for the effects of regulations and deterioration. PM emission factors also consider the in-use fuel sulfur level.

Generally, the calculation methods are similar to those for CHE, including use of the NONROAD scrappage function, the linear deterioration factor, and sulfur PM adjustments. Inventory results are calculated in bins of power (in kW), engine displacement (L/cylinder), and power density (kW/L) to accommodate the form of the regulations, which differ from the standard break points used in the NONROAD model.

Input Parameters. The population parameters were derived by displacement category, power density, and total power from historical sales estimates (provided by PSR [the Power Systems Research Database]), combined with scrappage, and then disaggregated into power and power density categories using the 2002 population and engine data. The average power values, load, and activity were population-weighted into appropriate bins to compute totals (see discussion under CHE in Section 3.7).

Category 1 main engine load factor and activity estimates were determined from industry analysis and prior rulemaking as 0.45 and 943 h/year (engines less than 750 hp) and 0.79 and 4,503 h/year (greater than 750 hp). A median life of 13 years is used for all Category 1 main engines from industry estimates, with an annual growth rate of 1.009 (for domestic shipping from EIA). Baseline emission factors were taken from the 1999 Marine Diesel rulemaking, based on emissions data for uncontrolled engines. Tier I emission factors are estimated for NO_x using 2006 certification data by displacement category; other pollutant factors equal the baseline values. Tier II PM, NO_x, and HC emission factors are derived from 2006 certification data. Certification data relies on sales-weighted values from the E3 duty cycle.

A parallel method was used for Category 1 auxiliary engines, but certification data from the D2 auxiliary cycle were used to derive load factors. Resulting load factor and activity estimates (from PSR) were 0.56 and 724 h/year for engines less than 750 hp and 0.65 and 2,500 h/year from the 1999 rulemaking for engines greater than 750 hp. A median life of 17 years is used for all Category 1 auxiliary engines.

Category 2 main engine emissions also were calculated with a similar methodology, although here separate estimates were made for underway and idling activity. In this parameterization, an activity-based approach is substituted with a TIM approach. Accordingly, the activity parameter (in hours per year) is substituted with the formula shown in Equation 11.

$$\underbrace{(\textit{Likely Annual Transit Days}) \times (24\ \textit{hours/day})}_{\text{for underway emissions}}$$

$$\underbrace{(\textit{Likely Annual Idling Days}) \times (24\ \textit{hours/day})}_{\text{for idling emissions}} \quad \text{(Equation 11)}$$

In both cases, a "likely" load factor is used. Minimum, maximum, likely load factors, and annual transit days are provided, as well as likely idle days. Activity estimates are discussed with a range of methods and resulting estimates, showing the uncertainty inherent in this parameter via this analysis. In fact, one method relies on a Monte Carlo analysis, thus directly incorporating uncertainty into the process. Additionally, for ferries (although not considered here as directly associated with goods movement), emissions are calculated using a total fuel consumption methodology. The median life for all Category 2 main engines is taken as 23 years. (*121*) Emission factors are taken from the 1999 commercial marine rulemaking (*122*) except for Tier I NOx, which was updated based on 2006 certification data.

Uncertainty. Total uncertainty in this method is due to both process and parameter uncertainty. As discussed for CHE (Section 3.7), three potentially significant sources of process uncertainty are the

1. Appropriateness and representativeness of the characterizations,
2. Groupings used to categorize H/C, and
3. Potential for bias in inputs.

The process used here is generally appropriate and tailored to its purposes. No spatial disaggregation is provided because this is a national-scale inventory, thus no uncertainty is associated with disaggregation or translation of values between regions, which is typical of a top-down inventory. Load and activity factors are based on industry characterization, binned, and averaged using power and population as weights since equivalent NONROAD factors are not applicable. Thus, uncertainty in the final emissions estimates is related to the number of engines in each bin and the estimates of other parameters by bin. The process used here is generally believed to rely on the best information available, minimizing grouping uncertainty and representativeness of the method.

However, some parameters differ significantly from previously published values, particularly load factors. This could either represent or correct significant bias. Reference is given to the duty cycles from which the load factors are derived, however without commonly accepted average harbor craft duty cycles, assessment of bias is impossible. The same is true for emissions and activity factors, which differ from those of other studies. (*123*)

Another source of uncertainty in binning is the difference in Category 1 and 2 main engines, especially for tug and tow boats. In the rulemaking, EPA cites two different methods to separate values based on power, hull displacement, and other categories. The differences in these two methods implied that around 6% of tug vessels could not be clearly categorized in this method. Although this does not affect the total number of vessels directly, it does affect the total emissions as emission factors, load factors, activity, and other parameters are dictated by the type of main engines equipped on the vessels. Also, the subdivision of values based on power, engine displacement, power density, and age is complex, although no known bias results from this method.

Finally, it must be noted that the methodology here generally does not distinguish between freight and non-freight movement. Thus, translation of the methods (and, particularly, parameters here) to freight-only calculations is likely to result in bias, due to the different engines used.

Summary of Strengths and Weaknesses. Exhibit 3-45 includes the analysis of strengths and weaknesses for the EPA RIA methodology.

3.6.3 Evaluation of Regional Methods and Models

As for CHE, the only regional analysis of emissions from commercial H/C has been prepared by CARB for its November 2007 rulemaking. (*124*) This rule has special provisions that apply to tug, tow, and ferry vessels.

CARB Harbor Craft Methodology. CARB developed a methodology to estimate emissions from all commercial H/C in California to support analysis of regulations to reduce commercial marine engine emissions. (*125*) Other goals of the inventory development included updating estimates to represent the current H/C fleet, showing effects of the various regulatory programs, and allowing allocation of the statewide emissions to local air pollution control districts (APCDs) and air basins. Particularly in this last goal, the CARB H/C methodology differs from the EPA RIA methodology.

The methodology is based on activity. It uses results from CARB's *2004 Commercial Harbor Craft Survey* (*126*) to estimate average emissions per engine per year for nine types of vessels: commercial fishing vessels, charter fishing vessels, crew and supply boats, ferry/excursion vessels, pilot vessels, tow boats, tug boats, work boats, and "others." These regional emissions are then aggregated to statewide emissions by multiplying number of engines in each engine category and in each region by average emissions per engine. Among the findings are that tugs and tows (that is, vessels most directly involved in freight movement) account for 4% of the statewide vessel inventory, 7% of the statewide engine inventory, but about 25% of the statewide emissions inventory (i.e., between 21% and 25%, depending on the pollutant).

Population. Base year populations are drawn principally from the CARB Harbor Craft Survey (*126*) and aggregated with data from the U.S. Coast Guard Vessel Documentation Program, the California Department of Fish and Game registration data, and information from the Port of Los Angeles emissions inventory. Then, spatial distributions to the air district and county level were calculated. Future year populations are based on base year populations aggregated with fleet growth rates from local air districts and scrappage rates based on the OFFROAD model.

The CARB survey on which estimates are based collected information for about 900 vessels (i.e., about 1,900 engines), or about 20% of the statewide H/C population. Although the emission methodology assumes the results of the survey are representative of the overall California commercial H/C fleet and scales results up to statewide values, uncertainty is introduced in the parameters resulting from this relatively small sample size. Further, although the survey was distributed to approximately 5,000 potential owners and operators, only 704 surveys were returned. (*127*) Uncertainty and potential bias exist in how well these limited responses represent the average H/C fleet operating in California.

Activity and Engine Parameters. Vessel activity parameters also were derived from the CARB survey, which included information on vessel use, age, annual fuel consumption, number of engines per vessel, engine make and model, age, horsepower, annual hours of operation, and other information. These data were aggregated into operating profiles by engine type by region. Number of engines per vessel by vessel type was also determined from the survey, as was engine lifetime. In this study, total life was defined as the age when 90% of engines retire and useful life (UL) was defined as half of total life. These definitions both differ from the standard NONROAD formula used in many studies, although the shape of the scrappage curve is very similar to that of the NONROAD model. The uncertainty in this method is due to the definitions of the terms as employed.

Annual activity was derived from the CARB survey. It is unknown if these values are biased, such as toward the activity at the state's largest ports. However, the same uncertainty exists here as with other parameters derived from the survey.

Auxiliary engine load factors were taken as 0.43, which is attributed to the NONROAD model, for all commercial H/C except tug boats, where a factor of 0.31 was used, based on the Port of Los Angeles' study. (*83*) These values differ from the EPA RIA method values, and it is unclear whether the attribution of the 0.43 factor is appropriate, since NONROAD does not include commercial marine vessels. Thus, some uncertainty is associated with use of these parameter values.

Main engine load factors are derived from results of CARB survey responses to fuel consumption, engine power, and annual operating hours as shown in Equation 12.

$$\mathrm{LF} = \mathrm{BSFC} \times \mathrm{HP} \times \mathrm{Hr}/\mathrm{TF} \qquad \text{(Equation 12)}$$

Where

LF is the vessel type specific propulsion engine load factor,

BSFC is brake-specific fuel consumption (here taken as 0.058 gal/hp-hr from manufacturers' marine engine data),

HP is the rated engine power,

Hr is the number of annual operating hours of the engine, and

TF is total, annual, per engine fuel consumption.

Uncertainty in this approach comes from both parameters and the process. There is uncertainty in the method since it relies on survey results, which may be biased or inappropriately aggregated. There also seems to be no accounting for potential deterioration. Parameter uncertainty comes from the derivation of parameters from the survey, but particularly from the reliance on BSFC. NONROAD estimates BSFC as 0.367 lb/bhp-hr for engines larger than 100 hp, based on measured fuel consumption values during engine certification (which translates to 0.052 gal/hp-hr at 7.09 lb/gal for diesel fuel). Although only a 10% discrepancy exists between the two, there is uncertainty as to which, if either, is more appropriate, on the whole, to commercial marine vessels for goods movement. Ultimately, the load factors derived here are smaller than those from the EPA RIA method, although more in line with other analyses.

In all cases, the uncertainties here are unquantifiable.

Emission Factors. Emission factors were taken from the OFFROAD model, except for the following:

- 1996–1999 model year engines use baseline/Tier 0 (1996) emission factors;
- 2000 and later model-year engines use the smaller of EPA emission standards for marine engines or the NO_x limits of the IMO MARPOL Annex VI; and
- OFFROAD model emission factors were adjusted to reflect an E3 test cycle for main engines and D2 test cycle for auxiliary engines.

Uncertainty in this approach is due primarily to the choices made in the method, but also to underlying uncertainty in the emission factors of the OFFROAD model and baseline EPA emission factors, as well as in duty cycle characterizations. In particular, the lack of differentiation between 2-stroke and 4-stroke engine emissions may be a significant source of uncertainty in the emission factors applied.

Fuel correction and engine deterioration factors employed are derived from the OFFROAD model. Section 3.7.3 discusses the uncertainty in this model.

Calculation Methodology. Commercial H/C emissions per engine are estimated as shown in Equation 13.

$$E = EF_0 \cdot F \cdot \left(1 + D \cdot {}^{A}\!/\!_{UL}\right) HP \cdot LF \cdot Hr \qquad \text{(Equation 13)}$$

Where

E is the amount of emissions inventory,

EF_0 is the model year, horsepower, and engine type (main or auxiliary) specific zero-hour emission factor,

F is the fuel correction factor,
D is the (power and pollutant-specific) deterioration factor,
A is the engine age,
UL is the (vessel type and engine-use specific) engine useful life,
HP is the engine-rated horsepower,
LF is the load factor, and
Hr is the annual engine activity (operating hours).

Each of the parameters in Equation 13 has already been discussed in Section 3.6.3. CARB calculated statewide and regional emissions using this equation, the aforementioned parameters, a database model to estimate vessel type specific emission rates, and scaled up the emissions to statewide populations.

Uncertainty in this methodology is due to process and parameter uncertainty. Uncertainty in each of the parameters has already been discussed in Section 3.6.3. Uncertainty in the process is due to any discrepancies between the analysis presented here and the physical processes estimated. Although the process used here is believed to rely on the best information available and capture the dominant processes contributing to commercial H/C emissions, three potentially significant sources of process uncertainty are as follow:

1. Appropriateness and representativeness of the characterizations, including those of the OFFROAD model,
2. Groupings used to categorize H/C, and
3. Potential for bias in the raw or extrapolated survey results.

Until a comprehensive nonroad mobile emissions model is produced and validated, reliance on models such as NONROAD and OFFROAD will be required to estimate emissions parameters. Thus, any process uncertainty in the models and on assumptions involving use of these models—which are not designed to simulate commercial marine emissions—is propagated to total emissions calculation. Process uncertainty from groupings is due to the employed methodology, which relies on use of "vessel type specific emission rates . . . scaled up to the statewide population" (*128*) in the database construction. Because parameters are specific to engine, fuel, age, vessel type and/or power, process uncertainty will propagate due to the grouping and application of appropriately weighted central values in each bin. These uncertainties are due to choice and assignment of values to equipment groupings. Additional process uncertainty—and potential bias—is due to the extrapolation of small sample set values to statewide H/C populations. Quantification of these uncertainties, however, generally is infeasible.

Summary of Strengths and Weaknesses. The strengths and weaknesses of the CARB H/C methodology are shown in Exhibit 3-46.

3.6.4 Evaluation of Local/Project Methods and Models

Several studies of port-related activity and emissions have been conducted that capture commercial H/C emissions at the local or project level. These are listed in Exhibit 3-47.

Exhibit 3-46. Summary of strengths and weaknesses—CARB H/C methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Overall average physical processes included	
Sensitivity to input parameters	Method relies on best available inputs	Method relies on OFFROAD model; uncharacterized overall uncertainty
Flexibility	Tailored methodology	
Ability to incorporate effects of emission reduction strategies		Not included in base methodology, but could be applied if information provided
Representation of future emissions	Method projects populations and associated factors	
Consideration of alternative vehicle/fuel technologies	Fuel effects included	No apparent treatment for alternative fuels or technologies
Data quality	Information included from survey of fleet	Unknown uncertainties from extrapolation scheme
Spatial variability	Emissions allocated to county and air basin, but not more finely	Underlying data applicable only to CA
Temporal variability		Only produces annual inventories
Review process	Available for public review as part of rulemaking	
Endorsements	ARB	

Exhibit 3-47. Recently conducted port inventories containing H/C.

Port		Year Published	Data Year	Pollutants	Contractor*
Selected Alaska Ports (*92*)		2006	2002	SO_2, NOx, PM_{10}, $PM_{2.5}$, CO, NH_3, VOC	Pechan
Beaumont/Port Arthur (*93*)		2004	2000	NOx, CO, HC, PM_{10}, SO_2	Starcrest
Charleston (*94*)		2008	2005	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2	Moffatt & Nichol
Corpus Christi (*95*)		2003	1999	NOx, VOC, CO	ACES
Houston/Galveston (*129*)		2000	1997	NOx, VOC, CO, PM_{10}	Starcrest
Houston (*96*)		2009	2007	NOx, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2, CO_2	Starcrest
Great Lakes (Ports of Cleveland, OH, and Duluth, MN) (*97*)	(Tugs only)	2006	2004	HC, NOx, CO, PM_{10}, $PM_{2.5}$, SO_2	Lake Carriers Assoc. (LCA)
Lake Michigan Ports (*98*)		2007	2005	NOx, PM_{10}, $PM_{2.5}$, HC, CO, SO_x	Environ
Los Angeles (*110*)		2005	2001	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Los Angeles (*83*)		2007	2005	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Los Angeles (*99*)		2008	2007	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
Long Beach (*130*)		2007	2005	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Long Beach (100)		2009	2007	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
New York/New Jersey (*131*)		2003	2000	NOx, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2	Starcrest
New York/New Jersey (*101*)	(Tugs only)	2008	2006	NOx, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2, CO_2, N_2O, CH_4	Starcrest
Oakland (*102*)		2008	2005	NOx, ROG, CO, PM, SO_x	Environ
Portland (*103*)		2005	2004	NOx, HC, CO, SO_x, PM_{10}, $PM_{2.5}$, CO_2, 9 Air Toxics	Bridgewater Consulting
Puget Sound** (*104*)		2007	2005	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
San Diego (*105*)		2008	2006	NOx, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest

Notes:

* Starcrest = Starcrest Consulting Group LLC, ACES = Air Consulting and Engineering Solutions; Environ = Environ International Corp.

** Includes the Ports of Anacortes, Everett, Olympia, Port Angeles, Seattle, and Tacoma.

mating emissions from limited information. In that sense, they are typically some variation of the streamlined methodology discussed in EPA's best practices document. (*9*) However, the level of detailed information on H/C available to the studies varies. The similarity of these studies is driven both by the trend to similar methodologies and by the fact that the majority of studies are made by the same contractor. They are also very similar to the EPA RIA methodology or the CARB H/C methodology, albeit with a more limited spatial scope, where variation is made for the amount of information avail-

is similar to that of NONROAD or OFFROAD models.

Two of the inventories presented in Exhibit 3-47 discuss Great Lakes activity (those by LCA and ENVIRON) and only one discusses inland river activity (Bridgewater). However, the nation's inland waterway system is a principal area of operations for line-haul tug and tow vessels, as well as an area of interest in terms of marine emissions. One study that estimates emissions at various ports along the inland river system is by ARCADIS. (*117*) That study collected information on several principal ports and performed a detailed emission inventory, then used a principal port-like port analysis to scale activity and emissions to other harbor areas.

The general method for producing a local/project scale commercial H/C emissions inventory—specifically targeted to goods movement—and its associated uncertainties are discussed in the remainder of this section. Here we focus only on vessels directly moving goods, as follows:

- Line-haul and short-haul tug and tow boats that make calls along the inland waterway systems, transporting barges and containerized goods, and
- Ocean-service tug and tow boats.

Specifics on the studies listed in Exhibit 3-47 are provided in the individual inventories cited.

Local Harbor Craft Methodology

Input Parameters. To calculate emissions from commercial H/C involved in goods movement, the following information needs to be collected from vessel owners and operators for the relevant types of harbor craft operating in the port area:

- Hours of operation (annual and average daily, plus schedules if relevant and available);
- Percentage of time-in-operational modes (e.g., idling, half power, full power);
- Vessel characteristics;
- Number, type, age, and rated power of main engine(s);
- Number, type, age, and rated power of auxiliary engine(s);
- Other operational parameters such as fuel consumption rates and fuel type;
- Qualitative information regarding how the vessels are used in service, including operating domain; and
- Any information on emissions-modifying methods applied to the vessels, such as exhaust after-treatment equipment installed or internal engine modifications.

Ideally, average values of annual operating hours, number of main and auxiliary engines, engine power, and engine age should be determined from the information collected from the vessels operating at the specific port. This approach minimizes parameter uncertainties because the calculations are made directly on the fleet in question. Process uncertainties remain on binning and methodology, and should be quantified where possible.

Inland river activity data often are taken from the ARCADIS study. (*117*) This provides detailed activity information including TIM and number of up- and down-river calls and passes for the 1995 base year segregated by HP bin for two principal inland river and two Great Lake ports. Although somewhat dated, the level of information contained is of high quality. Data may be updated to more current years by scaling, such as based on the calls or tonnage from other databases, although uncertainties would be associated with this scaling.

In many other cases, too, the required level of information is not available to determine governing parameters and, instead, must be developed from surrogate data or translated from similar studies. It is likely that this approach will have inferior data quality and greater overall parameter uncertainty, even if the process is identical.

For example, vessel counts by vessel type may be drawn from the USCG's Merchant Vessels of the United States database as done in CARB's harbor craft inventory. (*132*) However, this database includes no foreign vessels, may not be available for certain periods, suffers from much missing data, and has poor quality data for location of vessel activity. As discussed above, CARB was able to mitigate some of this uncertainty by focusing on larger domains and supplementing with locally specific information, however, this may not be available in all cases. Similar caveats apply to other databases, such as the U.S. Army Corps of Engineers' comprehensive and current inventory for tug and towboats in the United States. (*133*) Although this database contains details on approximately 5,000 tow boats, the same caveats on operating domain may apply. In any case, it is likely that a vessel inventory may need to be estimated from a variety of databases for local inventories, which will exacerbate uncertainty in the analysis. Uncertainty in the analysis can also arise from external databases if translation between vessel types is necessary. This process uncertainty can directly affect vessel population counts. Additional uncertainty may be caused by the need to distinguish Category 1 versus Category 2 engines for tug, tow, and push boats, as well as the lack of needed data in most databases.

In the case of insufficiently detailed engine age distributions from direct surveys, a typical approach is to employ continuous age distribution profiles such as those commonly used in the NONROAD model for both main and auxiliary engines. (*134*) In many cases, reliance on median life, growth, and scrappage will be taken from other studies and age distributions will be calculated for each vessel and engine type from the baseline year. Annual, linear growth in the population of harbor craft is commonly assumed, which may be taken from surrogate data, such as regional economic growth. Otherwise, default values for annual population growth, such as those used in the 2008 EPA RIA rulemaking, are employed. Process uncertainty is associated with the assumed shape of the age distribution. Parameter uncertainty in median age, growth, and other values assumed or translated from other studies is likely to be significantly larger than similar, directly observed parameters, although quantifying this uncertainty is infeasible. Particularly, estimates derived following NONROAD guidance are known to produce unrealistic values for engine lifetime in marine applications. This can be mitigated by forcing consistency between average model year predicted by the distribution and that drawn from surveys or translated from other studies.

To minimize uncertainty, load, activity, emission, fuel correction, and control factors also should be collected directly from the fleet being studied. This is not common. Rather, values are commonly translated from other studies, such as the 2008 EPA rulemaking (*119*), the ports of Los Angeles (*83*, *99*, *110*) or Puget Sound (*104*) studies, the EPA best practices (*9*) document, the ARCADIS (*116–117*) studies, or EPA- or CARB-approved technology lists. As previously stated, parameter uncertainties are directly associated with these original values. Process uncertainties generally are introduced in the use of these parameters and in the translation of these parameters for a particular study. Quantification of these uncertainties is generally not possible.

Emissions Calculation Methodology. Calculation of commercial H/C emissions in a local/project-scale inventory typically is done based on the parameters discussed in Section 3.6.3. As shown in Equation 14, emission estimates are generated as the product of the following:

Number of harbor craft vessels of a given type operating in the area ($N_{H/C}$),
Average number of main and auxiliary engines per vessel ($N_{Eng\ H/C\ main}$ and $N_{Eng\ H/C\ aux}$),
Load factor ($LF_{H/C\ main}$ and $LF_{H/C\ aux}$),
Average annual activity ($Activity_{H/C\ main}$ and $Activity_{H/C\ aux}$),
Average rated horsepower ($HP_{H/C\ main}$ and $HP_{H/C\ aux}$), and
Appropriate (pollutant, age, power, engine type, and, potentially, power density) emission factor ($EF_{pollutant\text{-}H/C\text{-}main}$ and $EF_{pollutant\text{-}H/C\text{-}aux}$).

$$Emissions_{pollutant,\,H/C} = N_{H/C} \cdot \left\{ \begin{array}{l} \left(EF_{Pollutant,\,Main} \cdot N_{Eng,\,Main} \cdot LF_{Main} \cdot Activity_{Main} \cdot HP_{Main}\right) \\ + \left(EF_{Pollutant,\,Aux} \cdot N_{Eng,\,Aux} \cdot LF_{Aux} \cdot Activity_{Aux} \cdot HP_{Aux}\right) \end{array} \right\} \qquad \text{(Equation 14)}$$

In cases based on the ARCADIS methodology for inland river operations, emissions are calculated from a time-in-mode-based activity perspective instead of annual activity and average load factors. Other parameters are as shown in the list of variables for Equation 14.

Transient adjustment and deterioration factors also may be considered and included in the emission factors parameterization for each engine. This approach parallels that for CHE discussed in Section 3.7. As there, uncertainty in these emission estimates is due to both process and input parameters. Uncertainty may be included by the limited representation of the emission processes, especially the use of overall average parameters. However, this total power approach is generally considered to be adequate. More significant to the total uncertainty from the resulting emission calculations is the uncertainty in each of the input parameters, as discussed in the parameters sections, above.

Summary of Strengths and Weaknesses. An analysis of local H/C methodology strengths and weaknesses is provided in Exhibit 3-48.

3.6.5 Evaluation of Parameters

Exhibit 3-49 summarizes all parameters relevant for calculating emissions from harbor craft. Each of these has been detailed under the discussion of the appropriate scale method in Sections 3.7.3 and 3.7.4. Only the primary parameters are discussed in detail here; the parameters that are used to derive these parameters may vary and are not listed here. The use of each is detailed in Section 3.6.4. Also as discussed above, no quantitative assessments are provided because the range of parameters is essentially unknown.

Pedigree Matrix. Exhibit 3-50 shows the pedigree matrix for the five primary parameters determining emissions from harbor craft. Criteria to assign scores in the pedigree matrix are included in Appendix A. Note that both main and auxiliary engine populations are ranked as “5” for Range of Variation. This is because the variation in the variation of values between methods is wide, which is also considered a “5,” as documented in Appendix A.

Population. Emissions are linearly related to engine populations. For commercial H/C, both main and auxiliary populations must be characterized, either directly or from vessel populations and average engines per vessel. Populations may be characterized either by engine type, horsepower and age bin, or may only be listed by average values, depending on the level of detail in the methodology. Thus, while accurate assessment of the engine inventory is critical, in many cases this parameter is uncertain, particularly for more streamlined approaches. For additional discussion, see Sections 3.7.3 and 3.7.4.

Load Factors. All methods require use of load factors for each engine and vessel type. This factor represents the average load experienced by the engine over a period of use, typically annually. This factor is ultimately derived from second order factors, such as the duty cycle. However, estimates for many specific types of equipment are not available and thus are aggregated from models, similar types of equipment, or similar studies. Because emissions are linearly related to the load factor, this can have a large impact on the uncertainty of the total emissions. More discussion is presented under Sections 3.7.3 and 3.7.4.

Exhibit 3-48. Summary of strengths and weaknesses—local H/C methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant physical processes typically included	Structure of methodology is fluid; it must be ensured that adequate representation is included
Sensitivity to input parameters		High overall sensitivity to parameters, which are generally uncertain; some sensitivity mitigated by ensuring consistency between interim results (e.g., average age)
Flexibility	Extremely flexible—fluid method structure allows variation for available inputs and surrogates	
Ability to incorporate effects of emission reduction strategies	Straightforward to include effects in calculations if use and effectiveness is known	
Representation of future emissions	Future-year populations calculated may be projected if growth factors are known	
Consideration of alternative vehicle/fuel technologies	Alternative technologies may be included by adjusting emission factors and populations	
Data quality		No specific model on which to rely; information often comes from sources and surrogates of varying quality
Spatial variability	Tailored methodology allows application to range of domains, down to small/project scale	
Temporal variability	Study may be designed for annual, daily, or seasonal inventories, depending on input data	
Review process		Varies by application
Endorsements		Varies by application

Engine Power. Engine power represents the total rated power of each of the engine types installed on commercial H/C. Calculation of H/C emissions may require either disaggregation into bins of specific type, age, and horsepower range or may just sum individual engines or even use overall averages, depending on the level of detail of the study. Because emissions are linearly related to total power, this can have a large impact on the uncertainty of total emissions. For additional discussion, see Sections 3.7.3 and 3.7.4.

Activity. Commercial H/C engine activity determines the average operating hours of a given engine and vessel type in an annual period, and is typically described in hours per year. It may be broken down into bins of total power, power density, engine size, or left aggregated only at the H/C type level, depending on the methodology. Because emissions are linearly related to activity, uncertainty in this parameter can have a large impact on the uncertainty of total emissions. However, because activity also figures into the age distribution of the NONROAD model, impact of its uncertainty may be somewhat mitigated if parameters are adjusted to ensure consistency in the age distribution. For additional discussion, see Sections 3.7.3 and 3.7.4.

Emission Factors. All methods require the use of emission factors, although their source and quality level may vary. They may be defined for a given combination of engine power, density, size, and age, or vary only by equipment type and/or age. As for other factors used to calculate emissions, the result is linearly proportional to this value, thus the impact of uncertainty in this parameter on that for the final calculations can be significant. For additional discussion, see Sections 3.7.3 and 3.7.4.

3.7 Cargo Handling Equipment

Cargo handling equipment (CHE) is used to move or support movement of freight between modes at intermodal facilities, such as ports. Particularly at ports, a wide range of CHE is in use due to the diversity of cargo. Examples of types of CHE include

- Cranes,
- Forklifts,
- Manlifts,
- Sweepers,

Exhibit 3-49. Parameters.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Main Engine Population	EPA RIA method, CARB H/C method	National, Regional	✓	✓	×
Auxiliary Engine Population	EPA RIA method, CARB H/C method	National, Regional	✓	✓	×
Harbor Craft Population	Secondary: used to derive engine populations in local H/C method	Local	×	×	×
Number of Engines per Vessel	Secondary: used to derive engine populations in local H/C method	Local	×	×	×
Load Factors	All	All	✓	✓	×
Emission Factor	All	All	✓	✓	×
Engine Power	All	All	✓	✓	×
Activity	All	All	✓	✓	×
Deterioration Factor	Optional and secondary: used to derive in-use emission factors.	All	×	×	×
Growth Factor	Optional and secondary: needed for future-year projections	All	×	×	×
Engine Age	Optional and secondary: needed to determine average emission factors	All	×	×	×
Median Life	Optional and secondary: needed to determine age distribution	All	×	×	×
Scrappage	Intermediary: derived from equipment age and median life	All	×	×	×
Duty Cycle	Secondary: used to derive load and transient adjustment factors	All	×	×	×
Use of Retrofit Devices	Optional, secondary. Used to calculate control factors on resulting emissions and/or correct modeled emission factors.	All	×	×	×
Fuel Type	Secondary: used to determine emission factors	All	×	×	×

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

- Container handlers,
- Generators,
- Specialized bulk handlers,
- Nonroad vehicles,
- Rail pushers,
- Stackers,
- Skid steer loaders,
- Top handlers,
- Tractors,
- Excavators,
- Welders, and
- Yard tractors.

Container terminals use CHE most extensively, while truck-to-rail equipment and dry bulk terminals also have high use of CHE. As examples, in 2007, the Port of Long Beach found that 81% of the CHE portwide was employed by its container terminals and that 8% of total NO_x emissions were due to CHE (*100*); the Port of Houston found that 15% of its 2007 total NO_x emissions came from CHE (*96*); New York/New Jersey found that 25% of their 2006 NO_x emissions were due to CHE. (*101*) Thus, determining emissions from container terminal CHE is important in any landside emission inventory.

Generally, CHE emissions from freight activities at ports are estimated using either the NONROAD or OFFROAD

Exhibit 3-50. Pedigree matrix—harbor craft equipment parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Main Engine Population	4	Varies	Varies	Varies	N/A	Varies	Varies	5
Auxiliary Engine Population	3	Varies	Varies	Varies	N/A	Varies	Varies	5
Load Factor	4	2-3	1	2	N/A	Varies	2	4
Emission Factor	4	2-3	1	2	N/A	Varies	3	4
Engine Power	4	1	Varies	Varies	N/A	Varies	1	1
Activity	4	Varies	1-2	3	N/A	Varies	3	4

emission models—or methods similar to those employed in these models—combined with parameters representing the CHE present, such as rated power, model year, type of fuel used, annual hours of operation, load data, use of retrofit devices or other emission mitigation measures, and fuel type. Uncertainty in each of these input parameters can lead to significant uncertainty in the final emissions estimated. Models/methods and parameters are discussed separately in the following sections, however, the relationship between the two must be kept in mind.

For example, the OFFROAD model generates emission inventories for a given type of equipment using an equipment-total power methodology as shown in Equation 15.

$$\text{Emissions} = \text{f} * \text{N} * \text{P} * \text{L} * \text{A} \qquad \text{(Equation 15)}$$

Where

f is the emission factor,
P is the maximum rated equipment horsepower,
L is the load factor,
A is the annual activity,
N is the equipment population, and

In which f incorporates adjustments due to deterioration, transient use, and age-related effects.

Uncertainty in the resulting CHE emissions can then be attributed to either the process uncertainty (that is, the degree to which Equation 15—or other OFFROAD algorithms—represents the actual emissions process) and parameter uncertainty (that is, the uncertainty in the individual elements of Equation 15). Evaluation of process uncertainty is presented in Sections 3.7.1 to 3.7.4. Evaluation of parameter uncertainty is presented in Section 3.7.5. In both cases, any known biases should be corrected. The effects of quantifiable uncertainty in input parameters on total calculated uncertainty may be made using standard error propagation methods, discussed in Section 4.3.4. If no covariance is assumed for the parameters in Equation 15, the net error in total emissions would be given by Equation 16, where σ^2 indicates the variance.

$$\sigma^2\ emissions = (NPLA)^2\,\sigma^2 f + (fPLA)^2\,\sigma^2 N + (fNLA)^2\,\sigma^2 P + (fNPA)^2\,\sigma^2 L (fNPL)^2\,\sigma^2 A \qquad \text{(Equation 16)}$$

3.7.1 Summary of Methods and Models

Two general categories of methods are used to estimate CHE emissions. These are referred to as the best practice and streamlined methodologies. (*10*) Generally, these two differ only in the level of direct information collected and employed in the calculations. The best practice methodology dictates surveys of all equipment to establish correct parameters and then employs the NONROAD or OFFROAD models; the streamlined methodology allows for a greater degree of freedom in collecting direct information by substituting surrogate or otherwise derived information. It may then either use the models, or adjust the methodologies of the models themselves for the available information. A special case, third methodology is used in CARB's CHE inventory, which is essentially the best practice methodology without directly

Exhibit 3-51. List of cargo handling equipment methods and models.

Method/Model	Type	Geographic Scale	Pollutants	Freight/Passenger
NONROAD	Emissions Model	County or Larger*	HC, NO_X, CO, CO_2, SO_X, and PM; for exhaust and non-exhaust emissions	Freight
OFFROAD	Emissions Model	County, Air Basin, or Statewide (CA only)	CO_2 and CH_4,** HC, CO, NO_X, and PM; for exhaust, evaporative, and start.	Freight
Best Practices Methodology***	Method	All	All	Freight
Streamlined Methodology†	Method	All	All	Freight
ARB Methodology††	Method	County, Air Basin, or Statewide (CA only)	All	Freight

Notes:

* Model use is restricted to countywide definitions, but emission factors and methods may be extracted at scales down to equipment level.

** CO_2 and CH_4 emissions are produced by OFFROAD, however, these estimates are not currently used as the basis for CARB's official GHG inventory which is based on fuel usage information. (*135*)

*** As documented in EPA's draft best practice document. (*10*) This method includes locally specific information on fleets and use of models.

† As documented in EPA's draft best practice document. (*10*) This method includes use of surrogates for missing locally specific information.

†† As documented by CARB. (*136*) The method used to derive the statewide CHE inventory is a slightly modified version of the best practices methodology, but without directly relying on the OFFROAD model, allowing a modified calculation of deterioration.

using the OFFROAD model. Exhibit 3-51 lists these three methods and two models.

3.7.2 Evaluation of National Methods and Models

There are currently no national scale inventories of CHE emissions exclusively. The EPA prepares the NEI every three years, which includes emissions from nonroad sources, generally broken out by SCC. Similarly, for the 2004 (Tier IV) Nonroad Diesel Rulemaking, EPA prepared a baseline national emission inventory for nonroad engines with populations based on commercial inventories of equipment sales and calculations made via national-scale runs of the NONROAD model. (*137*) However, no details are given specifically to CHE, as results are reported only for "land-based nonroad engines." Given the lack of a national-scale CHE emissions inventory, no uncertainties in such modeling are addressed here.

3.7.3 Evaluation of Regional Methods and Models

California has conducted the only regional analysis of CHE emissions. To evaluate statewide emissions from CHE in support of CARB's Mobile Cargo Handling Equipment Regulation (adopted December 2005, effective December 2006), (*138*) CARB developed a statewide emission estimation methodology and corresponding emission inventory for CHE. (*139*) The regulation is in support of a statewide emission control strategy for CHE at ports and intermodal railyards.

CARB CHE Methodology

The CARB methodology, based on a survey conducted by CARB in early 2004 and the ports of Los Angeles (*110*) and Long Beach (*84*) emission inventories available at that time, estimated population and activity data for CHE statewide by equipment type. The study developed emissions estimates at 16 ports and 14 intermodal railyards in the state for 8 equipment types. (CHE emissions also were estimated for the health risk studies for major rail yards in California.) Exhibit 3-52 shows these eight equipment types, the corresponding SCCs, and the SCC type. (Note that for most equipment types, multiple fuels are possible. The SCCs shown here are for off-highway diesel.)

CARB (*139*) summarizes the methodology as follows:

> Briefly, the approach used to develop the cargo handling equipment emissions inventory estimates entailed determining

Exhibit 3-52. NONROAD cargo handling equipment types.

Aggregated CHE Type	Estimated SCC	SCC Type
Cranes	2270002045	Construction
Excavators	2270002036	Construction
Forklifts	2270003020	Industrial
Container handling equipment	2270003050	Industrial
Other general industrial equipment	2270003040	Industrial
Sweepers/scrubbers	2270003030	Industrial
Tractors/loaders/backhoes	2270002063	Construction
Yard trucks	2270003070	Industrial

> the average annual emissions per engine for each equipment type and then multiplying that value by the total number of engines in that grouping. The majority of the inputs that went into developing the average annual emissions came from individual engine profiles developed using the information from a cargo handling equipment survey conducted by the [C]ARB in 2004 and cargo handling equipment population information provided by the ports of Los Angeles and Long Beach. These inputs were then processed using a template based on the [C]ARB's OFFROAD model to estimate annual emissions per engine for each equipment type. This data was then expanded to include the estimated statewide population of cargo handling equipment fitting a specific age and horsepower range. To estimate port specific emissions, the populations of cargo handling equipment were allocated based on the [C]ARB Survey and the port-specific data. Emission estimates were developed for the eight types of equipment described. . . . Estimates for NO_x, HC, and PM were made.

This methodology only differs from the best practice methodology by not relying directly on the OFFROAD (*140*) model and, instead, slightly modifying the calculation of deterioration. (*141*)

Total uncertainty in this method is due to both process and parameter uncertainty. Although the process used here is generally believed to rely on the best information available at the time, three potentially significant sources of process uncertainty are (1) the appropriateness and representativeness of the OFFROAD model characterizations of CHE, (2) the groupings used to categorize CHE, and (3) the potential for bias in survey results.

The OFFROAD model itself is discussed in the following subsection. The parameters used in this method are shown in Exhibit 3-53 and discussed in Section 3.7.5.

Equipment Groupings

The CARB CHE methodology states its choice to group equipment into eight categories (listed above) to make the analysis compatible with the OFFROAD model. (Note that this is different from the discussion in the Summary in that aerial lifts are grouped into general industrial equipment.) There is no particular bias or additional process uncertainty associated with groupings as long as the parameters within each group are appropriately weighted and applied, and results are provided at the same resolution. That is, the result of total emissions calculations from more highly resolved categories than those here should be consistent with the results of this study if values within each group are appropriately considered. As in all similar cases, resolution must be balanced with accuracy; here the level of resolution was dictated by the use in the OFFROAD model.

Specific discussion of uncertainty with parameters is given below. However, process uncertainty is associated with the assignment of average parameters to bins. For example, in preparing emissions for cranes, the load factor used should be a number-weighted average of the load factors from each crane in the sample set. However, this value is not well known. The error in this parameter is the difference between the value used and the true average from all equipment in the bin. This uncertainty can be due to choice and assignment of values to equipment groupings.

Potential Survey Bias. There is potential for bias in survey methods due to misreporting of equipment. This could be due

Exhibit 3-53. Parameters from the CARB CHE inventory.

Input Factor	Source of Data (Gas and Diesel)
Population (base year 2004)	2004 CARB Survey of Statewide Ports & Rail Yards; POLA & POLB data (2002)
Useful life	2004 CARB Survey of Statewide Ports & Rail Yards
Activity (h/yr)	2004 CARB Survey of Statewide Ports & Rail Yards
Average horsepower	2004 CARB Survey of Statewide Ports & Rail Yards; POLA & POLB data (2002); Power Systems Research (1996)
Load factor	Power Systems Research (1996)
Allocation factor	2004 CARB Survey of Statewide Ports & Rail Yards; POLA & POLB data (2002)
Growth factor	2002 POLA Container TEUs data
Survival rate	Power Systems Research (1996)

Source: CARB, *Cargo Handling Equipment One Pager.*

to a desire to underreport equipment or overstate control technologies to underestimate emissions resulting from activities at a facility, omission of specific facilities due to a size cutoff, for example, or many other reasons. As noted earlier, any known bias should be removed from a sample set prior to analysis.

Sampling was made by CARB for over 120 owner/operators statewide and results incorporated with detailed inventories from the 2001/2002 Port of Los Angeles (POLA) and Port of Long Beach (POLB) inventories. CARB corrected Los Angeles and Long Beach inventories to a common year assuming a 3% annual growth factor. To adjust for limited information, CARB applied corrections to survey results for equipment populations where data were under-reported or not reported. Thus, no residual bias is likely for this study.

Summary of Strengths and Weaknesses. CARB CHE methodology strengths and weaknesses are described in Exhibit 3-54.

OFFROAD Model

The OFFROAD2007 model is CARB's current emissions and emission factor model designed to incorporate effects of proposed regulations, technology types, and seasonal conditions on emissions of nonroad equipment except ocean-going vessels, commercial harbor craft, locomotives, agricultural irrigation engines, and gas cans. The model consists of three main modules: population, activity, and emissions factor. Population is determined from a calendar year 2000 baseline equipment population, adjusted for growth and scrappage to produce model-year specific population distributions for years 1970 to 2040, allocated to geographic regions. Baseline emission factors are corrected for in-use and ambient conditions. Emission inventories are resolved to the county, air basin, or air district by fuel type, engine type, equipment category, and horsepower group. (*140*)

Uncertainty in emission estimates by the OFFROAD model is driven by several aspects of the model, both in its structure and its input parameters.

Calculation Method. The basic emissions calculations in the model are summarized by Equation 17.

$$\text{Emissions} = f * N * P * L * A \qquad \text{(Equation 17)}$$

As noted above, this is essentially a total power approach to emissions calculations, rather than a TIM calculation or a fuel consumption approach. On average, a total power approach and a TIM approach should agree, if the more detailed activity profile and load in a given power setting agree with the average load factor employed by the power approach. (As noted by the lack of use of OFFROAD in creating the California GHG inventory (*10*), a fuel consumption approach is not generally expected to agree.) However, uncertainty is inherent in this parameterization due to the physical representation of annual activity.

Additional uncertainty due to best estimate parameters for average use conditions also exists in the model. This is discussed in Section 3.7.5. However, OFFROAD model-specific discussion follows here.

Exhibit 3-54. Summary of strengths and weaknesses—CARB CHE methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant physical processes included	
Sensitivity to input parameters	Method relies on well studied model inputs, and modifies when necessary	Uncharacterized overall uncertainty
Flexibility	Tailored methodology	
Ability to incorporate effects of emission reduction strategies	Information included from local authorities on reduction strategies implemented	
Representation of future emissions	Method relies on well studied model inputs	
Consideration of alternative vehicle/fuel technologies	Information included from local authorities on reduction strategies implemented	
Data quality	Information included from local authorities; known biases corrected	
Spatial variability		Applicable only to CA; emissions resolved only to county level
Temporal variability		Produces only annual inventories
Review process		Unclear from documentation
Endorsements	ARB	

Population Parameters. Population in OFFROAD2007 is determined as the calendar year 2000 baseline equipment population adjusted for growth and scrappage. Growth factors are based on socioeconomic indicators such as housing units and manufacturing employment by category, by county, and with respect to year 1990 sales. Scrappage is fixed by equipment age and/or use and depends on engine type and horsepower group. For all CHE types, useful life is represented in years and is driven by the engine's expected life (note that useful life for lawn and garden equipment and recreational vehicles is determined by the equipment life). As for the NONROAD model, the equipment useful life is defined by the sample median; total lifetime is twice the useful life.

Since emissions estimates are linearly proportional to population, significant uncertainties may result from uncertainties in population, as discussed in Section 3.7.5. For OFFROAD, particularly, many of these uncertainties are driven by the population projections to specific calendar years. These uncertainties may be mitigated by using observed counts of CHE instead, as in the CARB CHE methodology. Uncertainties also exist in the methods used to allocate populations to smaller domains, such as counties or air basins. Similarly, the shape of the age-to-median age curve could be inappropriate for a given equipment type. Neither of these uncertainties is generally quantifiable, but could lead to uncertainty in resulting inventories.

Activity Parameters. Activity estimates in OFFROAD 2007 include annual average usage, load factors, brake-specific fuel consumption (BSFC), and number of starts per year. Values are included for each equipment category by fuel and engine types and horsepower group. Activity profiles also include seasonal and temporal variations by industrial category. Uncertainty exists in these parameters on the appropriate category binning and application across categories. Particularly, this is true for equipment that could have uses in multiple industries or placed in a more general category. There also are issues with attributing usage fractions to freight activity only. For example, an average (no peak) usage pattern is exhibited by airport ground service and TRUs while construction and industrial equipment is assigned primarily a weekday profile. However, much CHE is likely to be considered industrial equipment, although having a profile more similar to air GSE. Similarly, a skid steer loader used in a mining application is not likely to represent the activity profile of one used at a bulk cargo terminal.

Emission Factors. Exhaust emission factors are engine-specific and vary by fuel type, horsepower group, and model year. Equipment-specific emission rates are based on the combination of engine emission factors and equipment duty cycles. Deterioration rates are generally based on on-road emissions data.

Use of on-road deterioration rates, application of estimated duty cycles, and assumed zero-hour emission factors all may add uncertainty into model results. Nonroad CHE active at ports is likely to have a different duty cycle than similar nonroad equipment used in other industrial applications. Further, the use of on-road deterioration factors from a 1990 study (*142*) seems unlikely to represent a current fleet of nonroad engines. Sources of zero-hour emission factors also are unclear. Each of these leads to an unquantified uncertainty in the model results. Note that the CARB CHE inventory did not rely on deterioration rates in the OFFROAD model.

Summary of Strengths and Weaknesses. Strengths and weaknesses of the OFFROAD model are described in Exhibit 3-55.

3.7.4 Evaluation of Local/Project-Level Methods and Models

Several studies of CHE emissions have been conducted at the local/project level. Principally, these include studies at ports throughout the United States, as detailed by Exhibit 3-56. Other studies of note include CHE active at intermodal railyards throughout California (*143*) and NEPA and CEQA studies that have characterized impacts from CHE. (*144*)

Typically, these studies either rely on the best practices methodology directly or a variation of it, where calculations are made externally, but in a similar method to that of NONROAD or OFFROAD models. In some cases, particularly for the less detailed studies, a streamlined approach is used. These methods and models are discussed in the following subsections.

Best Practice Methodology

Best practices in developing an emissions inventory from CHE activity dictate that one should gather detailed information on all CHE present at the port in question (within the study boundaries) and make simulations using the NONROAD (outside of California) or OFFROAD (in California) model. This methodology is rooted in observations of all active CHE, including information on the following:

- Equipment type,
- Rated horsepower,
- Model year,
- Type of fuel used, including fuel sulfur level for diesel,
- Annual hours of operation,
- Equipment load data, and
- Retrofit devices or other emission mitigation measures employed.

Using the data collected on equipment numbers, types, horsepower, model year, hours of operation and load data, inputs can be generated for the various NONROAD (OFFROAD)

Exhibit 3-55. Summary of strengths and weaknesses—OFFROAD model.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant physical processes included	
Sensitivity to input parameters	Model relies on user-customizable inputs; sensitivity to these inputs varies	Uncharacterized overall uncertainty
Flexibility		Moderately flexible; customization requires familiarity with model, or replication of calculations
Ability to incorporate effects of emission reduction strategies		May be included after model runs, using CARB-certified reductions; unclear how to include in simulations
Representation of future emissions	Projections available in the model	
Consideration of alternative vehicle/fuel technologies		Unclear
Data quality	Generally structured from best available information	
Spatial variability		Applicable only to CA; emissions resolved only to county level
Temporal variability		Produces only annual inventories
Review process		Unclear from documentation
Endorsements	ARB	

Exhibit 3-56. Recently conducted port inventories containing CHE.

Port	Year Published	Data Year	Pollutants*	Contractor*
Charleston (*94*)	2008	2005	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2	Moffatt & Nichol
Houston/Galveston (*145*)	2003	2001	NO_x, VOC, CO	Starcrest
Houston (*96*)	2009	2007	NO_x, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2, CO_2	Starcrest
Los Angeles (*110*)	2005	2001	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Los Angeles (*83*)	2007	2005	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Los Angeles (*99*)	2008	2007	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
Long Beach (*146*)	2004	2002	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Long Beach (*130*)	2007	2005	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest
Long Beach (100)	2009	2007	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
New York/New Jersey (*147*)	2003	2002	NO_x, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2	Starcrest
New York/New Jersey (*148*)	2005	2004	NO_x, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2	Starcrest
New York/New Jersey (*101*)	2008	2006	NO_x, VOC, CO, PM_{10}, $PM_{2.5}$, SO_2, CO_2, N_2O, CH_4	Starcrest
Oakland** (*102*)	2008	2005	NO_x, ROG, CO, PM, SO_x	Environ
Portland (*103*)	2005	2004	NO_x, HC, CO, SO_x, PM_{10}, $PM_{2.5}$, CO_2, 9 Air Toxics	Bridgewater Consulting
Puget Sound*** (*104*)	2007	2005	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM, CO_2, CH_4, N_2O	Starcrest
San Diego (*105*)	2008	2006	NO_x, TOG, CO, PM_{10}, $PM_{2.5}$, SO_2, DPM	Starcrest

Notes:

* Starcrest = Starcrest Consulting Group LLC, Environ = Environ International Corp.

** Definitive results are not included for cargo handling equipment in this inventory.

*** Includes the ports of Anacortes, Everett, Olympia, Port Angeles, Seattle, and Tacoma.

equipment types to determine emissions for CHE at the port. Use of retrofit or emission control devices must be treated outside the model. In these cases, emission factors may be determined using the NONROAD (OFFROAD) models for diesel equipment and then appropriate emission reduction percentages applied. For retrofit devices such as diesel oxidation catalysts, diesel particulate filters, or other technologies, reductions specified in the following sources should be applied: EPA's Verified Retrofit Technology website; (*149*) EPA's Diesel Emission Quantifier; (*150*) or CARB's list of currently verified technologies. (*151*) Other sources may be relied upon, but may be considered more uncertain.

Specific discussion of these models and their associated uncertainties is given in Section 3.7.3. Total uncertainty in this method is due to both process and parameter uncertainty. The process described here is generally structured to rely on the best information available for a given project. However, at the time, three potentially significant sources of process uncertainty are (1) the appropriateness and representativeness of the NONROAD (OFFROAD) model characterizations, (2) the groupings used to categorize CHE in analysis, and (3) the potential for bias or error in equipment inventory counts.

The appropriateness and uncertainty of the models is discussed in their respective sections.

Equipment Groupings. The best practice methodology should minimize uncertainty associated with grouping CHE into categories by following the categories already provided by each model to make the analysis compatible with the model being employed. As in all similar cases, resolution must be balanced with accuracy; here the level of resolution will be dictated by the emissions model.

There is no particular bias or additional process uncertainty associated with groupings as long as the parameters within each group are appropriately weighted and applied, and results are provided at the same level of resolution. That is, the result of total emissions calculations from more highly resolved categories should be consistent with the total emissions from a coarser study if values within each group are appropriately considered. Specific discussion of uncertainty with input parameters for the OFFROAD model is given above; discussion of the NONROAD model is below. However, process uncertainty is associated with the assignment of average parameters to bins. This uncertainty can be due to choice and assignment of values to equipment groupings. Because the bins are determined by model designations and the CHE sample size is expected to be moderate to small for local/project-scale analyses, fleet characterization should not cause much uncertainty in the emissions analysis.

Survey Error. There is potential for bias and error in survey methods due to miscounting of equipment at the facility for a variety of reasons such as inappropriate boundary conditions, accidental omission of facilities or equipment, a desire to misrepresent activity, or incorrect survey methodology or results processing, for example. As noted earlier, any known bias should be removed from a sample set prior to analysis. If an appropriate survey is conducted following the best practice guidelines, these uncertainties should be small.

Summary of Strengths and Weaknesses. Best practice methodology strengths and weaknesses are provided in Exhibit 3-57.

Streamlined Methodology

In cases where all necessary information is not available, resulting emissions from CHE activity may be approximated using a more streamlined approach than that of the best practice approach, allowing emission estimations without directly observed equipment inventories and other parameters.

Recently, a variety of detailed, local/project-scale CHE emission inventories have become available (see Exhibit 3-56). Unlike vessel emissions, there is no standardized methodology for developing estimates of port CHE emissions. Developing a detailed CHE inventory may require extensive time and resources to survey tenants within the study boundaries regarding their equipment. As an alternative to this level of effort, CHE emissions are sometimes estimated based on inputs developed for CHE inventories prepared by other sources. The essence of a streamlined CHE evaluation is to estimate any missing values in a local survey of equipment types, counts, and/or parameters from other published studies—commonly by applying ratios of known parameters, such as cargo tonnage throughput—to other detailed ports, followed by calculations using the NONROAD (OFFROAD) model or methodology.

Uncertainty in this method can be significant, although general quantification of this uncertainty is difficult. Uncertainty is propagated into the analysis via the parameters input to the model, such as in the number inventory and properties of CHE. For example, one might use tonnage throughput ratios between two projects to determine the number of cranes at a second project from that at the first, but translate all other parameters for those cranes (e.g., power, load, activity) directly from the values at the known port. The net uncertainty on resulting emissions could be tracked from the uncertainty resulting from the scaled input parameters, but the source of this uncertainty is the process used to translate the parameters. Specifically, it is due to the assumptions used and choices made. Bias can be minimized by selecting projects that are similar, both in scope (by using methodologies such as the principal port-like analysis of the ARCADIS guidance, (*116–117*) for example) and in equipment age, activity, and other parameters. Regardless, uncertainty in this methodology is likely to be significant.

Exhibit 3-57. Summary of strengths and weaknesses—best practice methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant physical processes included	
Sensitivity to input parameters	Method relies on detailed user inputs that may not be readily available, but should produce best results	General, overall uncertainty unknown
Flexibility		Low Flexibility; requires detailed data collection
Ability to incorporate effects of emission reduction strategies	Best information available; effects may be included after model runs	
Representation of future emissions	Projections available in the model and customizable to local information	
Consideration of alternative vehicle/fuel technologies	May be achieved in methodology with suitable model runs	
Data quality	Structured from best available information	
Spatial variability	Applicable to any location, but data requirements likely limit to smaller spatial scales	
Temporal variability		Most likely limited to annual inventories
Review process	Documented in EPA Methodology Guidance	
Endorsements	EPA	

Summary of Strengths and Weaknesses. Strengths and weaknesses of the streamlined methodology are shown in Exhibit 3-58.

NONROAD Model

In April 2009, EPA released the current version of its nonroad, mobile emissions and emission factor model, NONROAD2008. The NONROAD model (*152*) predicts emissions for recreational land and marine vehicles as well as logging, agricultural, construction, industrial, and lawn and garden equipment. It includes over 80 basic and 260 specific types of nonroad equipment stratified by horsepower rating, and considers equipment fueled by gasoline, diesel, compressed natural gas (CNG), and liquefied petroleum gas (LPG). NONROAD2008 also includes emission reductions

Exhibit 3-58. Summary of strengths and weaknesses—streamlined methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant physical processes included	
Sensitivity to input parameters	Method relies on surrogates for missing inputs; results highly sensitive to quality of inputs	
Flexibility	Highly flexible; customizable to data limitations	
Ability to incorporate effects of emission reduction strategies	Highly customizable.	
Representation of future emissions	Projections available in the model and customizable to local information	
Consideration of alternative vehicle/fuel technologies	May be achieved in methodology with suitable model runs	
Data quality		Structured from available information
Spatial variability	Applicable to any location. Data flexibility allows multiple spatial scales	
Temporal variability	Designed for annual inventories, but scalable with appropriate information	
Review process	Documented in EPA Methodology Guidance	
Endorsements		

associated with the 2008 diesel recreational marine standards from the locomotive/marine and small spark-ignition (SI) and SI recreational marine final rules. The model is capable of estimating subcounty emissions with specific inputs. However, the practical geographic domains vary between county and national extents. NONROAD is intended to eventually be replaced by a version of the MOVES model that will incorporate nonroad modeling capability. EPA has indicated that it intends to include this capability in the release of the final version of MOVES2010 (focused on on-road vehicles and scheduled to be released by the end of 2009), however, that version would not be expected to yield substantially different results compared to NONROAD2008. (*153*)

Exhibit 3-59 provides an example of equipment types and the corresponding SCC used in the NONROAD model to estimate emissions from CHE. The majority of CHE can be classified into one of these equipment types. (Note that for most equipment types, multiple fuels are possible. The SCCs shown here are for off-highway diesel.)

Uncertainty in emission estimates by the NONROAD model is driven by several aspects of the model, both in its structure and its input parameters.

Population Parameters. NONROAD maintains 1996, 1998, and 1999 baseline populations and determines future year populations by assigning an average growth rate to estimate emissions in subsequent years. (*154*) To produce emissions for a given calendar year, growth can be set to zero so that the emissions will not increase over time and the results will be accurate for the analysis year.

For future forecasts, updated inputs for population and activity are required. This is due to the NONROAD methodology, which calculates both population and age distribution in which the model uses a population growth rate to project equipment populations from a base year to an evaluation year. (*155*) For all base years (projected or current) the model fits the population numbers to a predetermined form as a function of growth and scrappage. The number of units of each model year (or, equivalently, age) is determined for each age for 50 years back. Populations with ages greater than twice the median life are assumed scrapped. (*156*)

Significant uncertainty in emissions may arise from this formulation of age distribution, due to the assignment of engine tiers to specific ages (and power bins). The driving parameters here are the growth rates, shape of the population distribution curve, and median lifetime of equipment. Any event that leads to a difference in real world age distribution from that assumed by the model will lead to different average emission factors, and thus different emissions. This bias could result from a mischaracterization of equipment median life or growth rates, both of which shift the overall curve of population versus age. The resulting uncertainty could bias the results in either direction, as an under- (over-) estimated median life

Exhibit 3-59. NONROAD cargo handling equipment types.

Aggregated CHE Type	Estimated SCC	SCC Type
Compressor	2270006015	Commercial
Crane	2270002045	Construction
Forklift	2270003020	Industrial
Manlift	2270003010	Industrial
Sweeper	2270003030	Industrial
Car loader	2270003050	Industrial
Chassis rotator	2270003040	Industrial
Empty container handler	2270003050	Industrial
Generator	2270006005	Commercial
Light tower	2270002027	Construction
Specialized bulk handler	2270003050	Industrial
Nonroad vehicle	2270002051	Construction
Gantry Crane	2270002060	Industrial
Rail pusher	2270003040	Industrial
Reach stacker	2270003050	Industrial
Roller	2270002015	Construction
Side handler	2270003050	Industrial
Skid steer loader	2270002072	Construction
Top handler	2270003050	Industrial
Tractor	2270002063	Construction
Excavator	2270002036	Construction
Welder	2270006025	Commercial
Yard Tractor	2270003070	Industrial

would lead to relatively more (fewer) newer engines and lower (higher) overall emissions. Similarly, a difference in the general shape of the real world age distribution from that parameterized in the model could lead to bias in either direction. This bias is more difficult to quantify without explicitly knowing the full age distribution of the sample population, but one example could be in cases where a type of equipment, engine, or technology is newly introduced and the older tail of the age distribution is not yet populated. In that case, the bias would be to higher emissions estimates by over-predicting the number of older, more polluting engines.

Uncertainty in the results may also be attributed to correct estimation of growth factors by equipment type. This parameter may be set in model inputs, however, and is directly controllable by the user. Mischaracterization, however, could lead to significant bias in resulting populations. A similar scenario exists with equipment population. Default NONROAD equipment populations by geographic areas are determined from national-level estimates using economic factors, such as construction expenditures, farm acreage, and building square footage. (*157*) Reliance on these, rather than directly observed current year population counts, may lead to bias in resulting emissions.

As emissions estimates are linearly proportional to population, significant uncertainties may result from uncertainties in population, as discussed in Section 3.7.5. In all cases, these uncertainties may be mitigated by using observed counts of CHE of each age for the given project.

Usage Parameters. Engine median lifetime shapes the population distribution, as discussed previously. Annual activity and load determine the engine usage. All are discussed together by EPA. (*158*) The parameters are related because NONROAD uses annual activity and load factor values to calculate emissions by engine type and uses activity, load factor, and median life together to calculate fleet age distributions. See Equation 18.

$$Median\ Life(years) = \frac{Median\ Life\ At\ Full\ Load(hours)}{Activity(hours/year) * Load\ Factor} \qquad \text{(Equation 18)}$$

NONROAD assumes equipment lifetime equals engine life; engine life is determined based on the expected lifetime of highway diesel engines operated continuously at full load and adjusted to in-use values by dividing by the average load factor and annual activity. The NONROAD methodology assumes that nonroad engines are not rebuilt and that equipment never fails before the engine is worn out. These underlying assumptions in the model may lead to significant resulting uncertainty in calculated emissions. However, engine rebuilds would lead the model to underestimate the equipment fleet, while engine wear out would lead to overestimation of the fleet, thus the net bias due to in-use lifetime is expected to be small. (*157*) Uncertainty due to the representativeness of on-road engine lifetimes for off-road applications is unknown, although EPA did consider the data underlying these estimates in NONROAD development. (*158*)

Load factors in NONROAD are based on seven operational duty cycles for agricultural tractors, backhoe-loaders, crawler tractors, skid-steer loaders, arc welders, wheel loaders, and excavators. Extrapolation of the seven duty cycles to every type of equipment was done by grouping the seven cycles into three categories—transient cycles with high loads (average of 0.59 with range 0.48–0.78), transient cycles with low loads (average of 0.21 with range 0.19–0.23), and steady-state cycles (average of 0.43)—and assigning all equipment to one of these three categories. (*157*) Uncertainty in the measured range of high- and low-cycle values is about 10% to 30%, although that for the steady cycles is uncharacterized, but could be as high as about 80%. Uncertainty due to assignment of measured emission factors to equipment groups is unknown. However, the assumed load factor is likely to be a significant source of uncertainty in NONROAD modeling, both in directly calculating equipment emissions and in determining population age distribution. EPA claims that the effects of load and lifetime in determining emissions and population are offsetting when computing total emissions, such that uncertainties in these parameters should have little effect on total emission uncertainty. (*157*)

Activity values in NONROAD are based on surveys of equipment users by a private company using proprietary methods that estimate annual activity by equipment type but not by engine size, age, or model year. The uncertainty in average values and the actual sensitivity of activity to equipment size and age are all unknown. (*157*) Thus, the effects of these on overall emissions estimates is unknown.

NONROAD estimates brake-specific fuel consumption (BSFC) as 0.408 lb/bhp-hr for engines smaller than (or equal to) 100 hp and 0.367 lb/bhp-hr for engines larger than 100 hp, based on measured fuel consumption values during engine certification. (*157*) Uncertainty in these estimates is unknown.

Emission Factors. Emission factors in NONROAD (*159*) consist of zero-hour, steady-state emission factors, transient adjustment factors, and deterioration factors; fuel sulfur impacts on emission rates are included. Zero-hour, steady-state emission factors (EFs) are a function of model year and power, which defines the technology type. Transient adjustment factors (TAFs) vary by equipment type. Deterioration factors (DFs) are functions of the technology type and engine age. See Equation 19.

$$EF_{InUse} = EF_{SteadyState} * TAF * DF \qquad \text{(Equation 19)}$$

In addition to exhaust emissions, crankcase HC emissions are computed as a simple 2% fraction of exhaust HC emissions for Tier 0 to III engines and are zero for Tier IV engines.

Zero-hour, steady-state emission factors are drawn from a variety of sources, including NEVES (baseline engines > 50 hp), CARB's OFFROAD values (Tier 0 engines less than 50 hp), emission rate tests (Tier 0 engines greater than 50 hp), EPA engine certification data (all Tier I engines and Tier II engines 300–600 hp), methods for the remaining Tier II and all Tier III engines (including compliance margins on emission standards, certification results, CARB engine test data, and engineering judgment). All Tier IV emission factors are based on compliance margins from emission standards. Since each element is chosen based on the best available information, all bias is assumed to be minimized. However, significant but unquantified uncertainty persists in most factors. Factors based on standards are likely to be less uncertain, since engines must be designed to meet specific thresholds, but a range of values is still likely.

TAFs (*159*) are applied to the emission factors of all engines except Tier IV, where transient control is expected to be part of all engine design. TAFs in NONROAD were calculated by averaging tests for each engine, pollutant, and test cycle, and comparing these measured emission factors for off-road equipment duty cycles to the zero-hour steady state emission factors. Thus, in-use emission factors should have reduced uncertainty relative to using zero-hour steady state emission rates as emission factors.

Deterioration factors (*159*) in NONROAD increase with engine age up to its median life, at which point it is held constant, under the assumption that increased deterioration is offset by maintenance. For compression ignition engines, deterioration is linear. In all cases, due to a lack of data for nonroad engines, the factors are based on data derived from highway engines. Uncertainty in these factors is unknown, particularly any additional effects due to deterioration, mal maintenance, tampering, or the effects from use of fuel with various sulfur levels.

Calculation Method. The basic emissions calculations in the model are summarized by Equation 20.

$$Emissions = \sum_i \sum_j Pop_{i,j} * Power_j * LF_i * A_i * EF_{i,j} \qquad \text{(Equation 20)}$$

Where

$Pop_{i,j}$ is the population of engines of equipment type i within power bin j,

$Power_j$ is the average power (hp) of bin j,

LF_i is the load factor (fraction of available power) of equipment type i,

A_i is the annual activity (hours/year) of equipment type i, and

EF is the emission factor (g/hp-hr).

As noted, this is essentially a total power approach to emissions calculations, rather than a TIM calculation or a fuel consumption approach. On average, a total power approach and a TIM approach should agree, if the more detailed activity profile and load in a given power setting agree with the average load factor employed by the power approach. However, uncertainty is inherent in the model due to the physical representation of annual activity. Additional uncertainty due to best estimate parameters for average use conditions also exists in the model. This is discussed in Section 3.7.5.

Summary of Strengths and Weaknesses. NONROAD model strengths and weaknesses are shown in Exhibit 3-60.

OFFROAD Model

The OFFROAD model was discussed in Section 3.7.3. Since the model is appropriate at the project/local scale as well as the regional scale, the discussion is not repeated here.

3.7.5 Evaluation of Parameters

Exhibit 3-61 summarizes all parameters relevant for calculating emissions from CHE. Each of these has been detailed under the discussion of the appropriate model or method in Section 3.7.3 and 3.7.4. Only the primary parameters are discussed in detail here. That is, many of the parameters are used to derive the parameters in Equations 15 and 20, but not discussed here. The use of each is detailed above. Also as discussed previously, no quantitative assessments are provided, because the range of parameters is essentially unknown.

Pedigree Matrix. Exhibit 3-62 shows the pedigree matrix for the five primary parameters determining emissions from CHE. Criteria to assign scores in the pedigree matrix are included in Appendix A. Note that population is ranked as a "5" for the range of values. This is actually because the variation in the variation of values between methods is wide, which is also considered a "5" in Appendix A.

Population. Emissions are linearly related to the equipment population, as shown by the previously provided equations. Populations should be determined for each type of equipment, for each horsepower and age bin employed. Thus, although accurate assessment of the equipment inventory is critical, in many cases this parameter is uncertain, particularly for projected years or streamlined methods. More discussion has been presented under Sections 3.7.3 and 3.7.4. Note that population is shown as "varies" in Exhibit 3-62 because the range of values varies too widely to be ranked, depending on the methodology employed.

Exhibit 3-60. Summary of strengths and weaknesses—NONROAD model.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant physical processes included	
Sensitivity to input parameters	Sensitivity to some parameters mitigated by model structure (load, activity); overall sensitivity depends on the parameters	
Flexibility	Moderately flexible; most inputs adjustable in input files	
Ability to incorporate effects of emission reduction strategies		Unclear
Representation of future emissions	Future year populations calculated in the model	
Consideration of alternative vehicle/fuel technologies		Unclear
Data quality	Model relies on best available information at time of development, with public review	
Spatial variability	Applicable to domains from countywide to national	
Temporal variability	Designed for annual inventories	
Review process	Publicly reviewed	
Endorsements	EPA	

Exhibit 3-61. Parameters.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Population	All	All	✓	✓	×
Load Factor	All	All	✓	✓	×
Emission Factor	All	All	✓	✓	×
Engine Power	All	All	✓	✓	×
Activity	All	All	✓	✓	×
Deterioration Factor	Optional and secondary: used to derive in-use emission factors	All	×	×	×
Growth Factor	Optional and secondary: needed for future-year projections	All	×	×	×
Engine Age	Optional and secondary: needed to determine average emission factors	All	×	×	×
Median Life	Optional and secondary: needed to determine age distribution	All	×	×	×
Scrappage	Intermediary: derived from equipment age and median life	All	×	×	×
Duty Cycle	Secondary: used to derive load and transient adjustment factors.	All	×	×	×
Use of Retrofit Devices	Optional, secondary: used to calculate control factors on resulting emissions and/or correct modeled emission factors	All	×	×	×
Fuel Type	Secondary: used to determine emission factors	All	×	×	×

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

Exhibit 3-62. Pedigree matrix—cargo handling equipment parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Population	4	Varies	Varies	Varies	N/A	Varies	Varies	5
Load Factor	4	2-3	1	2	N/A	Varies	2	4
Emission Factor	4	2-3	1	2	N/A	Varies	3	4
Engine Power	4	1	Varies	Varies	N/A	Varies	1	1
Activity	4	Varies	1-2	3	N/A	Varies	3	4

Load Factors. Most models either require input of, or use default values for, load factors for a piece of equipment. This factor represents the average load experienced by an engine over a period of use, typically annually. This factor is ultimately derived from second-order factors, such as the duty cycle. However, estimates for many specific types of equipment are not available and are aggregated from average values of similar equipment types. Because emissions are linearly related to load factor, this can have a large impact on the uncertainty of total emissions. More discussion has been presented in Sections 3.7.3 and 3.7.4.

Engine Power. Engine power represents the total rated power of CHE engines. Calculation of CHE emissions generally requires disaggregation of equipment into bins of specific horsepower range since the power and age typically determine the engine category for regulatory purposes. Databases of CHE within these bins are incorporated into the NONROAD and OFFROAD models, or should be collected through surveys. Because emissions are linearly related to total power, this can have a large impact on the uncertainty of total emissions. More discussion has been presented in Sections 3.7.3 and 3.7.4.

Activity. Engine activity determines the average operating hours a given piece or group of equipment types have in an annual period, typically described in hours per year. It is not commonly broken down into power bins, but left at the CHE type level. Because emissions are linearly related to activity, uncertainty in this parameter can have a large impact on the uncertainty of total emissions. However, because activity also figures into the age distribution of the NONROAD model, impact of its uncertainty is somewhat mitigated. More discussion has been presented in Sections 3.7.3 and 3.7.4.

Emission Factors. Most models either require input of, or use default values for, emission factors. Typically, these are defined for a given combination of engine power and age. As for other factors used to calculate emissions, the result is linearly proportional to this value, thus the impact of uncertainty in this parameter on that for the final calculations can be significant. Emission factors are determined from a range of activities, including measurements, certification databases, and engineering judgment. More discussion has been presented in Sections 3.7.3 and 3.7.4.

3.8 Air Transportation

For aviation-related emissions the following two modeling approaches are reviewed and evaluated:

- Version 1.5 of the FAA's System for Assessing Aviation's Global Emissions (SAGE) modeling system is the primary method for national or regional emission analysis in the United States. Other national or regional aircraft models are under development but these are focused on non-U.S. regions (e.g., AEM [EUROCONTROL], AERO2k [UK/QinetiQ], and FAST [UK/MMU]). The emphasis of these models is on global-scale emission inventories with regional emphasis on european issues. (*160*)
- Version 5.1 of the Emissions and Dispersion Modeling System (EDMS), released September 19, 2008, was developed by FAA specifically to address the impacts of airport emission

sources, including ground-level sources and associated support activity. FAA requires the use of the model in performing air quality analyses for aviation sources. Recent improvements to the model include speciated air toxic emissions, CO_2 emissions from aircraft, improved methodology for PM emission estimates, and the addition of 63 new engines and 40 aircraft. FAA also is sponsoring ongoing research through the Partnership for Air Transportation Noise and Emission Reduction, to understand and evaluate the potential role of aviation emissions in local and regional air quality. The main objective of the project is to quantify the potential incremental contribution of aviation emissions to local and regional air quality though their chemical interaction with the background air.

A summary of air freight methods and models is shown in Exhibit 3-63.

3.8.1 Evaluation of National and Regional Models

The FAA has been working on the development of a national-to-global version of SAGE since 2001. The most current version has been used to develop annual emission inventories for commercial (civil) aircraft fuel consumption for CO, NO_x, SO_2, HC, H_2O and CO_2. (*37*) Because the model operates at the level of individual flight by airport it can potentially be applied to a limited regional analysis as well as at the national level. This version of SAGE dynamically models aircraft performance, fuel consumption, and emissions, and includes such factors as capacity and delay at airports. The model does not have the current capability to separate freight-only travel from freight and passenger operations nor does the model include military air cargo activity.

The model is driven primarily by a set of databases that are used to develop the emission inventory. The key databases include the following:

- International Civil Aviation Organization (ICAO) emissions databank with information on certification emissions and fuel flow rates for a wide variety of jet engines that have entered service;
- Base of Aircraft Data (BADA), which is a collection of aircraft performance and operation parameters, includes coefficients in the data that allow calculation of lift and drag forces;
- Information on airport location and altitude;
- Official Airline Guide (OAG) database contains information on trip origination, trip length, type of aircraft, destination, and aircraft type for all commercial activity;
- Enhanced Traffic Management System (ETMS), a database on the electronic recording of flight position and flight plan used for air traffic management, captures every flight within coverage of FAA radars;
- ICAO's Forecasting and Economics Sub-Group Forecast contains forecasts of the number of aircraft, number of aircraft seats, number of flights, capacity, and average seating numbers per aircraft by region;
- FAA's Terminal Area Forecast provides information on passenger boarding and aircraft operations for each U.S. airport;
- USDOT's Bureau of Transportation Statistics (BTS) database provides on-time performance for the 10 largest U.S. air carriers;
- FAA's annual runway capacity "benchmarking" report of U.S. airports provides a basis for delay data; and
- Aircraft retirement parameters (data that categorize the survivor curves [i.e., polynomial equations] for the aircraft fleet population that survived the retirement process) by aircraft category type and age.

Model Overview

The fundamental modeling unit in SAGE is a single flight. All data, including those related to flight schedules, trajectories, performance, and emissions, are represented at a level of detail sufficient to support the modeling of a single flight. This allows high resolution modeling of emission inventories. Each flight is modeled from gate to gate. Although a single flight in SAGE is the modeling unit, the simulation is con-

Exhibit 3-63. Air freight methods and models.

Method/Model	Type	Geographic Scale	Pollutants	Freight/Passenger
FAA SAGE (version 1.5)	Model	Global, National to Regional	CO, hydrocarbons NO_x, CO_2, H_2O,* and SOx	Commercial freight and passenger (no military)
EDMS (version 5.1)	Model	Local	Criteria pollutants, NMHC, CO_2 and 44 air toxics	Freight and passenger

* Water (H_2O) is included here because when emitted at cruising altitude into the lower stratosphere/upper troposphere, it acts as a greenhouse gas via contrail development.

ducted at a more detailed level (i.e., each individual segment of flight—referred to as a flight chord—is calculated by the model). Typical flights in SAGE are represented by 40 to 50 chords, depending on the stage length and availability of detailed radar trajectory data. The flight chords allow the ability to express outputs in a variety of different formats (e.g., gridded and per flight mode) and allow for dynamic aircraft performance modeling in SAGE. Such modeling provides an opportunity for improvements in accuracy relative to those based on aggregated TIMs or simplified performance lookup tables. To accomplish the detailed flight-by-flight modeling, SAGE includes information on a variety of aircraft fleet, operations, and performance data, as well as the modules to process the information and perform computations. The model reports information both on a vertical and horizontal distribution.

The SAGE model was last updated in September 2005. The model's primary purpose is to provide FAA and, indirectly, the international aviation community, with a tool to evaluate the effects of various policies, technology, and operational scenarios on aircraft fuel use and emissions. The current version of the model is not considered a standalone model; it is used primarily as an FAA research tool.

The information presented on SAGE is principally based on the analysis, review, and discussion of the *SAGE Version 1.5 Technical Manual,* (*161*) *SAGE: Validation Assessment, Model Assumptions, and Uncertainties,* (*162*) "System for assessing Aviation's Global Emissions (SAGE), Part 1: Model Description and Inventory Results," (*163*) and "System for Assessing Aviation's Global Emissions (SAGE), Part 2: Uncertainty Assessment." (*164*)

Summary of Strengths and Weaknesses. An analysis of the strengths and weaknesses of FAA's SAGE is included in Exhibit 3-64.

Analysis of Process Uncertainty. To estimate emissions, SAGE uses Boeing Fuel Flow Method 2 (BFFM2), which is a method developed based on engine performance and emissions data obtained from ground-level engine tests. BFFM2 uses ICAO certification fuel flow and emissions data taken at 7%, 30%, 85%, and 100% rated outputs at sea level pressure as the basis for correcting emissions indices for installation effects, ambient conditions, and flight speed. At the four certification points, BFFM2 provides an agreement between measured and calculated emissions indices that is within ±10% for most jet engine types. Increased uncertainty occurs in estimating idle emissions below 7%, particularly for HC, and these errors may be large and tend to be an underprediction. (*165*)

The interpolation method (curve fitting), used between certification emission portions, is another source of uncertainty. A comparison undertaken by ICAO found agreement between direct measurement and fuel flow correlations using curve-fitted ICAO data to within a standard deviation of 6% and a maximum error of 13%. (*166*) Other sources of uncertainty in most emissions data, including certification data, consist of the variability in emissions inherent among engines in the fleet and aging of the engine. (*11, 165, 167*)

Overall the emission indices for NO_x have been estimated to have a standard deviation for an approximate normal distribution of ±24% based on the aggregation of 16% uncertainty incorporated in the engine certification process, adding (using sum of squares) the uncertainty in curve fitting and BFFM2 (6% and 10%, respectively) and then accounting for the bias error due to aircraft engine degradation (4%). (*11*) The uncertainties implied in the certification process for HC and CO emission indices are 54% and ±23%, respectively, and also have been aggregated with those of curve fitting and BFFM2 with a resulting estimated standard deviation in the uncertainty of ±55% HC and ±26% for CO. However, these estimated uncertainties need to be confirmed by comparing SAGE emissions results to measured emissions over a wide range of emission points, power settings, and engine types that are not readily available at present.

Below the mixing height (i.e., around 3,000 ft) where aircraft emissions have the greatest impact on local air quality, the landing and takeoff (LTO) procedures are an important source of uncertainty. LTO procedures mainly consist of engine throttle setting, rate of climb/descent, and flight speed. The analysis of a major carrier's computer flight data recorder results showed that the throttle setting and resulting change in the emission index for NO_x, HC, and CO were the most important parameters, accounting for 30% to as much as 70% of the total variance of the emissions. Other LTO procedures such as the rate of climb, descent plus flight speed, and aerodynamic drag explained most of the remaining variance in the emissions estimates below 3,000 ft.

Finally, although individual uncertainties for specific aircraft may be large, it is likely that the current version of SAGE can distinguish between the emissions associated with the typical policy options that are directed across all aircraft and engine types. However, it would be important to analyze the uncertainties and account for them when interpreting any type of policy scenario analyses.

3.8.2 Evaluation of Local/Project-Level Models

Starting in the mid-1980s, the FAA developed the Emissions and Dispersion Modeling System (EDMS) to assess local air quality impacts in the near airport vicinity for a single airport. The current version of EDMS incorporates EPA-approved emissions inventory methodologies and dispersion models to ensure that analyses performed are consistent with EPA guidelines. EDMS is used primarily in complying with local

Exhibit 3-64. Analysis of strengths and weaknesses—FAA SAGE.

Criteria	Strengths	Weaknesses
Representation of physical processes	The model details actual flight path and trajectories with flight-by-flight modeling. SAGE includes specific aircraft fleet information and operations, combined with the use of engine performance data. Such detailed modeling represents an improvement in accuracy over other methods based on aggregated TIMs or simplified performance lookup tables.	The model only includes emissions from commercial aircraft—no general aviation or military flights. Studies have suggested that military aviation in the U.S. is responsible for up to 15% of aircraft emissions. Requires an extensive database to make the emission calculations. Relies on emissions indices as a function of fuel consumption to estimate emissions.
Model sensitivity to input parameters	No formal sensitivity analysis has been conducted with the model but the model is highly dependent upon the emission indices, which are a function of the fuel burn which, in turn, are sensitive to aerodynamic and engine performance, aircraft take-off weight, and flight speed. Individual flights not using winds aloft information also use standard day ambient temperature. The fuel burn rate is based on engine performance and emissions data obtained from ground-level, full-scale engine tests. These are the ICAO certification fuel flow and emissions data taken at 7%, 30%, 85%, and 100% rated outputs at sea level with corrections for installation effects, ambient conditions, and flight speed. NO_x emission indices are the best developed, having been created for a broad range of engine types, and power settings and measured fuel flow rates.	Lack of a model-specific sensitivity analysis makes it difficult to quantify the model's sensitivity. Emission indices are best developed for NO_x, followed by HC, CO, and water vapor.
Ability to incorporate effects of emission reduction strategies	This design of SAGE allows a user to quantify the effects of communication, navigation, and surveillance/air traffic management (CNS/ATM) initiatives, determine the benefits of reduced vertical separation minimum (RVSM), investigate trajectory optimizations, and compute potential emissions benefits from the use of a continuous descent approach (CDA).	Requires detailed knowledge of the model databases and can only be performed by FAA or their supporting organizations.
Representation of future emissions	The forecasting module uses flight forecasts from the FAA's Terminal Area Forecast (TAF) for U.S. flights and ICAO's Forecasting and Economics Sub Group (FESG) for the rest of the world. The TAF method involves creating a week's worth of official airline guide scheduled flights to represent the growth in demand for a future year. The week was a balance between accuracy and computational efficiency. Also included are the effects of aircraft retirements and replacements. The result is a future schedule of flights reflecting the effects of fleet growth and retirements with replacements	The forecast is created from airport-based projections. Model can be updated through database for new aircraft and engines but it has been almost 4 years since last public update.
Data quality	Use of radar-based flight trajectories and speed are highly accurate in most cases. Although specific flights may be in error by up to 40%, average fleet emissions showed less than 10% error.	The most important default assumptions in determining the modeled emission rates are the use of the International Standard Atmosphere temperature, not correcting for winds aloft, use of Base of Aircraft Data (BADA) aerodynamic performance, and aircraft take-off weight and flight speed. Other important concerns are the OAG-based flight trajectories and the use of the Boeing Fuel Flow method to estimate the emission indices.
Separation of air cargo from passenger travel	In general, commercial aircraft fly the same airframe design and engine technology whether the intended load is passengers or air freight. For airports that can separate aircraft operations performed exclusively for air freight transport, the current version of SAGE can be used to assess air freight emissions.	The model does not have a method for separating air cargo from passenger transport activity, nor does the approach separately identify those aircraft used exclusively for air cargo transport.
Spatial variability	The model's accuracy for spatial representativeness is directly tied to the quality of the TAF and FESG databases. It is anticipated that the accuracy of results from the model is dependant upon the depth of activity and load information in these databases. Vertical distributions are anticipated to be more accurate because of the use of actual flight path and trajectories with flight-by-flight modeling.	Most aircraft activity is in the U.S. and Europe, although substantial growth is projected over Asia.
Greenhouse gas emissions	Unlike criteria pollutants, the locations of emissions are irrelevant, but all of the emissions from aircraft need to be determined. The Intergovernmental Panel on Climate Change (IPCC) protocol recommends that each flight's emissions be attributed to the departure airport. Also, the IPCC prefers that the method be based on aircraft performance and operating data rather than fuel sales. This is the approach employed in SAGE for CO_2 emissions using extensive information on aircraft fleet, flight schedules, trajectories, and aircraft performance. Based on results from applying SAGE, FAA is expected to begin releasing these results publicly in the near future for airport operators to use in determining GHG emissions. This information would be reported as fuel burned and CO_2 emissions for ground level (taxi/idle mode), above ground to below 3,000 ft (takeoff, climb-out, and approach modes), and above 3,000 ft (reflecting cruise).	The fuel consumption data must be used with generic emissions factors for jet fuel to calculate emissions of CH_4 and N_2O. The FAA SAGE dataset will not include future emission projections. Emission rates are not separated into cargo and passenger modes.
Review process	Review process has been limited to peer review publications of model results and meeting presentation on findings and methodology.	Only user guide documentation available, code and databases are not publicly available. This limits full and open comparison. The large database sizes have limited the model's distribution. The model has been made available to support various International Civil Aviation Organization/Committee on Aviation Environmental Protection (ICAO/CAEP) activities but with FAA running the model.
Endorsements	FAA recommends that the model may be used in developing policy, technology, and operational scenarios on aircraft fuel use and emissions.	Neither ICAO nor EPA have made statements about the model. FAA continues to support the model, but it has been almost 4 years since the last public update to the model.
Model comparison/evaluation studies	Comparison with research-oriented methodologies such as the NASA/Boeing scheduled inventory and SAGE totals show a 30% difference, which may partly be explained through differences in trajectory modeling (Great Circle used by NASA/Boeing versus track distributions used in SAGE) and the inclusion of unscheduled flights in SAGE (unaccounted for in NASA/Boeing studies). However, estimates for any given flight may be off by ±50% or more. An assessment of the aircraft performance module showed that when comparing point-by-point fuel flows from SAGE against data from a major U.S. airline and NASA, the overall agreement was good with mean errors of 6.95% and 0.24%, respectively. Similarly, system-level (aggregated flight-level) comparisons of fuel burn against data from one major U.S. airline and two major Japanese airlines also showed good agreement with mean errors of 2.62% and 0.42%, respectively	Lack of a public availability of the model has hampered external review by outside agencies and the international community.

air quality requirements (e.g., NEPA documents, EIS/EIR, air toxic risk assessments, and general conformity). The model uses a comprehensive database of aircraft engines and emission factors in different modes, ground support equipment, auxiliary power units, and vehicular and stationary source emission factor data. The model includes emissions for CO_2, CO, THC, NMHC, NO_x, SO_x, $PM_{2.5}$, PM_{10}, and 395 speciated hydrocarbons for use in air toxic assessments. The CO_2 emissions are calculated only for aircraft. Aircraft PM emissions are only available for aircraft with ICAO-certified engines. The model offers two approaches for estimating emissions: one based on an ICAO EPA TIM approach and another that uses an aircraft performance module that dynamically models the flight of an individual aircraft based on its flight profile. The air quality dispersion analysis uses EPA's AERMOD dispersion modeling system. Concentrations of the pollutants are output for comparison with the NAAQS. The model does allow the specification of user-created aircraft modes when operated with the aircraft performance module in which specifications can be made for cargo-only aircraft. However, the model does not determine the freight fraction for aircraft that move both cargo and passengers. The model has no future forecasting capabilities. (*168*)

The model is driven primarily by a set of databases that are used to develop the emission inventory. The key databases include the following:

- ICAO emissions databank containing information on certification emissions, default TIM, and fuel flow rates for a wide variety of jet engines that have entered service.
- Aircraft performance-based database using system aircraft-engine (SAE AIR 1845) TIM as an alternative to the ICAO emissions databank. These data were developed for, and adapted from, the Integrated Noise Model (INM). EUROCONTROL Base of Aircraft Data [BADA] is used in the aircraft performance modeling. (*169*)
- Various ground support equipment emission factors for use in EDMS are based on EPA's NONROAD2005 model using the fuel type, brake horsepower, and load factor variables. In addition, a deterioration factor is applied based on the age of the engine. A national default fleet average age may be used for a particular equipment type or a facility-specific age of an individual piece of equipment may be specified.
- Motor vehicle activity can be incorporated into the model using information on the number of vehicle trips and average speed while traveling on roadways with emission factors based on EPA's MOBILE 6.2. National default age distribution can use a base year assignment up to 2025.

Model Overview

The EDMS is both an emissions inventory development model and an air dispersion model. It is used to assess air quality impacts in the near airport vicinity by developing an emission inventory from the emissions from aircraft, auxiliary power units, ground support equipment, and stationary sources. Emissions are developed based on a combination of EPA models and best-available models from other sources such as an aircraft performance module for calculating aircraft emissions, on-road (MOBILE6.2) and off-road vehicles (NONROAD2005). EDMS has an extensive database with information from engine manufacturers, FAA, and EPA on the aircraft flight performance arrivals (approach and taxi-idle) and departures (takeoff and climb out). This information is indexed by aircraft types, which is cross-referenced with nominal takeoff weight and glide slope angle. The dispersion-modeling module uses EPA's AERMOD (version 07026) and its supporting weather and terrain processors to determine air concentrations. EDMS offers the flexibility of allowing the user to perform an emissions inventory only or to perform air dispersion modeling as well. Results are reported as ground-level concentrations. (*170*)

EDMS was last updated in September 2008 (version 5.1). EDMS is used primarily to assess the local air quality impact in the vicinity of individual airports as part of an environmental impact assessment under NEPA or general conformity requirements. Recent integration efforts are underway to integrate EDMS as part of an Aviation Environmental Design Tool (AEDT) that will result in the ability to model noise and emissions interdependencies in the same modeling platform. A research version of EDMS, funded by FAA and NASA, is underway to develop a 3D representation of aviation emissions at the regional scale, coupled with a regional-scale air quality model (i.e., community multiscale air quality [CMAQ] model) to assess air quality impacts for regional-scale air pollutants of fine particulate matter, ozone, and air toxics.

The primary information on EDMS comes from the analysis, review, and discussion of the EDMS 5.1 *User's Manual* (*171*) and the EDMS 4.2 *Technical Manual.* (*172*)

Summary of Strengths and Weaknesses. An analysis of the strengths and weaknesses of EDMS is provided in Exhibit 3-65.

Analysis of Process Uncertainty. Ideally, a comprehensive validation of the EDMS model would be conducted using field data to scientifically determine the accuracy of the model and ensure the model results are defensible. This effort would include a multi-year measurement plan and analysis following EPA protocols so that EDMS could be fully evaluated using several detailed steps as follows:

1. Identification and collection of previously collected field data that potentially could be used in validation,
2. Assessment of the quality/applicability of collected data,

Exhibit 3-65. Analysis of strengths and weaknesses—FAA EDMS.

Criteria	Strengths	Weaknesses
Representation of physical processes	The model details aircraft activity based on dynamic aircraft performance-based modeling. The model includes operational profiles in 15-minute bins of aircraft delay and sequencing.	Model only examines primary emissions; does not allocate aircraft emissions in a full 3D environment.
Model sensitivity to input parameters	Aircraft emissions in EDMS are dependent upon two main parameters: the emission factors obtained from the aircraft/engine combination and the vertical flight profile. Within the flight profile the least well-established parameter is the TIM.	FAA has announced plans to conduct a robust sensitivity analysis on EDMS, but has not published results from any studies to date. This is because the EDMS system has undergone a tremendous number of changes over the past 6 years with the release of 2 major changes (EDMS 4 and EDMS 5) and 6 extensive model changes.
Ability to incorporate effects of emission reduction strategies	By providing user-specified aircraft emission factors and performance data, emission reductions for aircraft engines can be assessed.	No capabilities for testing operational changes such as aircraft approach and descent changes.
Representation of future emissions	The model has the capability for assessing future emission changes for on-road and nonroad vehicles. The Voluntary Airport Low Emissions (VALE) Program can be evaluated for selected airports.	Lacks a capability for assessing aircraft emission reductions. Latest version of NONROAD model is now NONROAD2008. Similarly, MOVES is to be released in 2009 and current version of EDMS incorporates MOBILE6.2.
Data quality	Comparison tests with other local-scale airport models suggest overall emission strength is reasonable, but that a large variability exists in aircraft grouping, TIMs, and emission factors.	Large variability exists for the TIM between aircraft grouping (e.g., business jet vs. small jet) and TIM default varies widely from airport to airport. Also, emission factors vary widely from one grouping to another.
Separation of air cargo from passenger travel	The model allows the specification of user-created aircraft modes when operated with the aircraft performance module in which specifications can be made for usage as cargo-only aircraft.	The model does not determine freight fraction for aircraft that move both cargo and passengers.
Spatial variability	User specifies horizontal locations of emissions. Vertical profiles in 2D are specified for the aircraft approach and takeoff grids from which the emissions are released.	Does not represent aircraft emissions on a full 3D grid.
Greenhouse gas emissions	Includes CO_2 emissions for aircraft only. Uses same approach as criteria pollutants. Emissions reporting can be reported by aircraft mode.	No emission estimates for N_2O or CH_4. Emission rates are not separated into air cargo and passenger modes.
Review process	Validation and uncertainty studies have not been made publicly available to date. Although, FAA has announced plans to actively pursue a better understanding of the uncertainties of the modeling components for the new Aviation Environmental Design Tool (AEDT)/EDMS with plans for formal parametric sensitivity and uncertainty analyses.	No external peer review has been performed although DOT's Volpe Center reports that a program is underway for modeling validation and uncertainty assessment. FAA continues efforts to improve model but moving towards development of AEDT. Source code not publicly available. Technical User Guide was last released with version 4.2 of EDMS now at version 5.1. Executable of model available but requires licensing with EUROCONTROL Base Aircraft Data.
Endorsements	FAA requires that EDMS be used in air quality impacts of airport emission sources for purposes of complying with NEPA and general conformity. In addition, FAA and EPA have co-written a recommended best practice document with an accompanying technical support document for issuance by each agency scheduled for the summer of 2009.	Only *User's Manual* and *Technical Manual* available. To date, little documentation and/or model verification testing has been reported or made publicly available. FAA has plans to improve this as they move toward release of AEDT in December 2011.
Model comparison/evaluation studies	Intercomparison of three different local airport emission inventory tools—ALAQ, LASPORT, and EDMS—showed that all models have similar global results for aircraft, but that aircraft emissions were dependent mainly on the engine emission factors and climb-out profiles. (*160*)	Limited comparison or model validation has occurred by outside agencies or from the international community. Lack of a performance evaluation dataset has hampered this type of evaluation.

3. Collection of additional field-measured data,
4. Rigorous exercising of EDMS for comparison with collected data, and
5. Comparison of EDMS performance with that of other similar models (e.g., the ADMS-Urban or Eurocontrol's ALAQ).

The results of this effort would be used to identify EDMS limitations, correct major deficiencies, as well as determine the overall accuracy and sensitivity of EDMS. However, current FAA priorities are focused on the development and evaluation of ADET, the replacement model for EDMS. FAA's priority is that this model has a complete and informed process analysis so that a comprehensive understanding of the model's uncertainty, inputs, and assumptions is developed. As part of the development of AEDT, FAA plans to conduct a formal parametric sensitivity and uncertainty analysis. This analysis would be completed on individual components of AEDT as well as on the whole tool. The analysis would consist of quantifying uncertainties of AEDT and rank ordering of the most important assumptions and limitations. Gaps in functionality potentially would be identified that significantly impact AEDT, leading to the identification of priority areas for further research and development. In addition, the evaluation would examine the modeling factors that contribute to model output uncertainty.

3.8.3 Freight Disaggregation

EDMS does not distinguish between freight and passenger movements. To solve this problem, the study team developed an approach to allocate each airport's total commercial aircraft emissions to the freight and non-freight sectors. (*67*) For each airport of interest, the team used the BTS Air Carrier Statistics Database to obtain aircraft departure records with the following data fields:

- Carrier,
- Origin,
- Number of departures performed,
- Tonnage of freight, tonnage of mail,
- Number of passengers,
- Seating capacity, and
- Payload.

Using this database, it is possible to estimate the number of aircraft departures attributable to freight transport and the number attributable to passenger transport, then to use the freight fraction to split each airport's aircraft emission total into a freight and non-freight component. This allocation process can be summarized as follows:

- Air cargo aircraft
  - Aircraft departures that do not have any passengers or seats but have payload capacity of 18,000 lbs or larger are assumed to be air cargo commercial aircraft. This definition is consistent with that used by FAA for categorizing the aircraft type when reporting emissions.
  - Aircraft departures for which no freight tonnage and no passengers are reported are assumed to be non-freight (passenger) movements if departure was reported as having a seating capacity greater than zero, otherwise it was assumed to be a freight movement.
- Passenger aircraft
  - For flights with passengers, it is assumed the flight is a commercial flight if the plane has 60 or more seats. This definition is consistent with that used by FAA for reporting aircraft emissions.
  - For those aircraft that are commercial and that carry both freight and passengers, the number of departures is allocated to freight activity and non-freight activity based on weight fractions. The freight weight fraction is the combined weight of the freight plus mail divided by the sum of all weight—passengers, mail, and freight (average passenger weight of 240 lbs was used based on a March 21, 2003 FAA-sponsored weight survey of more than 6,000 passengers that included an average adult passenger weight of 196 lbs, 16 lbs of carry-on items, and 29 lbs of checked baggage). Similarly, the passenger weight fraction is the weight of all passengers divided by the sum of all weight. These fractions are then multiplied by the number of departures for each record.
  - The weighted freight and non-freight departures are summed for all flights departing from the airport in 2002, using the ratio of freight departures to total departures to apportion the airport's emission total to a freight component. This approach assumes that all departures have a corresponding arrival, so the freight departure fraction is equivalent to the freight LTO fraction.

3.9 Air Quality

Air quality refers to the level of contaminants in ambient air. It is either determined through measurement techniques and/or estimated through applications of models—numerical techniques to predict ambient levels of pollutants from atmospheric releases. Most air quality impacts from goods movement activities are assessed either by modeling studies alone or coupled with measurements. This section discusses air quality modeling assessments and associated uncertainties.

3.9.1 Summary of Methods and Models

To characterize ambient concentrations, all air quality models require some level of input information for meteorology (e.g., winds, stability, atmospheric structure) and source information (e.g., emission rate, stack height, initial plume size, temporal profile). Numerous other inputs may be required, depending on the complexity of the model and application.

Most commonly applied air quality model formulations are deterministic and include Gaussian plume, puff, and box models. These models approximate the physical (e.g., transport, dispersion, and removal) and chemical (e.g., scavenging, secondary formation) processes that operate on pollutants released into the atmosphere. These models work by parameterizing the controlling processes that occur at emission source(s) and between the source(s) and receptor(s) at discrete time steps. Other special modeling cases include approaches based on computational fluid dynamics (CFD)—used particularly to characterize source-induced and downwind turbulence effects on the flow, and stochastic approaches that approximate air quality distributions from data sets of controlling variables—including regression, Monte-Carlo, and extreme-value theory-based approaches, (*173*) as well as those that incorporate stochastic properties in a deterministic setting such as combined puff-particle models (e.g., Puff-Particle Model inclusions in CALPUFF). (*174*)

EPA (*175*) distinguishes air quality models into the following three categories:

- Dispersion models typically are used for small spatial scales and to estimate impacts from individual source(s). These models contain either no or limited chemistry and may be plume or puff formulations. EPA recommended/guideline dispersion models include the following:
  - AERMOD and
  - CALPUFF.
  - Other specialized preferred/recommended models in this category include
    - BLP,
    - CALINE3,
    - CAL3QHC(R),

    - CTDMPLUS, and
    - OCD.
  - Other models in this category include
    - ADAM,
    - ADMS-3,
    - AFTOX,
    - ASPEN,
    - Canyon-Plume-Box Model (not a regulatory model but a research-grade FHWA model to demonstrate nonlinear effects of vortex separation and resulting dispersion from roads within cut sections),
    - EDMS,
    - HOTMAC/RAPTAD,
    - HYROAD,
    - ISC3 (ISC-PRIME),
    - Panache,
    - PLUVUEII,
    - SCIPUFF, and
    - SDM.
- Photochemical grid models typically are used to assess cumulative impacts or interactions of a range of sources over large spatial scales. These are box models but typically also contain plume or puff formulations. This group of models includes the following:
  - Community Multiscale Air Quality (CMAQ),
  - Comprehensive Air quality Model with extensions (CAMx), and
  - Regional Modeling System for Aerosols and Deposition (REMSAD).
- Receptor Models that relate observed concentrations to source types and contributions.

The focus of this analysis is not a review of the models commonly used to estimate the ambient concentrations associated with goods movement, but rather the methodologies and inputs used by these models. That is, how the emission outputs discussed in Sections 3.2 to 3.8 are used to predict downwind pollutant concentrations. As such, this section does not review the uncertainties in any given model or the uncertainties in any other parameter input to these models. The focus here is only on the emissions-relevant model parameters and processes and does not include other necessary model inputs (such as meteorological data, surface and terrain characteristics, biogenic or coincidental emissions data, chemical schema, etc.).

Generally, one of two methods will be employed in air quality modeling, depending on the domain size, the physical and chemical processes to be included, and the desired output resolution. Note that there is significant overlap between these criteria. The two methods we consider here are grid modeling for national and regional scales (typically applied to citywide and larger analyses) and dispersion modeling for local/project scales (facility to citywide analyses). Note that at some scales, either method could be appropriate. Exhibit 3-66 shows these methods.

3.9.2 Evaluation of National and Regional Methods and Models

National or regional simulations of air quality will most likely be made with a photochemical grid model. In many cases, these are limited in time to episodic simulations, although annual or even multi-annual simulations are capable in some models. In all cases, input preparation and model executions are resource intensive.

Photochemical Grid Model Methodology

Photochemical grid models (PGMs) rely on gridded model domains and simulate all processes that influence concentration (chemistry, diffusion, advection) in each grid cell during a time step. However, this approach is physically limited for small spatial scale applications due to artificial dilution of emissions, unrealistic near-source concentrations, and spatially unresolved receptors for sizes smaller than an individual grid cell. Most current models allow for plume in grid (PiG) or other subgrid scale treatment of gas, aqueous, and aerosol chemistry, at least for major or elevated point sources. Other parameters are (horizontally) resolved only at the grid-cell level (typically 2 km to 36 km), including emissions and meteorology. Some

Exhibit 3-66. Air quality modeling methods.

Method/Model	Type	Geographic Scale	Pollutants	Freight/Passenger
Grid modeling methodology	Method	National and regional	Primary and secondary criteria, toxics	All*
Dispersion modeling methodology	Method	Local/project	Primary criteria and toxics**	Both

* Typically requires simulation of all sources, but specialized techniques may be used to identify impacts from individual elements.
** Some limited chemistry may be included for primary reactions and secondary species.

current models extend subgrid cell treatment to nonpoint sources, such as resolution of individual roads and receptors within a grid cell, such as the use of PiG for near roadway concentrations of mobile source air toxics (MSATs). (*176–177*) This formulation highly parallels that of the dispersion modeling methodology discussed in the following section, but offers the additional ability of full chemistry simulations. It is, however, highly computationally expensive.

Inputs to PGMs are typically in the form of detailed input files describing the emissions, meteorology, initial and boundary conditions, underlying surface geographical and topological characteristics, appropriate chemical reactions and rates, as well as domain and simulation period. Each of these must be derived from other sources by a series of typically complex processes and carries inherent uncertainty. For example, meteorological inputs are commonly derived from a diagnostic application of a different model that simulates the meteorological environment during the period. As discussed, however, the only uncertainty in a photochemical grid modeling methodology related to goods movement activities is that of the emissions parameters.

Emissions Parameters. Emission parameters are typically detailed for the PGMs using emissions input files. These describe both low-level and elevated emissions. Low-level emissions are those released within the lowest atmospheric layer (surface layer—typically tens of meters), and are comprised of area, mobile, low-level point, and biogenic sources. Area sources are representations of groups of point sources that are either spatially distributed or poorly spatially characterized, but collectively important. They include, for example, various industrial and agricultural processes, dry cleaners, etc. Elevated emissions include releases from tall point sources, such as power plant stacks. Emission inputs are generally prepared for PGMs using external tools, such as SMOKE or EPS.

Goods movement activities are included in PGMs either as mobile (e.g., trucking) or area (e.g., cargo handling equipment) sources. In air quality modeling, the strength, location, and profile of emissions are all influential. Because goods movement emission inventories, such as those described previously, are typically annual totals, temporal profiles must be assigned. This may be an additional source of uncertainty. The spatial distribution of mobile and area sources is not typically critical within a given grid cell, since that is the minimum resolution of PGMs in most contexts. However, uncertainty in locations that lead to source placement across cell borders may lead to biased predictions of concentration. This, too, is an additional source of uncertainty for emissions not characterized previously. Also, PGMs require simulation of all sources in the model domain for correct chemical analysis, not just those of a given project or those from freight transport. This additional burden may introduce uncertainties or lead to bias.

Total uncertainty in predicted concentrations from PGMs is due to uncertainty in the emission inputs as well as the uncertainties in all other inputs (meteorology, chemistry, model formulation, etc.) and model formulations. This value is generally unquantifiable. It is possible, however, to characterize the sensitivity of predicted concentrations to the representation of emissions, particularly emission strength. Because PGMs involve nonlinear processes, this is typically done numerically by performing multiple PGM simulations of varying emission levels while other parameters are kept fixed to estimate the relative change about a default state (linear error term). However, this sensitivity would be context specific and, in general, could not be generalized to overall model sensitivity (or uncertainty).

Summary of Strengths and Weaknesses. Strengths and weaknesses of the photochemical grid modeling methodology are summarized in Exhibit 3-67.

3.9.3 Evaluation of Local/Project-Level Methods and Models

Evaluation of the impacts of emissions from project-specific scale applications, such as individual ports, intramodal yards, freeways, or intersections, are typically done with a dispersion modeling method.

Dispersion Modeling Methodology

Dispersion models simulate the effects of atmospheric turbulence, mixing depth, and wind flow that drives the advection and diffusion of pollutants following their release into the atmosphere. Dispersion models simulate these processes as either a straight line Gaussian plume or as an advecting puff. Both formulations have advantages and disadvantages.

Most Gaussian plume models—including AERMOD, which is the EPA's preferred model for near-field regulatory applications—have either no or highly simplified chemistry. Furthermore, guideline models such as AERMOD were designed to predict peak concentration distributions, not to accurately assess temporally and spatially varying concentrations. (*178*) Although skill is being improved, the limitations of these model formulations (i.e., assessing source contributions to all receptors at each simulated hour) must be considered. These models are relatively straightforward, however, and have shown reasonable predictive skill in their operating range (50 km for AERMOD). (*179*) They also have several advanced or specialized treatments that make their application for specific projects advantageous. For example, AERMOD has state-of-the-science boundary layer physics, plume rise, deposition, and building downwash methods. (*180*) The CALINE series of models is designed to characterize

Exhibit 3-67. Summary of strengths and weaknesses—photochemical grid modeling methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Complex physical and chemical processes parameterized	Limited to model spatial (and temporal) resolution
Sensitivity to input parameters	A number of parameters may affect model results	Highly susceptible to uncertain, complex inputs
Flexibility		
Ability to incorporate effects of emission reduction strategies	Yields most realistic air quality impacts since model explicitly treats nearly all of the important chemical and dispersion processes	Indirect: incorporated via emission characterization
Representation of future emissions	Incorporated via emission characterization.	
Consideration of alternative vehicle/fuel technologies		Indirect: incorporated via emission characterization
Data quality	Models are typically verified against observed data for some air pollutants, lending confidence to other air concentration predictions	Relies on numerous inputs of varying quality and uncertainty
Spatial variability		Generally limited to grid cell resolution (typically 2 km or more)
Temporal variability	Current concentration is a function of all of the previous hour's emissions	Generally limited to hourly time steps
Review process	Models and methods have undergone continuous revisions since the 1970s.	
Endorsements	EPA and other federal, state, and local agencies	

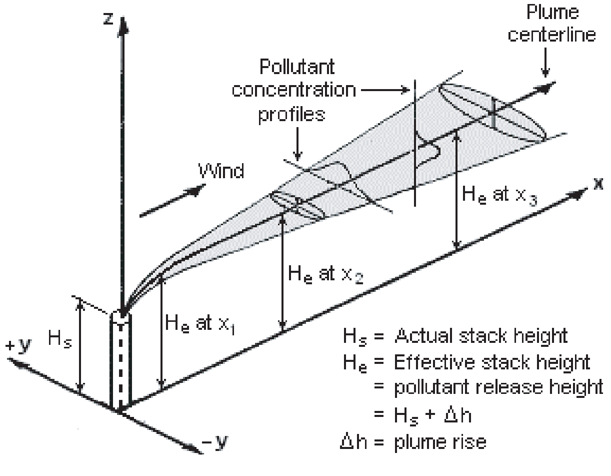
enhanced turbulence from vehicle motions and hot-exhaust rise near the emission sources on roadways. (*181*) The OCD model is designed to simulate pollutants on-shore after being dispersed in the over-water boundary layer. (*182*) Gaussian plume models are relatively straightforward to apply, however, these models cannot predict more complex impacts from air circulation, stagnation, or other non-steady-state conditions. Exhibit 3-68 shows a schematic illustration of Gaussian dispersion, and Equation 21 provides the general equation for Gaussian dispersion.

$$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\left\{\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\right\}\left\{\exp\left[-\frac{y^2}{2\sigma_z^2}\right]\right\} \quad \text{(Equation 21)}$$

Where

C is the concentration at point (x, y, z),
Q is the emission rate,
u is the wind speed,
σ_y and σ_z are the horizontal and vertical dispersion coefficients (at a downwind distance), and
h is the effective stack height.

Exhibit 3-68. Gaussian dispersion.



Source: http://upload.wikimedia.org/wikipedia/commons/1/10/Gaussian_Plume.png

Advecting puff models, such as CALPUFF, simulate noncontinuous plumes. CALPUFF is a non-steady-state Lagrangian puff model that can include the effects of a three-dimensional wind field on the puff as it migrates through complex terrain. CALPUFF is EPA's preferred model for long-range transport applications (greater than 50 km, and primarily for Class I increment studies) or for near field applications involving complex winds, although complete verification of current versions is still being undertaken by EPA. (*183*) In these models, a "puff" of pollutants is followed from emission source, through the atmosphere, and to a receptor. During this transport, simple chemical changes, effects of wind shear, effects of terrain, and wind circulations are simulated. This allows the models to more completely parameterize atmospheric effects than simple straight-line, steady-state Gaussian models. However, the setup, execution, and model formulation are all more complex. In many circumstances, their performance is not sufficiently enhanced over Gaussian plume models to justify their use.

Emission Parameters. Although the atmospheric effects on pollutants are parameterized differently using the two types of dispersion models discussed in this section, the parameterization of emissions is similar. Most dispersion models treat emission sources as either point, area, volume, or line sources. In all cases, the locations of the emission releases do not change during simulations.

Point sources typically represent emissions from stationary stacks and are generally buoyant. They could be used to represent exhaust stacks of hotelling vessels, for example. Input parameters required include location, instantaneous or average emission rate, release height, exit temperature, exit velocity, and stack inside diameter (or flow rate). For stacks where building downwash is important, additional parameters also must be included to simulate these effects. Uncertainty in any of these parameters will lead to uncertainty in output concentrations. The relationship between most of these parameters and concentrations may be complex, due to interactions with input meteorology as formulated in the model. Concentration is linearly proportional to emission rate in all cases; standard propagation of uncertainty can be used to show uncertainty in concentration from a known emission uncertainty. Uncertainty due to other (nonlinear) parameters may be derived between a specific source and receptor due to propagation of uncertainty and Equation 21.

Line, area, and volume sources are one-, two-, and three-dimensional source types commonly used to describe emissions where the spatial distribution of emissions within a particular boundary is not fully known (e.g., an industrial complex) or within which the emissions occur more or less uniformly (e.g., a freeway link). Their governing equations are a variation on the equation for point sources found in Equation 21. Area and volume sources may be non-buoyant (AERMOD) or buoyant (CALPUFF, area sources only). Further, some models do not contain the ability to model line sources explicitly (e.g. AERMOD); instead, modeling sources such as roads, rail lines, or shipping channels may be achieved by assembling adjacent groups of volume or area sources. Emission inputs for these source types include emission rate, location, orientation, release height, and initial plume size (lateral and vertical dimensions). If buoyancy is considered, exit temperature must also be included. As for point sources, uncertainty in any of these parameters will lead to uncertainty in output concentrations.

Here, too, the relationships between most of these parameters and concentrations are complex, except for the linear relationship between concentration and emission rate. If uncertainty in any input parameter is known, standard propagation of uncertainty can be used to show uncertainty in concentration. Commonly, uncertainty is not known, especially for methodological or choice issues to fit model requirements. For example, when modeling freight emissions from HDVs, some line source models (e.g., CALINE) may only require a single release height for both light- and heavy-duty vehicles. Selection of an appropriate value is sometimes discussed in modeling guidance documents.

Total uncertainty in predicted concentrations from goods movement represented using a dispersion methodology is due to uncertainty in the emission input parameters, uncertainties in all other input parameters (e.g., meteorology), as well as uncertainties in methodology (e.g., model formulation and choice). This value is generally unquantifiable without comparison to observed concentrations. Those uncertainties due to calculated emission rate, however, may be characterized directly from the input uncertainty. Other emission parameters due to the methodology by which the emitting process is represented—such as spatial scale of activity—generally can not be characterized, but could be assessed for any particular scenario.

Summary of Strengths and Weaknesses. Strengths and weaknesses of the dispersion modeling methodology are summarized in Exhibit 3-69.

3.9.4 Evaluation of Parameters

Exhibit 3-70 summarizes all emissions-related parameters relevant for calculating concentrations from goods movement activities. Each of these has been discussed. Other parameters, such as initial and boundary chemical conditions, meteorology, and selection of appropriate models and methods, are not included here.

Pedigree Matrix. Exhibit 3-71 shows the pedigree matrix for the seven general parameters that relate goods movement emissions to pollutant concentration through the use of air quality modeling methodologies. Criteria to assign scores in the pedigree matrix are included in Appendix A. Note that all entries here are ranked as "5" for "Range of Variation." This is because the variation in the variation of values between methods, models, and applications is wide, which is also considered a "5." See documentation in Appendix A for further explanation.

Exhibit 3-69. Summary of strengths and weaknesses—dispersion modeling methodology.

Criteria	Strengths	Weaknesses
Representation of physical processes	Dominant processes generally parameterized, as long as operated within model limitations (e.g., spatial scale)	Model formulations are generally simplistic
Sensitivity to input parameters	Generally rely on readily available inputs	Susceptible to uncertain inputs
Flexibility	Generally adaptable to a variety of scenarios and available information	Gaussian plume models operate on an underlying assumption of a steady-state
Ability to incorporate effects of emission reduction strategies		Indirect: incorporated via emission characterization
Representation of future emissions	Indirect: incorporated via emission characterization	
Consideration of alternative vehicle/fuel technologies		Indirect: incorporated via emission characterization
Data quality		Varies: relies on input data quality and model formulations; is particularly susceptible to inappropriate model choice or input variables
Spatial variability	Can model concentrations in close proximity to source and with arbitrarily high spatial resolution	Gaussian plume model formulations may not represent variability well in complex terrain or wind flow regimes
Temporal variability	Limited only by input data resolution	
Review process	Models and methods continuously updated and expanded.	Result is model-specific
Endorsements	EPA and other federal, state, and local agencies	Result is model-specific

Emission Rate. Concentrations are always directly proportional to emissions. Uncertainty in characterizing the total emissions from any given source (and from all modeled sources, if chemistry is included) leads directly to uncertainty in concentrations. In this case, emission rate refers to the emissions, usually in grams/second, emitted by a given source at a given time, which is usually determined from the (annual) emission inventory and the emission temporal profile. The relationship of concentration to emissions becomes more complicated as the modeling becomes more complex, but accurate emission inventories for given sources are the keystone of reasonable model predictions. Uncertainty in emissions has been discussed in all previous sections.

Source Location. Uncertainty in geographic placement of sources leads to uncertainty in concentration at a given receptor site due to the uncertainty in transit distance between the two locations. In plume or puff modeling, this distance allows the pollutants to be more (less) diffuse and have greater (less) time for chemical transformation reactions, settling,

Exhibit 3-70. Parameters.

Parameter	Methods/Models	Geographic Scale	Pedigree Matrix	Qualitative Assessment	Quantitative Assessment
Emission rate	All	All	✓	✓	✗
Source location	All	All	✓	✓	✗
Emission temporal profile	All	All	✓	✓	✗
Release height	All	All	✓	✓	✗
Initial plume size and shape	All	All	✓	✓	✗
Source orientation, size, and shape	All	All	✓	✓	✗
Exhaust temperature and other buoyancy parameters	All (if plume rise is considered)	All	✓	✓	✗

Exhibit 3-71. Pedigree matrix—harbor craft equipment parameters.

Parameter	Impact on Result	Acquisition Method	Independence	Representativeness	Temporal Correlation	Geographic Correlation	Technological Correlation	Range of Variation
Emission rate	4	Varies	Varies	Varies	N/A	N/A	Varies	5
Source location	3	Varies	Varies	Varies	N/A	N/A	Varies	5
Emission temporal profile	3	Varies	Varies	Varies	N/A	N/A	Varies	5
Release height	3	Varies	Varies	Varies	N/A	N/A	Varies	5
Initial plume size and shape	3	Varies	Varies	Varies	N/A	N/A	Varies	5
Source orientation, size, and shape	2	Varies	Varies	Varies	N/A	N/A	Varies	5
Exhaust temperature and other buoyancy parameters	3	Varies	Varies	Varies	N/A	N/A	Varies	5

and other removal processes to act if the source is placed further (closer) to the receptor. In a grid modeling application, the locations of the sources (within the model resolution) are less important, as long as they are assigned to the correct grid cell. The general relationship between location and concentration is unquantifiable, but uncertainties in location will impact simulated concentrations and are likely to change the spatial distribution of concentrations.

Emission Temporal Profile. Concentration estimates are highly sensitive to the temporal profile imposed on the total, annual emission rate determined from an inventory of goods movement activities. The temporal profile assigns emissions to specific hours of the year where the model pairs them with corresponding meteorological and other parameters. If the diurnal, weekly, or other cycles are mischaracterized, the dispersion will be, too. Values of the profiles are often taken from published studies of activity of specific equipment types (*184*) based on SCCs. More accurate representation would require knowledge of activity profiles throughout the inventory period, which are often unavailable. The impact of emission temporal profile on total concentration uncertainty is not generally quantifiable, but may be determined for specific scenarios.

Release Height. Release height is the vertical component of source location. The relationship between release and receptor height, in combination with terrain, stability, initial dispersion, building downwash, and other parameters can greatly influence modeled concentrations. Because of these complex relationships, concentration uncertainty caused by uncertainty in release height can not generally be quantified.

Initial Plume Size and Shape. Dispersion generally increases plume/puff size, and therefore dilutes concentrations. Thus, the concentration observed at a particular receptor location will be due to both the processes acting on the pollutants after emission and on the initial state of the emissions. As the size and shape of the initial plume influences the downwind concentration at a given location, uncertainty in initial shape will lead to uncertainty in resulting concentrations. This uncertainty can be mitigated by following published modeling guidance and characterizing the sources in as realistic a method as possible.

Source Orientation, Size, and Shape. Particularly for nonpoint sources, the initial size, shape, and orientation of the source can dictate the dispersion characteristics. Orientation can change the size of the source relative to a given wind direction, and therefore influence the downwind concentration. Generally, the initial plume size is related to the source size; thus, the uncertainties discussed for initial plume size relate here, too.

Buoyancy Parameters. Buoyancy and rise of the emitted pollutants is related to the initial exhaust temperature relative to the ambient temperature and exhaust flow rate. This has an effect similar to raising the release height. Thus, uncertainties here propagate to concentration in a method similar to that discussed for release height.

CHAPTER 4

Conceptual Model

This chapter includes the development of a Conceptual Model for freight transportation activity as it relates to emissions calculations. The Conceptual Model offers a structure for comprehensive representation of freight activity in the United States, covering all modes and relationships between modes. In order for this model to be effective in improving emissions estimates, the Conceptual Model captures factors in freight movement and freight equipment that most influence emissions.

The Conceptual Model is a functional model, which includes the specifications of an information system in the form of functional areas, business processes, and information flows between them. The Conceptual Model does not include a formal data model, so it does not contain the description of all data elements that are necessary for all business processes. It does, however, identify the information needs from business processes.

The Conceptual Model serves several purposes, as follows:

- Estimates multimodal emissions associated with specific supply chains, transportation corridors, freight facilities, and geographic regions;
- Assists shippers, carriers, and logistics providers in incorporating emissions in the planning and operations of their logistics activities;
- Assists public agencies in incorporating emissions in the planning of transportation infrastructure, transportation investment decisions, and development of transportation regulations and/or voluntary programs;
- Identifies elements of freight activity that are not well represented by available data and methods;
- Identifies how new and emerging freight data and methods relate to existing data and methods, and how they can present a comprehensive picture of freight movement;
- Identifies opportunities to link modal-specific freight activity data and tools in a unified framework that spans multiple modes and possibly geographic and temporal dimensions;
- Identifies the major sources of potential errors in emission estimation parameters and the steps in emissions calculations that warrant improvement; and
- Tracks trends in freight emissions over time, and identifies which parameters were responsible for changes in emission outputs.

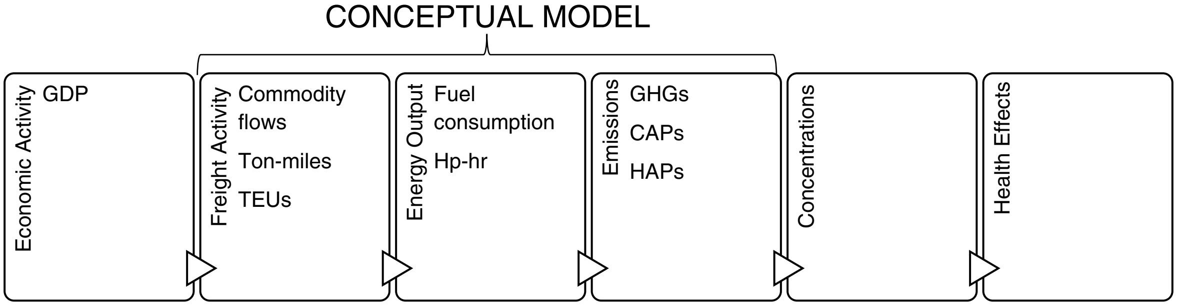
4.1 Model Overview and Uses

The Conceptual Model provides the link between economic activity, freight transportation activity, freight-related emissions, and associated health effects. The Conceptual Model uses commodity flows derived from economic activity forecasts to determine freight activity (Exhibit 4-1). Even though the Conceptual Model does not model dispersion of emissions or health effects, it provides the spatial and temporal allocation of emissions, which are necessary inputs for dispersion models and health risk assessments.

The Conceptual Model is based on a “link and node” transportation network. The link and node framework is the basis for representing roadway networks in travel demand models, and it is also regularly applied to other modes (e.g., rail). The link and node concept provides an effective way to link different modes in one supply chain and to represent the intermodal connections and freight transloading that are common in urban freight systems but poorly represented in current modal-specific analyses.

The Conceptual Model includes the definition of all functional areas and business processes necessary for the calculation, allocation, and evaluation of freight transportation-related emissions. Based on input parameters, the Conceptual Model includes a set of information flows (between business processes) that are needed to calculate freight transportation emissions. Some basic equations for emissions calculations are provided, but the Conceptual Model is not designed to replace existing emission models. Instead, it is designed to calculate and characterize transportation activity in such a way that it

Exhibit 4-1. Conceptual framework.

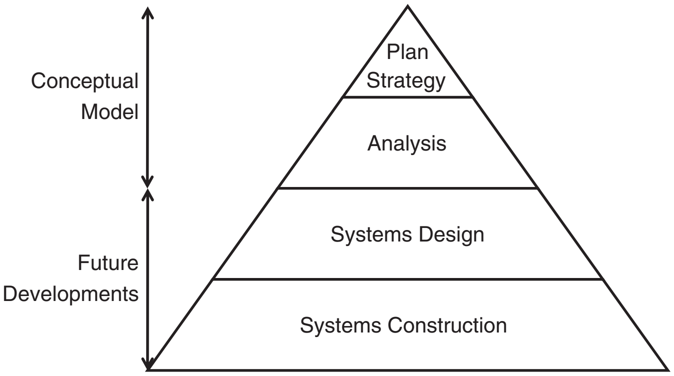


improves the accuracy of freight transportation emissions. The emission outputs are associated with either a product (or quantity of a given commodity), vehicle activity (e.g., VMT), freight activity (e.g., measured in ton-miles), link, node, or a geographic area. The Conceptual Model includes processes for the spatial and temporal allocation of emissions in order to support dispersion models and health risk assessments. Lastly, it includes processes for the evaluation of emissions, including scenario analysis and uncertainty analysis.

The broad nature of the assignment warrants the use of an established methodology to ensure that the Conceptual Model will lead to the development of an actual model in the future. Information engineering allows a hierarchical and structured analysis of a business area (i.e., freight transportation emissions), and uses simple but comprehensive modeling/diagrammatic techniques. There are four main phases in information engineering, typically depicted in a pyramid (Exhibit 4-2).

- Strategy planning is the phase that addresses how technology can be used to achieve specific goals such as creating new opportunities, creating a competitive advantage, or advancing environmental stewardship. Strategy planning creates a high-level overview of the information needs of the stakeholders and the system functional areas that will fulfill such needs. In this case, this entails a closer look at the information needs of the four main categories of stakeholders (private industry, transportation agencies, environmental regulatory agencies, and environmental organizations), which are addressed in Section 4.3.1. Based on these needs, five types of applications are created as discussed in Section 4.3.2 (global/national, freight corridor, metropolitan, facility, and supply chain). To fulfill the objectives of these five types of applications, six functional areas are discussed in Section 4.3.3 (transportation network design, planning of transportation services, execution of transportation operations, calculation of freight emissions, allocation of freight emissions, and evaluation of freight emissions).
- Analysis is the phase that examines the business processes needed to run a functional area, how these processes interrelate, and which input parameters are needed. Section 4.3.4 describes the business processes included in the Conceptual Model, and Section 4.3.5 provides a simplified process flow describing how information flows between processes.
- System Design is the phase that determines how selected processes in the selected business area are implemented in procedures and how these procedures work. This phase is outside the scope of this project.
- System Construction is the phase when the system is constructed with the assistance of programming tools and code generators, and coupled with system design tools. This phase is not included in the scope of this project.

Exhibit 4-2. Four phases of information engineering.



4.2 Freight Modeling

The design of the Conceptual Model must take into consideration current developments in freight modeling. As presented in *NCHRP Synthesis 364: Forecasting Metropolitan Commercial and Freight Travel,* (*185*) good freight models should incorporate the following attributes:

- **Ability to depict local characteristics:** the model should consider the appropriate spatial resolution to capture the unique characteristics of the specific region for which it is developed, including the appropriate characterization of freight facilities and transportation links with their particular restrictions to freight vehicles.

- **Link with national and regional databases and models:** freight flows into, out of, or through the region of interest should be related to the "outside world." The model should distinguish between external trips serving the region, internal trips, and through trips.
- **Link to economic forecasts and trends:** independently of the geographic scale of an application, consideration should be given to the interaction between freight flows, commodity flows, and economic forecasts.
- **Ability to consider technological changes:** a freight model should be flexible enough to incorporate the effects of new technologies on logistics patterns.

Freight modeling applications are typically divided by geographic scale and application purpose. First, national-level applications are based on high-level national and international economic flows and trade activity, providing a framework for different geographic regions to assess overall freight activity generated by economic trends. Second, state-level or corridor applications are generally based on commodity flows, which are linked to economic activity and translated to freight flows by allocation to specific transportation modes. Third, metropolitan/urban applications tend to focus on truck movements modeled through traditional travel demand models, which are based on the four-step process. Finally, shipper/carrier applications focus on modeling goods distribution through tour-trip optimization to maximize delivery efficiency and minimize logistics costs.

The Conceptual Model incorporates these four levels of application into a common framework, but it recognizes the inherit differences in objectives and analytical procedures to model freight activity. The Conceptual Model also considers a fifth application that models activity at a specific freight facility (e.g., port terminal, railyard, airport), which is an important application for the analysis of local emissions and air quality.

4.2.1 National/International Models

The Freight Analysis Framework (FAF), developed by FHWA, is a commodity origin-destination database that estimates tonnage and value of goods carried by mode of transportation within 114 domestic and 7 international regions. Different methods are used to disaggregate interregional flows into flows among individual counties over specific transportation facilities. These methods are based on geographic distributions of economic activity rather than on accurate depictions of local conditions.

4.2.2 State/Intercity Corridor Models

Statewide models, typically developed by state DOTs, represent a variation of the four-step process used by MPOs to model transportation activity at the metropolitan level described in the following subsection. The main difference to MPO models is that their focus is on (multimodal) commodity flows rather than truck flows. The primary source of this information is the TRANSEARCH database and FAF, as well as other roadside data sources. Flows are assigned geographically through the application of an economic input-output model that links commodity flows to land use and employment activity in traffic analysis zones (TAZs). Most models then allocate the assigned commodity flows to modes by using estimates of vehicle payload. Methods for mode split, as well as treatment of non-truck modes, range widely in terms of levels of sophistication.

4.2.3 Metropolitan/Urban Models

Very few MPOs attempt to do freight modeling, and most travel demand models are limited to truck movements derived from the four-step process. In the first step, trip generation, the models estimate trip production and consumption based on economic activity (i.e., land uses) by truck type and TAZ. The models also estimate external trips. In the second step, trip distribution, the model combines internal and external truck trips by truck type onto an origin-destination matrix. The third step, mode split, is not performed since only trucks are considered. Finally, in the fourth step, network assignment, the model assigns truck trips by truck type to highway links, usually at specific time-of-day periods.

MPO models have three main pitfalls when applied to freight. First, there are concerns regarding whether truck activity can be modeled effectively without a direct link to the economic activity that is creating the demand for a particular commodity. Second, the standard trip generation/attraction methods are based on unique trip tours (one origin and one destination), but many truck shipments are based on multistop pick-ups/deliveries. Third, even though trucks account for the majority of urban freight movements, consideration should also be given to other modes of transportation. This is important in emission studies, given that the local air quality impacts of freight facilities can be substantial.

4.2.4 Shipper/Carrier Models

Shippers, carriers, and logistics operators are responsible for the logistics of goods movements, and use processes and models to manage these operations. These models, usually in the realm of the private industry, range from strategy-level models that handle supply chain design (e.g., facility location) to tactical models that design routes and multistop deliveries to operational models that handle day-to-day operations such as carrier selection. Commercial vehicles engaged in distribution operations typically travel in multistop tours, rather than a one origin–one destination trip. As a result, such movements are not well modeled by MPO models.

Previous research suggests the following three core ideas about how logistics organizations should be handled in a good freight model:

- Logistics organizations focus on total logistics costs (transportation and inventory) when making decisions on how to ship materials across the supply chain. As a result, models should also account for how changes in transportation patterns could affect inventory costs.
- Logistics costs are heavily influenced by how supply chains are designed, especially by how facilities are located in comparison with the locations of suppliers and final consumers. Therefore, a freight model should take supply chain design into consideration.
- As shipment sizes decrease in exchange for increased frequency (to minimize inventory costs), carriers increasingly combine shipments in vehicles using cross-dock operations, use special routing software to optimize routes with multiple stops, and reduce empty equipment repositioning costs.

EPA's SmartWay Transport Partnership has developed a number of tools that are directly relevant to the private industry, including the Carrier FLEET Model, the Shipper/Logistics FLEET Model, and the DrayFLEET Model. The Carrier FLEET Model allows firms to estimate the environmental performance of their fleet using different technologies and operational strategies. The Shipper/Logistics FLEET Model allows shippers to score their operations on the use of different operational strategies, including the use of SmartWay carriers. The DrayFLEET model is focused on ports, providing the ability to measure the air emissions impacts of employing such strategies as container chassis pools, off-peak gate hours, etc. EPA also has developed the Diesel Emissions Quantifier to assist firms in estimating the benefits of retrofits. These tools tend to be limited in scope, focusing on single modes individually or on the assessment of individual emission reduction strategies.

There is also a rapidly growing number of private software products intended to help businesses measure their carbon footprint, including from transportation operations and supply chains. Examples include Microsoft Dynamics AX's Environmental Sustainability Dashboard, (*186*) CSRWare's Enterprise Sustainability Management Platform, (*187*) Revolution ID's Foundation Footprint, (*188*) and Enverity's ghgTrack. (*189*) The main issue with these current tools is the use of simplistic methodologies to calculate fuel consumption that do not consider factors that might be relevant in the evaluation of freight transportation emissions. For example, emissions occurring at nodes are not always considered, nor are idling emissions. Calculated fuel consumption in these models is generally not sensitive to changes in equipment payload, nor are other parameters such as terrain grade or congestion considered. Additionally, only CO_2 emissions can be estimated since the software tools calculate emissions from fuel consumption.

4.2.5 Other Models, Methods, and Data Sources

This section discusses alternative or developing models, methods, and data sources used to measure emissions from freight transportation. In contrast to the models described previously, these new or developing models represent freight emissions in novel ways. Because these models, methods, and data sources are currently in development, they are not explored in depth, but are briefly summarized.

GIFT

The Geospatial Intermodal Freight Transportation (GIFT) model, developed by researchers at the Rochester Institute of Technology, assists users in understanding the environmental impacts of shipping routes and choosing routes that minimize fuel use and emissions. Compared to models discussed previously that focus on modal activity, the GIFT model offers a more complete supply-chain analysis of freight movement. (*190*)

Instead of using modal activity and emission factors, GIFT models a supply chain as a collection of links and nodes, in which each link represents a trip by specific mode, and each node represents freight handling locations, including railyards, intermodal centers, and warehouses. Each link and node incorporates properties of the selected mode, such as truck emissions and fuel economy, as well as properties of the trip, including grade, distance, and congestion. In addition, each link and node includes freight cost information.

By analyzing this structure, model users can make an informed choice about freight shipment routes, depending on their shipping needs. For example, a shipper could use GIFT to select the most economical route, the "greenest" route, or a route that includes specific modes or waypoints. Alternatively, a shipper could apply weighted preferences to each characteristic to optimize the shipping route considering all parameters.

GIFT is currently in development with support from federal and state governments, as well as private industry.

CARB Freight Efficiency Program

In 2006, California enacted ambitious statewide greenhouse gas reduction goals, aiming to reduce state GHG emissions to 1990 levels by 2020, and 80% below 1990 levels by 2050. In response to these targets, CARB enacted a detailed scoping plan that determined the share of GHG reductions by sector and source, as well as mitigation programs to be used to reach each goal. To reduce freight emissions, CARB is implementing a Freight Transport Efficiency Measure to increase the fuel economy and decrease the carbon footprint of freight modes. The goal of this measure is to reduce CO_2 emissions by 3.5 million metric tons (equivalent) by 2020. (*191*)

The CARB Freight Efficiency Program is patterned after EPA's SmartWay Program, and is intended to reduce fuel economy by introducing system and technology improvement across modes. The program has identified several near-term opportunities for reducing fuel consumption, including vessel speed reduction; on-road and nonroad anti-idling, transport refrigeration unit programs, and freight truck efficiency initiatives. As of September 2009, CARB is working with industry stakeholders to craft an implementation plan for the Freight Efficiency Program.

NCFRP 12: Specifications for Freight Transportation Data Architecture

The goal of NCFRP Project 12 (*192*) is to develop a structure for storing freight data from existing data sets and new data collections. Prior studies by TRB and the Cooperative Research Programs have identified challenges in applying freight data stored in disparate forms by several agencies, and the opportunities to improve freight analysis by uniting these data sources. The desired outcome of NCFRP 12 is to create a unified data architecture and evaluate the costs and benefits of implementing the structure in industry. The results of this project will complement the results of the NCFRP 12 report, and inform decisions about optimal storage methods for data sources identified here.

International Fuel Tax Agreement

The International Fuel Tax Agreement (IFTA) is an agreement between the continental U.S. states and Canadian provinces to measure cross-border truck activity and apportion fuel tax revenues to the appropriate jurisdiction. Under this agreement, implemented by the International Fuel Tax Association (also referred to as IFTA) truckers submit quarterly fuel tax reports, in which operators report the miles driven and fuel consumed in each state and province. These data are used to correctly apportion fuel tax revenue to each jurisdiction and to determine if operators are due a fuel tax surcharge or refund.

Although the primary goal of IFTA is to correctly distribute tax revenue, the reports collected by the association contain a wealth of information about truck activity, geographic distribution, and fuel consumption. Although these data are only collected for trucks involved in freight movement across the U.S.–Canadian border, they could be extrapolated to represent the entire trucking industry. However, the information stored by IFTA is currently unavailable to freight researchers and practitioners.

4.3 Model Scope and Structure

This section describes the scope and structure of a variety of Conceptual Model components. The discussion starts with a description of the target audience, whose needs drive the development of five applications (global/national, freight corridor, metropolitan, facility, and supply chain) and functional areas. Business processes fulfill the requirements of the functional areas, and the process flows describe information flows between processes.

4.3.1 Target Audience

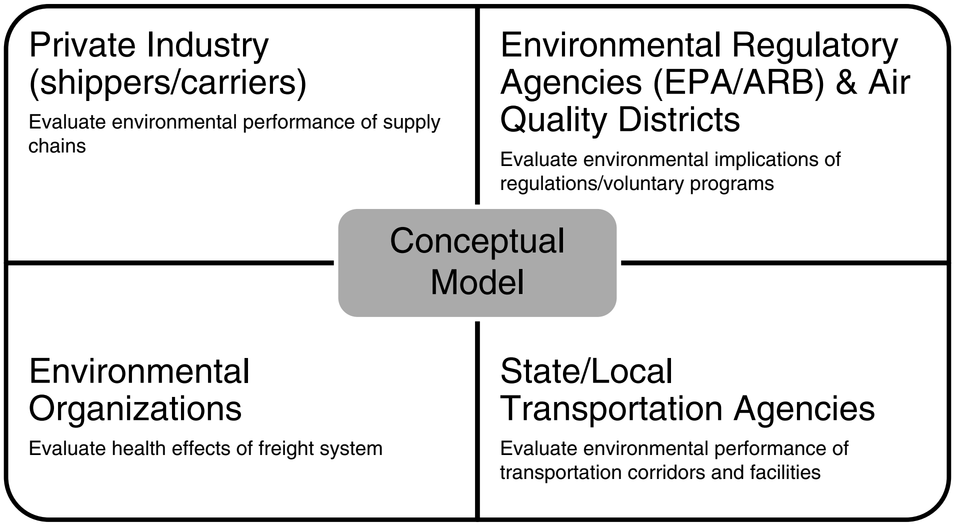
The Conceptual Model targets four types of stakeholders, each with different needs: the private industry (shippers, carriers, and logistics providers), environmental regulatory agencies, transportation agencies, and environmental organizations (Exhibit 4-3).

Private Industry

The private freight transportation industry consists of manufacturers, carriers, and logistics providers, as well as others responsible for the storage and distribution of parts and finished products. The private industry's modus operandi has been to provide the right product at the right place at the right time at the lowest possible cost. Typically, consideration of environmental criteria has been related to compliance costs. In recent years, however, many firms have started to address environmental considerations to capture and keep new markets that are environmentally conscious, to fulfill the needs of corporate social responsibility requirements, and to address concerns of potential new regulations. Additionally, firms have realized that GHG emission reductions are often associated with cost reductions (because of the direct correlation between CO_2 emissions and energy consumption), so they can develop leaner and more cost-effective supply chains while promoting environmental stewardship.

Private firms will use the model to understand how choices in terms of supply chain design, facility location, mode choice, route choice, inventory levels, packaging, and delivery patterns affect the environmental performance of their supply chains.

Exhibit 4-3. Stakeholders.



They could also compare their operation's performance against best-in-class performance through a benchmarking analysis.

Environmental Regulatory Agencies

Public agencies responsible for environmental regulations include U.S. state and local environmental regulatory agencies. Freight transportation emissions estimates can be prepared in response to federal or state regulations. These include the National Environmental Policy Act (NEPA) and similar state laws, the Clean Air Act, and federal conformity regulations. In other cases, freight emissions estimates are used in non-mandatory studies that serve to educate stakeholders and guide government programs or policy. At the federal level, EPA is responsible for setting criteria pollutant emission and ambient air quality standards. Most states follow these guidelines, although others set their own standards (notably, California via the California Air Resources Board). Air quality districts set local/regional policy to meet federal and state air quality guidelines. In many applications, freight emissions are combined with emissions from other mobile and local sources to identify the net impact on local populations and, in the case of nonattainment areas, plan progress toward meeting air quality standards.

Environmental regulatory agencies also sponsor studies of public health effects of air pollution, and many of these studies begin with estimates of emissions, including freight emissions. For example, the National Air Toxics Assessment (NATA) produces screening-level estimates of cancer and non-cancer health effects of air toxics by census tract for the entire United States. Additionally, under the Clean Air Act, EPA is required to periodically review the National Ambient Air Quality Standards (NAAQS) and, if warranted, modify them to protect public health and welfare. This review typically includes an assessment of human exposure at various concentration thresholds, which is combined with results from epidemiological studies in the decision to modify the NAAQS.

EPA also compiles nationwide GHG emissions in the official EPA GHG Inventory. (*1*) This national GHG inventory provides a common and consistent mechanism for all nations to estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change. Complementary studies to the GHG inventory influence federal programs that, in turn, leverage programs targeting the freight sector (e.g., EPA's SmartWay program).

Transportation Agencies

Transportation agencies include metropolitan planning organizations (MPOs), as well as state and federal DOTs. Transportation agencies have a key role in influencing transportation emissions. Transportation infrastructure investment can result in traffic flow improvements (that typically reduce emissions), as well as in mode shifts due to capacity improvements in certain modes. Transportation agencies also can enact finance mechanisms such as taxes, fees, and tolls that can have a direct influence on freight transportation behavior through policies and transportation infrastructure investments.

Transportation agencies will be interested in analyzing the environmental performance of different transportation corridors to inform infrastructure investment decisions. The Conceptual Model provides a framework to analyze freight activity and emissions along potential goods movement corridors.

Environmental Organizations

Environmental organizations include those groups interested in public health and environmental justice. These groups examine transportation decisions from a health impact perspective and environmental justice framework. They tend to make sure existing environmental laws are upheld when new transportation investments are made so that public health is not adversely impacted or toxic hot spots are not created. As such, these groups might use the model to determine the incremental emissions impact of a new transportation project.

4.3.2 Model Applications

Depending on the analysis objectives and available input parameters, the Conceptual Model allows emissions estimation for five different categories of analysis. Four of these are geographic scales and one describes a business enterprise perspective, as shown in Exhibit 4-4.

Global/National

The objective of this application is to calculate freight emissions inventories associated with large geographic areas, typically at the state, national, or global level. Because this application considers all transportation facilities where freight moves or is transloaded, all freight modes are included. The main users for this application will be government agencies aiming to estimate and track freight emissions over time, as well as to compare the environmental performance of freight systems in different geographic regions.

The model input will be generators of freight activity (i.e., commodity flows) from which vehicle activity can be estimated, or direct vehicle or freight activity if statistics of vehicle-miles traveled or freight ton-miles are available. Alternatively, fuel consumption data can be used to estimate freight emissions of particular pollutants (especially GHGs) if there is a reasonable way to allocate them to freight sources. Outputs from this application include freight emissions associated with particular modes on a large geographic scale.

In instances where this application is intended to provide the necessary inputs for air quality models, the spatial and temporal allocation of emissions also will be required to properly characterize emissions released to the atmosphere.

Freight Corridor

This application calculates freight emissions from a transportation corridor, which could fall within a single state or across multiple state boundaries. Objectives of this application include the following:

- Analyze current environmental performance of freight corridors;
- Analyze how future capacity improvements could affect environmental performance of a corridor (this could include environmental improvements from congestion relief, as well as from mode shift due to investments in a given mode);
- Identify corridors that are particularly energy efficient (possibly for benchmarking purposes, or as candidates for further investment) or inefficient (as candidates for future improvements);
- Compare environmental performance of different corridors in order to understand the correlations between corridor capacity, commodity mix, mode share, and environmental performance;

Exhibit 4-4. Types of model applications.

Type of Analysis	Objective	Modes	Audience
Global/National	Calculate freight emissions inventories associated with large geographic areas.	All	Environmental Regulatory Agencies
Freight Corridor	Calculate freight emissions associated with a specific corridor.	Typically truck and rail	Transportation Agencies Private Industry State/Local Environmental Agencies
Metropolitan	Calculate freight emissions inventories within a metropolitan area.	Typically truck only, but other modes can be included	Transportation Agencies Air Quality Districts
Facility	Calculate emissions from freight activity at a specific facility (truck terminal, railyard, port, and airport).	Varies, depending on the facility	Air Quality Districts Private Industry Environmental Organizations
Supply Chain	Calculate freight emissions associated with the logistics of a product.	Varies, depending on the supply chain	Private Industry

- Analyze how different freight modes compare in terms of environmental performance on specific corridors; and
- Analyze environmental effects of mode shift on specific corridors.

Typically, a freight corridor application will evaluate land-based modes, particularly truck and rail. However, other modes also could be compared against truck and rail in some freight corridors, including inland waterways, short-sea shipping, and air freight. It is also possible to use this application for intercontinental sea routes.

Potential users of this application include transportation agencies interested in investigating the environmental consequences of different types of infrastructure investments. The private industry also could use this application to evaluate the effects of specific route choices (e.g., Chicago to Los Angeles via I-80 or I-40) on their environmental performance. Route length, mode availability, terrain grade, and availability of backhaul traffic could all affect the environmental performance of a freight corridor.

The model input data sources used to calculate the amount of freight activity will depend on data availability. Ideally, estimates of vehicle activity and commodity flows are both available; otherwise vehicle payload needs to be assumed. This can be problematic since payload can vary widely, and it has a strong effect on emissions. Other important input parameters include fleet characteristics (e.g., model year, vehicle technology, engine power, equipment capacity, emission controls), and network characteristics (e.g., link capacity, node capacity, congestion levels).

Outputs from this application include freight emissions associated with particular modes under different scenarios that can be characterized by commodity mix, mode share, traffic capacity by mode, traffic volumes by mode, link characteristics (e.g., pavement quality, electrified railways), fleet characteristics, and timeframe.

In instances where this application is intended to provide the necessary inputs for dispersion models, the spatial and temporal allocation of emissions also will be required to properly characterize emissions released to the atmosphere.

Metropolitan

This application calculates freight emissions inventories with temporal and spatial resolution within a metropolitan region with the following goals:

- Analyze current and future environmental performance of the freight system within a metropolitan region;
- Analyze how future expansion/improvements in transportation infrastructure could affect the environmental performance of a metropolitan region (this could include environmental improvements from congestion relief, as well as from mode shift due to investments in a given mode);
- Compare environmental performance of different metropolitan regions, which would identify benchmarking regions, as well as those that are particularly inefficient regarding emissions from moving freight (this type of analysis also would examine the correlations between infrastructure capacity, traffic volumes, mode share, fleet characteristics, and environmental performance);
- Analyze the impact of freight emissions on local air quality and human health; and
- Compare freight emissions with emissions from other sectors.

A metropolitan application will evaluate and geographically situate all freight modes that are within metropolitan boundaries, including all classes of heavy-duty trucks, rail, marine, and other intermodal facilities, as well as airports.

Potential users include local government agencies that will find value in this type of application for planning purposes in order to identify how future improvements in transportation infrastructure and/or freight forecasts will influence freight emissions, as well as to compare a local region with regions in the rest of the country. Air quality districts can use this application to support air quality analyses and health risk assessments.

Input parameters to determine freight activity will differ by mode. Trucking activity likely will come from travel demand models, and it is important to understand how such estimates are determined. As indicated in Chapter 3, methods to estimate trucking activity in travel demand models can be somewhat inaccurate. Rail-related activity can be obtained directly from local railroads, or estimated from published statistics. Freight activity in terminals typically needs to be calculated separately with facility-level analyses. Examples include truck terminals, warehouses, railyards, ports, and airports. Because of the high uncertainty in some of these input parameters, it is important that some indication of uncertainty levels be included in the calculations, in order to identify which data elements warrant further improvement to make the calculations of metropolitan freight estimates more accurate.

Outputs from this application include freight emissions associated with different scenarios characterized by traffic volumes, infrastructure capacity, mode share, link characteristics, node characteristics, fleet characteristics, and timeframe.

Because this application also is intended to provide the necessary inputs for dispersion models, the spatial and temporal allocation of emissions is important. These allocations are necessary to determine where and when emissions are released to the atmosphere.

Facility

A facility-level application calculates freight emissions from freight facilities including truck terminals, railyards, marine and inland ports, and airports. The application has the following objectives:

- Develop current and future emissions inventories associated with a freight facility;
- Optimize facility environmental performance;
- Analyze how future expansion/improvements in the facility could affect its environmental performance (this could include environmental improvements from congestion relief, as well as from mode shift due to investments in a given mode);
- Evaluate effects of different regulations/initiatives on the emissions from a freight facility (e.g., extended idling restrictions, fleet renewal programs, chassis pools, and mode shift);
- Compare environmental performance of (comparable) freight facilities, which could identify benchmarking regions, as well as those that are particularly inefficient regarding emissions from freight handling (this type of analysis would also examine the correlations between environmental performance and infrastructure capacity, operational characteristics, traffic throughput, and fleet characteristics); and
- Analyze the impact of a freight facility on local air quality and human health.

Different modes will be included depending on the facility. The analysis of trucking terminals will involve only trucks, but the evaluation of railyards can include rail, CHE, and trucks, since most rail terminals are connected to the rest of the freight system by roadways. Marine and inland terminals could include OGVs, harbor craft, CHE, trucks, and possibly rail if on-dock or off-dock rail terminals exist. The evaluation of airports will include air freight and CHE as well as trucks.

Users of this scale will include regulators involved in permitting facilities, owners, and operators seeking permits or improvement in operations, local air agencies considering facility contributions to local air emissions, and environmental organizations concerned with public health and environmental justice.

Input parameters for the following modes will depend on the facility and the level of resources available for data collection:

- Trucking terminals are likely to have records of the number of trucks entering and leaving the facility. Estimates of loading and unloading times can provide an estimate of idling time, which needs to be evaluated in conjunction with whether anti-idling programs exist. Although it is unrealistic to expect a detailed evaluation of the fleet characteristics, an indication of the general truck size, as well as fleet age, will be necessary. For example, emissions can be quite different if the truck fleet is a long-distance fleet versus a drayage fleet. If trucking activity on the surrounding roads is included, traffic levels also need to be estimated in order to provide accurate emission estimates (because congestion can have a strong effect on local emissions).
- Railyards analysis typically can rely on detailed information about locomotive activity, including fuel consumed by switch locomotives. More sophisticated analyses include information about the share of time in each notch setting, which is an important determinant of average emission factors. Cargo handling equipment information is necessary, including number and type of equipment. In the case of intermodal rail terminals, there are drayage trucks accessing the railyard. In this case, the same input parameters described for trucking terminals also apply.
- Marine and inland port terminals' emission calculations rely on amount of cargo moved by cargo type. More sophisticated analyses include information on individual ship and harbor craft movements, engine type, engine model year, fuel used, and geographic port information to calculate emissions, as well as information on amount and type of CHE, hours of use, and duty cycle. Truck and rail servicing ports also need to be accounted for by determining the amount of cargo moved by each, as well as general truck and rail characteristics. Similar information described for trucking terminals and railyards apply to trucks and rail that service ports.
- Airport operations analysis would use detailed information on the number of air cargo aircraft and the fraction of weight associated with cargo movement when aircraft operate in mixed modes. More sophisticated analysis would include detailed information about each aircraft TIM (approach, landing, taxi, takeoff, and climb out), along with specifics on the aircraft type (jet, turboprop, and piston) and engine type. Ground support equipment used to service air cargo also needs to be accounted for—this would include information on the hours of use, duty cycle, and fuel type.

Outputs from this application include freight emissions associated with different scenarios characterized by traffic throughput, operational characteristics (e.g., idling times), infrastructure capacity, equipment characteristics, and timeframe.

Because this application also is intended to provide the necessary inputs for dispersion models, the spatial and temporal allocation of emissions is important. These allocations are necessary to determine where and when emissions are released to the atmosphere.

Supply Chain

This application calculates the emissions associated with a specific supply chain, including the supply of materials to manufacturing/assembly facilities, and/or the distribution of intermediate or finished products to other facilities, storage locations, distribution centers, or consumers. As follows, this application will:

- Calculate the emissions associated with all freight transportation required to manufacture and distribute a product;
- Optimize routing for best environmental performance; and
- Evaluate the effects of mode, route, and equipment choice on the environmental performance of the transportation components of a supply chain (however, this application will not evaluate emissions embedded in materials or those emissions associated with the actual manufacturing and assembly of products).

The modes included in this application will depend on the specific supply chain, and can potentially include all modes of transportation. This type of application will be most useful to shippers, carriers, or logistics providers interested in evaluating the environmental performance of their supply chains, and in understanding the effects of mode, route, and equipment choice on emissions. Input parameters will include supply chain design, facility location, mode choice, route choice, inventory levels, packaging, delivery patterns, and equipment characteristics.

Outputs from this application include freight emissions associated with the transportation necessary to manufacture and distribute a product under different scenarios. These scenarios can be characterized by product type, supply chain configuration (location of suppliers, manufacturing/assembly facilities, storage locations, and consumers), mode choice, route choice, fleet characteristics, and timeframe.

4.3.3 Functional Areas

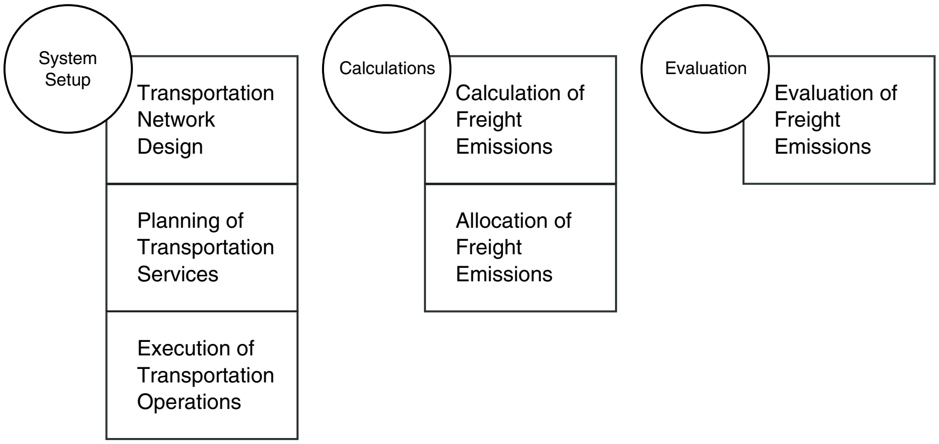
The Conceptual Model is divided into functional areas to fulfill the objectives of the five types of applications described in the previous section. These functional areas enable a user to define the freight movement framework, calculate freight emissions, and evaluate freight emissions. Functional areas can be thought as general categories of modules in a system, under which business processes run.

Exhibit 4-5 illustrates the six proposed functional areas. The first three functional areas—transportation network design, planning of transportation services, and execution of transportation operations—are part of the system description. These three functional areas allow the user to configure the network and enter the necessary input parameters to describe commodity activity, vehicle activity, and equipment configuration. The following two functional areas—calculation of freight emissions and allocation of freight emissions—use the system setup information to calculate emissions and allocate them to specific geographic areas and points in time. The last functional area—evaluation of freight emissions—enables the comparison of different scenarios, as well as sensitivity and uncertainty analyses, to improve freight emission estimates. These six functional areas are described in detail in the following subsections.

Transportation Network Design

This functional area consists of inputs describing the simulated transportation network. Freight transportation activity and associated emissions will be calculated on a transportation network, which will be based on a link-node system. Nodes will represent freight facilities, including trucking terminals, railyards, marine/inland ports, and airports. Nodes also can be virtual points dividing two continuous links with different characteristics. For example, two consecutive sections of the

Exhibit 4-5. Functional areas.



same roadway with different traffic volumes can be divided by a virtual node (e.g., freeway exit, interchange). Links will represent transportation facilities where freight moves, including roadways, railways, inland waterways, ocean routes, and air routes. Freight activity and emissions will be allocated to either a link or a node.

The Conceptual Model enables the creation of flexible networks with different levels of aggregation that can fit the objectives and accuracy requirements of an emission analysis. Although virtual nodes can be created to divide one link into shorter links with different characteristics, the opposite is also possible in the case of more aggregate analysis. Comparative analyses could also be made to evaluate the loss in accuracy by increasing the level of aggregation when defining links and nodes.

Because the Conceptual Model will be setup to assist users in incorporating environmental criteria in the design of a transportation network, the Conceptual Model enables the creation of alternate nodes and links to test future potential transportation networks. Allowance for changes in node structure (e.g., additional nodes to simulate the effects of a new (or modified) distribution center) will enable the user to compare emissions between scenarios.

As described in the following section, there are three business processes that fall under this functional area—supply chain design, link characterization, and node characterization. The specific attributes of links and nodes are described under link characterization and node characterization, respectively.

Planning of Transportation Services

This functional area configures the necessary input parameters for the determination of freight flows over a specified transportation network, including the determination of commodity flows, service levels (i.e., requirements in terms of transit time, and transit time reliability), mode choice, and route choice.

For those applications that rely on commodity flows as input parameters, input data can be obtained from published sources, such as the Commodity Flow Survey, (*193*) or by internal sources of freight transportation demand in the case of private firms. In the latter case, requirements for transit time and transit time reliability also will assist in the selection of mode. After mode selection, one or more routes will be chosen for the analysis.

Other types of applications will not require the determination of commodity flows and, instead, transportation activity will be determined directly from measured (or estimated) vehicle activity. For example, the analysis of freight emissions in a metropolitan area is to likely rely on travel demand models to estimate truck activity on a local transportation network. In this case, mode choice and route choice will already be determined.

Users will be able to create different scenarios to test the effects of changes in freight demand, service levels, mode choice, and route choice on associated supply chain emissions.

Execution of Transportation Operations

This functional area takes the perspective of day-to-day transportation operations, and it collects inputs for three business processes. First, the equipment configuration determines which type of equipment will handle the freight flows. Required input parameters for equipment configuration include model year, vehicle technology, engine power, emission controls, equipment capacity, and fuel type. All of these parameters are important for the determination of emission factors associated with a specific equipment type.

Second, loading patterns will be determined based on the specified commodity and equipment configuration. Based on commodity density and packaging requirements, payload will be determined. Loading patterns will also define requirements for loading and unloading times, which will assist in the estimation of idling or hotelling times.

Finally, vehicle activity will be determined based on commodity flows, mode choice, route choice, equipment configuration, and loading patterns. Alternatively, vehicle activity can be provided as a direct input parameter to the model.

Calculation of Freight Emissions

This functional area is responsible for calculating freight emissions. Emission factors are determined based on equipment characteristics and how the network is configured. Emissions can either be determined from vehicle activity directly by using emission factors in terms of freight activity (ton-mile, hp-hr, hour), or from fuel consumption. In the latter case, fuel consumption either can be a direct input parameter to the model, or it can be estimated from freight activity.

The functional unit of the analysis determines how freight activity is measured. Typical functional units are VMT, ton-mile, horsepower-hour (hp-hr), kilowatt-hour, and hour. For example, truck activity is typically measured in terms of VMT, but vessel activity is measured in kilowatt-hours.

Allocation of Freight Emissions

After freight emissions are calculated, they need to be allocated to either a node or a link (i.e., spatial allocation). This functional area groups calculated emissions spatially and temporally. Because links and nodes are associated with geographic regions, this will provide the necessary information for air quality models and health risk assessments. Additionally, emissions also need to be allocated to a specific time (i.e., temporal allocation) since this is also an important input parameter for air quality models. Emissions also can be allocated to a specific product or commodity.

Evaluation of Freight Emissions

This functional area allows comparisons between a variety of emission scenarios calculated by the Conceptual Model. The model may be used to calculate emissions under a range of scenario alternatives that may be compared against a baseline or a benchmarking target, allowing alternatives to be differentiated based on a variety of input parameters. This functional area also allows the effects of emission reduction strategies to be analyzed by the Conceptual Model, including the strategies affecting emission factors, freight activity, fuel efficiency, and congestion. The ability to perform sensitivity analysis of specific parameters is important for evaluating and improving the performance of supply chains and testing the effectiveness of transportation policies. For example, freight emissions can be evaluated over time to examine emission changes based on economic forecasts (which drive commodity flows), mode share forecasts, and advancements in vehicle fleet technology. Scenarios also can be modified based on specific input parameters, enabling sensitivity analyses. Thus, users can create different scenarios to test the effects of changes in the level of network aggregation, freight demand, service levels, mode choice, route choice, and equipment configuration.

4.3.4 Processes

Each of the six functional areas described in the previous section are essentially aggregations of related processes. Each of these processes is responsible for specific activities required to fully describe a functional area and, eventually, for the calculation and evaluation of freight emissions. Exhibit 4-6 summarizes the processes included in each functional area.

Some of these processes will apply only to some types of applications. For example, for those analyses that rely on travel demand models to estimate truck activity over specific links, all processes under the planning of transportation service

Exhibit 4-6. Processes.

FUNCTIONAL AREAS	PROCESSES
1. Transportation Network Design	• Supply chain design • Link characterization • Node characterization
2. Planning of Transportation Services	• Determination of commodity flows • Determination of service level • Mode choice • Route choice
3. Execution of Transportation Operations	• Equipment configuration • Determination of loading patterns • Determination of vehicle activity
4. Calculation of Freight Emissions	• Determination of emission factor • Calculation of fuel consumption • Calculation of emissions
5. Allocation of Freight Emissions	• Spatial allocation of emissions • Temporal allocation of emissions
6. Evaluation of Freight Emissions	• Analysis of alternative scenarios • Sensitivity analysis of freight emissions based on changes in input parameters

functional area will not be required. Processes also will need to be adapted depending on the application because of different analysis objectives, input parameters, calculation methods, and accuracy needs. For example, fuel consumption can be a direct input to the model (i.e., facility-level applications where fuel consumed is available for participating carriers), it can be calculated from vehicle activity based on equipment fuel efficiency, or it might be disregarded altogether if emission factors are not based on fuel consumed.

Objects

All entities in the Conceptual Model are considered objects. Objects may be either calculated from other objects or are external input parameters. Higher-order objects are inputs to lower-order objects. For example, emissions are a first-order object and are the product of two second-order objects: freight activity and emission factors. Emission factors are produced from third-order objects such as equipment model year, and so on. The discussion of processes sometimes refers to objects as input parameters; the terms are regarded as interchangeable in this report.

Exhibit 4-7 provides a list of some of the most important objects in the Conceptual Model.

Supply Chain Design

No objects are involved in this process.

This process enables users to define the facilities included in a product supply chain, as well as the possible material flows between facilities. Facilities can be divided into the following two types:

- Logistics facilities where products are processed and/or stored, including suppliers' locations, manufacturing and assembly plants, warehouses, distribution centers, wholesalers, retailers, and final consumers; and
- Transportation facilities, such as trucking terminals, railyards, intermodal facilities, ports, and airports.

The objective of this process is to determine the set of nodes involved in the analysis of freight emissions, as well as the flows that will move between these nodes. This process is conceptually simple, and it requires only the determination of possible

Exhibit 4-7. Main objects.

Variable	Code	Description
Activity	ACT	Freight activity is a measure of vehicle activity, cargo activity, or fuel consumption.
Activity Profile	PRO	Activity profiles represent driving cycles, duty cycles, or any other distribution of vehicle activities that has an effect on emission factors.
Area	ARE	Combination of links and nodes.
Commodity	COM	In analyses in which vehicle (or freight) activity is not an external input parameter to the model, commodity flows will determine vehicle activity. Each commodity group will be assigned with ranges of possible densities for different types of equipment, so that a commodity can be converted into number of vehicles.
Emission Factor	EF	Determines the amount of a given pollutant emitted as a function of freight activity, which can be measured in vehicle-miles traveled, idling hours, ton-miles, energy, fuel, etc.
Emissions	E	Product of freight activity and emission factors.
Transportation Equipment	EQP	This includes the information necessary to characterize transportation equipment (or a fleet), including vehicle type, weight class, engine technology, fuel type, power ratings, model year, and emission control technologies.
Link	LNK	A link represents transportation facilities where freight moves, including roadways, railways, inland waterways, ocean routes, and air routes.
Mode	MOD	Trucking, rail, water, cargo handling equipment, air.
Node	NOD	At the local/project level, nodes represent freight facilities, including trucking terminals, railyards, marine/inland ports, and airports. Nodes can also be virtual points dividing two continuous links with different characteristics. At the regional and national level, nodes can represent cities or regions.
Payload	PAY	Payload represents the amount of cargo that can be loaded into transportation equipment. Payload can be measured in terms of weight or volume.
Pollutant	POL	Emissions are reported separately by pollutant.
Route	RTE	A route is a series of links and nodes. Because links are mode-specific, a route is responsible for linking multiple modes into a single supply chain.
Scenario	SCE	Scenarios can be differentiated by a variety of parameters, including year, equipment type, route choices, commodity flows, payload, emission reduction strategies, etc.
Time Period	TIM	Time period represents the point in time at which emissions occur.

facilities as well as flows between facilities. There also might be flows within the same facility, which can include the operations of drayage trucks within an intermodal terminal, switch locomotives within railyards, waterborne vessels maneuvering at port terminal facilities, or aircraft taxiing on runways.

There is a mutual dependency between supply chain design and other processes. Both mode choice and route choice depend on an initial selection of logistics facilities, while the selection of transportation-related facilities depends on mode and route selection. Required inputs for this process include freight transportation demand. For outputs, this process will determine the level of service required for a supply chain, given consumer preferences (e.g., fashion-related products require fast deliveries), production requirements (e.g., just-in-time systems require specific and reliable transit times), and commodity characteristics (e.g., high-value commodities require fast transit times because of inventory costs).

Node Characterization

The following object is involved in this process:

- Node (NOD).

Nodes represent freight facilities, including trucking terminals, railyards, marine/inland ports, and airports. Nodes also can be virtual points dividing two continuous links with different characteristics. At the regional and national level, nodes also can be cities or regions.

Nodes need to be characterized not only because they are the source of freight-related emissions, but because they provide the connectivity between links, thus influencing mode and route choice.

Exhibit 4-8 presents the input parameters that will characterize a node, the transportation modes to which a parameter applies, and the purpose of a parameter (e.g., determination of emission factor).

Link Characterization

The following object is involved in this process:

- Link (LNK).

A link represents a transportation facility connecting two nodes. Examples of links are roadways, railways, water routes, and air travel lanes. Links must be characterized based on a series of parameters required to determine freight emissions along a transportation link. Exhibit 4-9 includes the input parameters that will characterize a link, the transportation modes to which a parameter applies, and the purpose of the parameter (e.g., determination of emission factor).

Link characterization is dependent on mode choice, since not all modes will be present between two nodes. The

Exhibit 4-8. Parameters for node characterization.

Parameter	Description	Mode	Purpose
Type	A node can be a freight facility (where transportation operations occur), or a virtual node (that exists to connect two links).	All	N/A
Link connectivity	Determines which links are associated with a specific node.	All	Determine nodes associated with a trip
Mode availability	Determines which modes can be associated with a specific node. For example, a marine terminal with road access but no on-dock rail access will be associated with truck transportation but not rail transportation. Consequently, node characterization will have an influence on mode choice because nodes will only be associated with certain modes.	All	Determine mode choice
Equipment availability	Because there are freight transportation-related operations taking place at certain logistics and transportation facilities, those can be associated with specific types of transportation equipment. For example, marine terminals are specifically associated with cargo handling equipment that does not leave the terminal's premises. Similarly, switch locomotives can operate strictly within a rail terminal, and ground support equipment is confined to an airport. As a result, node emissions will depend on the characteristics of these types of equipment.	All	Estimate freight activity at nodes and estimate emission factor
Geographic area	Associates a node with a geographic region, which can be defined as a city, county, air basin, metropolitan region, state, country, continent, or another region defined by the user.	All	Allocate emissions to physical locations

Exhibit 4-9. Parameters for link characterization.

Parameter	Description	Mode	Purpose
Mode	By definition, a link is mode-specific because link attributes are also mode-specific.	All	N/A
Length	Measured in miles.	All	Calculate freight activity
Initial node		All	Provide link with trip
End node		All	
Link capacity	Generally measured in vehicles per hour.	Truck	Estimate congestion and average speed
Number of lanes/tracks		Truck, Rail	Determine link capacity
Facility type	Can be the roadway classification (for trucks) or track class (for rail).	Truck, Rail	
Traffic volume	Generally measured in vehicles per hour.	Truck	Estimate congestion and average speed
Average speed	Measured in miles per hour, average speed either can be an input parameter as in the case of travel demand models, or it can be estimated based on link capacity and traffic volumes.	Truck	Estimate emission factor
Congestion	Road level of service, varying from A to F.	Truck	Estimate emission factor
Equipment restrictions	Determines any type of equipment restriction on a link, including size and weight restrictions, and emission control systems.	Truck, Rail, OGV	
Equipment mix	If the typical fleet operating at a link has different characteristics from the area's average, the user can determine a customized equipment mix for a link.		Configure equipment
Terrain grade	Terrain grade is an important attribute of a link since it has a strong influence on fuel consumption and emissions.		Estimate emission factor
Geographic area	Associates a link with a geographic region, which can be defined as a city, county, air basin, metropolitan region, state, country, continent, or another region defined by the user.	All	Allocate emissions to physical locations

characteristics of different links also will influence route choice. For example, a longer route with smoother grades might be preferable to a shorter (but steeper) route.

Determination of Commodity Flows

The following object is involved in this process:

- Commodity (COM).

Commodity flows define the weight and volume of commodities between different origin-destination (O-D) pairs. In global/national and supply chain applications, commodity flows are the main drivers of freight activity and, consequently, of emissions. In the freight corridor and facility applications, freight activity might be determined by either commodity flows or direct estimates of freight activity. This process is not applicable for the metropolitan application because vehicle activity is estimated directly from travel demand models.

Commodity flows will be determined by either the supply chain design process (in the case of the evaluation of specific supply chains), or by economic activity forecasts (in the case of national/regional analyses). Commodity flows will influence the following processes:

- Mode choice: O-D pairs will influence mode choice because not all modes are available for all O-D pairs;
- Determination of service level: commodity selection will influence service level requirements because of commodity value (e.g., high-value commodities will require faster transit times in order to minimize inventory levels in transit); and
- Activity: in the global/national and supply chain applications, commodity flows will determine freight activity.

Determination of Service Level

No objects are involved in this process.

Service level is generally described as a combination of travel time (e.g., 2-day delivery), travel time reliability (± 4 hours), and delivery frequency. This process is only applicable for the supply chain application, in which users can determine the required service level for a given supply chain. This process depends on the supply chain design process, as well as on freight transportation demand (input parameter). Service levels affect the following three processes:

- Mode choice: service levels will influence mode choice because certain modes can provide faster and/or more reliable transit times;

- Route choice: service levels will influence route choice because some routes are shorter or faster; and
- Determination of loading patterns: load sizes are usually determined by the frequency of deliveries.

Mode Choice

The following object is involved in this process:

- Mode (MOD).

Based on a given O-D pair, mode choice will be determined by mode availability, as well as other criteria (e.g., service level, travel time, travel distance, cost, and emissions). The Conceptual Model assumes that a user will evaluate these parameters outside of the model.

For the applications that can estimate vehicle activity from commodity flows—national/global, freight corridor, and supply chain—more than one mode might be necessary for a given flow. For example, a corridor analysis between Chicago and Los Angeles could require the use of a double-stack train, plus a drayage truck movement on each end of the trip.

Mode choice will determine the following processes:

- Equipment configuration: mode selection will determine the different types of vehicles involved in the analysis; and
- Route choice: mode choice also will have an influence in the selection of a route.

Route Choice

The following objects are involved in this process:

- Route (RTE),
- Link (LNK), and
- Node (NOD).

A route is a series of links and nodes. Because links are mode-specific, a route is responsible for linking multiple modes along a single supply chain. The selection of a route is important because a route is associated with travel distance, and other characteristics specific to the links and nodes represented in a route (e.g., terrain grade, average speed, congestion). For a given O-D pair and mode, more than one route might be available from origin to destination. In such cases, a route will be determined based on travel distance, travel time, travel time reliability (which depends on congestion), and cost.

This process applies for three types of applications: national/global, freight corridor, and supply chain. The metropolitan application does not require this process because routes are determined within a travel demand model. Because the facility application analyzes emissions at a node, route choice is not necessary.

Initially, the Conceptual Model does not include an algorithm to assist users in route choice based on selection criteria. Instead, the user needs to consider all relevant criteria for route choice, and simply assign a route in the model.

Route choice will influence equipment configuration because different equipment types might be associated with different regions.

Equipment Configuration

The following objects are involved in this process:

- Transportation Equipment (EQP), and
- Payload (PAY).

This process is the determination of equipment characteristics for a specific route or combination of routes (for regional/national analyses). Exhibit 4-10 includes the parameters necessary for equipment configuration by mode. Some of these parameters are necessary for the calculation of payload

Exhibit 4-10. Parameters for equipment configuration by mode.

Mode	Parameter
Heavy-Duty Trucks	Model year, mileage accumulation, truck weight class, payload, truck weight, fuel type, engine power, vehicle technology, emission control technology, truck capacity (weight and volume), commodity types
Rail	Locomotive type, engine power, locomotive tier (emission control technology)
Ocean-Going Vessels	Calls, ship type, engine type, engine model year, propulsion and auxiliary engine power, ship size (DWT or TEUs), fuel type
Harbor Craft	Population by engine type, number of engines per vessel, engine power by type, deterioration factor, growth factor, engine age, median life, scrappage, use of retrofit devices, fuel type
Cargo Handling Equipment	Population, engine power, deterioration factor, growth factor, engine age, median life, scrappage, use of retrofit devices, fuel type
Air Freight	Engine type, fuel type, fraction of payload used for air cargo, aircraft type, fuel flow rates, aircraft performance (throttle setting)

(e.g., truck capacity), while others are used for the estimation of appropriate emission factors (not all parameters listed are always necessary for the determination of emission factors).

Equipment configuration depends on commodity type, mode choice, and sometimes on route choice because some regions might have restrictions regarding which types of equipment are permitted. Equipment configuration also is influenced by loading patterns, which will determine payload.

Equipment configuration will determine the following business processes:

- Determination of loading patterns: load capacity influences loading patterns;
- Determination of emission factor: emission factors are dependent on equipment type, model year, engine characteristics, and equipment weight; and
- Determination of vehicle activity: load capacity and equipment utilization determine how many vehicles are necessary to transport a given load.

Determination of Loading Patterns

The following objects are involved in this process:

- Payload (PAY), and
- Commodity (COM).

Loading patterns consist of how commodities are loaded onto the transportation equipment. Loading patterns depend on the service level—which will drive delivery frequencies—and equipment capacity. The determination of loading patterns is important because it will influence vehicle activity and payload, which in turn has an effect on emission factors.

This process is required for the supply chain and facility applications because vehicle activity might be determined from commodity activity. The determination of loading patterns is required for those applications in which vehicle activity is determined from commodity activity. This is the case in the supply chain and facility applications, and it is sometimes true for the national/global and freight corridor applications. This process is not required for the metropolitan application because vehicle activity for that application is determined directly by travel demand models.

Loading patterns will influence the equipment configuration process because it will determine the payload, and consequently vehicle weight. Additionally, some supply chains prioritize delivery frequency over equipment capacity maximization (e.g., just-in-time systems). In these cases, the normal decision to optimize capacity might not be a good decision given the specifics of supply chain requirements.

Determination of Freight Activity

The following objects are involved in this process:

- Activity (ACT),
- Scenario (SCE),
- Mode (MOD),
- Transportation Equipment (EQP),
- Link (LNK), Node (NOD),
- Time (TIM), and
- Activity Profile (PRO).

This process consists of the determination of freight activity, which can be measured in terms of vehicle activity (e.g., vehicle-miles traveled), product activity (e.g., ton-miles), or fuel consumption (e.g., total gallons of fuel per functional unit). Vehicle activity either can be calculated from commodity flows, or it can be an external input parameter from travel demand models. Fuel consumption either can be estimated from vehicle activity or provided to the model as an input parameter. For example, the calculation of GHG emissions and the analysis of rail emissions commonly rely on fuel consumption. Exhibit 4-11 provides examples of activity metrics specific to each mode of transportation.

Exhibit 4-11. Vehicle and freight activity by mode.

Mode	Activity Metrics	Activity Profile Parameters
Heavy-Duty Trucks	VMT, idling time, ton-miles	Driving cycle, level of service, average speed, bin allocation
Rail	Train-miles, car miles, idling time, ton-miles	Duty cycle
Ocean-Going Vessels	Calls, propulsion power	Load factors, vessel speed
Harbor Craft	Annual activity, fuel consumption	Load factors by engine type, duty cycle
Cargo Handling Equipment	Load factor, activity	Emission factor, duty cycle
Air Freight	TIM (cruise, approach, taxi/idle, takeoff, climb out)	Throttle setting (aircraft performance),emission indices, fuel flow rate

Activity profiles characterize freight activity based on parameters that affect energy consumption and/or emissions from an activity. Exhibit 4-11 also summarizes the parameters that describe activity profiles.

This process will be handled differently depending on the type of analysis. For those analyses that rely on commodity activity to determine vehicle and freight activity, this process provides the necessary formulas to make the calculations. Other types of analyses will rely on direct estimates of vehicle and freight activity as input parameters. An additional type of analyses relies on direct fuel consumption estimates as input parameters, in which case estimates of vehicle or freight activity will not be necessary.

In addition to emission factors, freight activity will be the most important input in the calculation of emissions. Freight activity will be calculated separately by scenario, mode, activity profile, transportation equipment, link/node, and time period. The specific formulas that will be used to calculate freight activity will depend on the specific type of analysis and the exact input parameters. Equations 22 through 25 provide some examples of calculations of freight activity at the link level.

Calculating vehicle activity from commodity activity (e.g., vehicle-miles traveled) is performed as follows:

$$ACT_{SCE,MOD,PRO,EQP,LNK,TIM} = \frac{COM_{SCE,MOD,PRO,EQP,LNK,TIM} \times Link\_Length_{LNK}}{PAY_{SCE,MOD,EQP}} \qquad \text{(Equation 22)}$$

Calculating product activity from commodity activity (e.g., ton-miles) is performed as follows:

$$ACT_{SCE,MOD,PRO,EQP,LNK,TIM} = COM_{SCE,MOD,PRO,EQP,LNK,TIM} \times Link\_Length_{LNK} \qquad \text{(Equation 23)}$$

Calculating fuel consumption from commodity activity (e.g., gallons) is performed as follows:

$$ACT_{SCE,MOD,PRO,EQP,LNK,TIM} = \frac{COM_{SCE,MOD,PRO,EQP,LNK,TIM} \times Link\_Length_{LNK}}{PAY_{SCE,MOD,EQP} \times Fuel\_Efficiency_{EQP,PRO,LNK}} \qquad \text{(Equation 24)}$$

Calculating fuel consumption from vehicle activity is performed as follows:

$$ACT_{SCE,MOD,PRO,EQP,LNK,TIM} = \frac{Vehicle\_Activity_{SCE,MOD,PRO,EQP,LNK,TIM}}{Fuel\_Efficiency_{EQP,PRO,LNK}} \qquad \text{(Equation 25)}$$

Since empty equipment activity will affect emissions, they also will need to be included and allocated to the load in the case of the analysis of specific supply chains.

Determination of Emission Factors

The following objects are involved in this process:

- Emission Factor (EF),
- Pollutant (POL),
- Mode (MOD),
- Transportation Equipment (EQP),
- Activity Profile (PRO), and
- Link (LNK).

Emission factors determine the amount of a given pollutant emitted based on a given functional activity unit, which can be related to vehicles (e.g., VMT, vehicle-hours, energy), or related to freight (e.g., ton-miles). Emission factors can account not only for fuel combustion, but also for the refining and distribution of fuel if a full fuel cycle analysis is desired. Alongside vehicle/freight activity (or fuel consumption), this process is the main input for emissions calculations.

Emission factors will be determined separately by pollutant, mode, transportation equipment, activity profile, and link (in the case of emissions at a link). Depending on the mode, emission factors can be determined from emissions models or based on guidance documents, as summarized in Exhibit 4-12. The Conceptual Model does not replace previous models that estimate emission factors or guidance documents. Instead, it relies on emission factors from these sources. Factors related to cleaner fuels or emission control retrofits also should be used to adjust emission factors where needed.

Exhibit 4-12. Source of emission factors by mode.

Mode	Source of Emission Factors
Heavy-Duty Trucks	MOVES, Mobile6
Rail	EPA guidance
Ocean-Going Vessels	EPA guidance
Harbor Craft	ARB NONROAD or EPA OFFROAD models, other EPA guidance, other studies
Cargo Handling Equipment	ARB NONROAD or EPA OFFROAD models, other EPA guidance
Air Freight	ICAO emissions certification databank and fuel flow rates

Calculation of Emissions

The following objects are involved in this process:

- Emissions (E),
- Scenario (SCE),
- Mode (MOD),
- Link (LNK),
- Node (NOD),
- Activity (ACT), and
- Emission Factor (EF).

Although some methods and models are mode-specific, there are standard methods that can be applied to all modes. As illustrated in the Equation 26, freight emissions are generally the product of freight activity (e.g., fuel consumed, energy generated, or vehicle miles traveled), and emission factors (in grams of pollutant per measure of freight activity).

$$\text{Emissions} = \text{Freight Activity} \times \text{Emission Factor} \quad \text{(Equation 26)}$$

Depending on data availability and the complexity of analytical methods, emissions might be calculated separately by vehicle type or other factors that affect emission factors (e.g., average speed, road level of service), and added up to a total by pollutant. With the exception of GHGs, which are summed by multiplying their respective emissions by their global warming potential, the emissions of other pollutants are always reported separately.

The calculation of emissions will provide information for the following processes:

- Spatial allocation of emissions: emissions will be allocated to specific links, nodes, and geographic areas; and
- Temporal allocation of emissions: emissions can be allocated to specific times during the day, days of the week, or months of the year.

Emissions will be calculated for each pollutant, scenario, mode, link/node, and time period, as shown in Equations 27 and 28.

Calculating mode emissions at a link is performed as follows:

$$E_{SCE,POL,MOD,LNK,TIM} = \sum_{PRO,EQP} ACT_{SCE,MOD,PRO,EQP,LNK,TIM} \times EF_{MOD,PRO,EQP,LNK,POL} \quad \text{(Equation 27)}$$

Calculating mode emissions at a node is performed as follows:

$$E_{SCE,POL,MOD,NOD,TIM} = \sum_{PRO,EQP} ACT_{SCE,MOD,PRO,EQP,NOD,TIM} \times EF_{MOD,PRO,EQP,NOD,POL} \quad \text{(Equation 28)}$$

Spatial Allocation of Emissions

The following objects are involved in this process:

- Area (ARE),
- Emissions (E),
- Scenario (SCE),
- Link (LNK), and
- Node (NOD).

Freight emissions will always be associated with specific links and nodes, which in turn are linked to geographic areas. As a result, freight emissions can always be allocated spatially to specified geographic areas, thus supporting dispersion models and health risk assessments. This process is only applicable for the metropolitan and facility applications because of their narrow geographic scope.

The user will be able to define different geographic areas, which are defined as a combination of links and nodes. A GIS interface also can be created to provide a visual representation of emissions. Emissions at an area are calculated as shown in Equation 29.

$$E_{SCE,ARE,POL} = \sum_{LNK,MOD,TIM} E_{SCE,POL,MOD,LNK,TIM} + \sum_{NOD,MOD,TIM} E_{SCE,POL,MOD,NOD,TIM} \quad \text{(Equation 29)}$$

Temporal Allocation of Emissions

The following objects are involved in this process:

- Time (TIM),
- Emissions (E),
- Scenario (SCE),
- Link (LNK), and
- Node (NOD).

Freight emissions can be allocated to specific times during the day, days of the week, or months of the year in order to support dispersion models and health risk assessments. Because the dispersion of pollutants relies on variables that are time-dependent (e.g., temperature, winds), the temporal allocation of emissions also is an input for dispersion models and health risk assessments. This process is applicable to any spatial scale for which air quality modeling might be applied. Emissions at an area at a given time are calculated as shown in Equation 30.

$$E_{SCE,ARE,TIM,POL} = \sum_{LNK,MOD} E_{SCE,POL,MOD,LNK,TIM} + \sum_{NOD,MOD} E_{SCE,POL,MOD,NOD,TIM} \quad \text{(Equation 30)}$$

Model Calibration

This process allows the calibration of the Conceptual Model based on results or input parameters from other studies or models. Invariably, there will be instances where surrogate input parameters will be used due to a lack of information about a given project, or a lack of resources to collect project-specific data. If input parameters from surrogate studies are available, they can be used directly in the Conceptual Model. If only final results are available, however, the Conceptual Model can be calibrated so that the final results can "match" the results from surrogate studies. The Model Calibration process will let the users select one or more input parameters that will need to be modified to enable the adjustment of final results.

Analysis of Scenarios

This process allows the creation of alternative scenarios that can be compared against a baseline or a benchmarking target. Scenarios can be differentiated based on any parameter in the model. For example, freight emissions can be evaluated over time to examine emission changes based on economic forecasts (which drive commodity flows), mode share forecasts, and advancements in vehicle fleet technology. Scenarios also can be modified based on specific input parameters, which will enable sensitivity analyses. For example, users can create different scenarios to test the effects of changes in the level of network aggregation, freight demand, service levels, mode choice, route choice, and equipment configuration. The effects of emission reduction strategies also are captured by the Conceptual Model, including the strategies affecting emission factors, freight activity, fuel efficiency, and congestion. The ability to perform sensitivity analysis of specific parameters is important to evaluate and improve the performance of supply chains and to test the effectiveness of transportation policies.

The emissions associated with a mode in one scenario are calculated as shown in Equation 31.

$$E_{SCE,POL,MOD} = \sum_{LNK,TIM} E_{SCE,POL,MOD,LNK,TIM} + \sum_{NOD,TIM} E_{SCE,POL,MOD,NOD,TIM} \qquad \text{(Equation 31)}$$

Subsequently, total emissions associated with one scenario are calculated as shown in Equation 32.

$$E_{SCE,POL} = \sum_{MOD} E_{SCE,POL,MOD} \qquad \text{(Equation 32)}$$

Sensitivity/Uncertainty Analysis

The evaluation of uncertainty associated with methods to estimate freight emissions needs to consider that error propagates as freight activity is converted into emissions, which are then used in air quality models and health risk assessments.

Uncertainty in the emissions calculations can generally be attributed to either process or parameter uncertainty. Process uncertainty is taken to be the degree to which algorithms used in the calculations represent the actual emissions processes. These include uncertainties in the models themselves, as well as uncertainties in choices made during parameterization, such as choice of models and geographic boundaries. Parameter uncertainty is the uncertainty in the individual elements of the equations utilized. This includes uncertainties in emission factors, populations, activity, and other inputs.

In cases of both process and parameter uncertainty, any known biases should be corrected before calculations are made; it is assumed here that any calculations will be made with the best available information and methods. However, unknown bias and uncertainty may still influence resulting estimates. In some cases, this may only be estimated qualitatively. In others, quantitative estimates of uncertainty may be made. Particularly, if the uncertainty (for example, the standard deviation, error, or other measure for various input parameters) is known, then a quantitative estimate of the resulting uncertainty can be made using standard error propagation methods.

A full discussion of error propagation methods is available elsewhere. (*194*) Generally, overall uncertainty is derived from a Taylor's Series expansion of the controlling equation, such that if emissions can be described by $f(x_1, x_2, \ldots x_n)$, then the variance of emissions is as shown in Equation 33.

$$\sigma^2 emissions = \left(\frac{\partial f}{\partial x_1}\right)^2 \sigma^2 x_1 + \left(\frac{\partial f}{\partial x_2}\right)^2 \sigma^2 x_2 + \cdots + 2\left(\frac{\partial f}{\partial x_1}\right)\left(\frac{\partial f}{\partial x_2}\right)\sigma^2 x_1 x_2 + \cdots \qquad \text{(Equation 33)}$$

Where

σ_i^2 represents the variance on variable *i* and
σ_{ij}^2 represents the covariance between variables *i* and *j*.

In many cases, the fluctuations between two input variables are uncorrelated, such that the cross-terms average to zero. In that case, the error equation is simplified, as shown in Equation 34. This equation may be used to approximate overall uncertainty in emissions from a quantified set of parameter uncertainties.

$$\sigma^2 Emissions = \left(\frac{\partial f}{\partial x_1}\right)^2 \sigma^2 x_1 + \left(\frac{\partial f}{\partial x_2}\right)^2 \sigma^2 x_2 + \cdots \qquad \text{(Equation 34)}$$

Another method to estimate parameter uncertainty is the use of Monte Carlo simulation. By specifying probability distributions for selected input parameters, a Monte Carlo analysis simulates real-world conditions in order to assess the uncertainty in emissions outputs. The biggest challenge remains in the selection of the most influential parameters and the determination of their probability distributions. Literature research, data availability, and expert judgment can be used. It is important to emphasize that an uncertainty assessment does not make emission outputs more accurate. However, probabilistic simulation models (e.g., Crystal Ball) can determine the contribution of each parameter to the final outcome. Based on that information, priority can be given to find more reliable sources of data for those parameters, and suggest the use of ranges, instead of point estimates, for results.

4.3.5 Process Flows

Process flows, or the way data and calculations flow into and between analytical process steps, will vary depending on the type of application. Some of these processes can apply to all types of applications, including equipment configuration, determination of freight activity and emission factors, calculation of emissions, scenario analysis, and uncertainty analysis. However, other processes do not apply to all applications. Exhibit 4-13 summarizes how each process applies to the five types of applications. Variations among the applications are described in the following subsections.

Global/National

This application calculates freight emission inventories associated with geographic areas at the state, national, or global level. Supply chain design is not relevant because the application does not intend to model a specific supply chain. The level of link and node characterization will need to be commensurate with the level of detail and accuracy required by the analysis. Because freight activity will be determined from commodity flows, the processes regarding commodity flows, mode choice, and route choice are required. The determination of service levels however, is not applicable because of the aggregate nature of the analysis (i.e., at an aggregate level, it is not possible to determine requirements such as transit times and delivery frequencies). All of the subsequent processes are necessary, including equipment configuration,

Exhibit 4-13. Relationship between processes and applications.

Facility Type	Global/National	Corridor	Metropolitan	Facility	Supply Chain
Supply Chain Design	×	×	×	×	●
Link Characterization	✓	●	●	✓	✓
Node Characterization	✓	✓	✓	●	✓
Determination of Commodity Flows	●	✓	×	✓	●
Determination of Service Level	×	✓	×	✓	●
Mode Choice	●	●	×	●	●
Route Choice	●	●	×	×	●
Equipment Configuration	●	●	●	●	●
Determination of Loading Patterns	✓	✓	×	●	●
Determination of Freight Activity	●	●	●	●	●
Calculation of Fuel Consumption	✓	✓	✓	✓	✓
Determination of Emission Factors	●	●	●	●	●
Calculation of Emissions	●	●	●	●	●
Spatial Allocation of Emissions	×	×	✓	✓	×
Temporal Allocation of Emissions	×	×	✓	✓	×
Analysis of Scenarios	✓	✓	✓	✓	✓
Uncertainty Analysis	✓	✓	✓	✓	✓

● Mandatory ✓ Applicable × Not Applicable

Key: ✓ indicates that a parameter is analyzed in the way denoted by the column: × indicates that the parameter is not discussed in the way denoted by the column.

determination of loading patterns (to calculate payload), freight activity, and emission factors, as is the calculation of fuel consumption (if emissions are calculated from fuel consumption) and emissions. The spatial and temporal allocation of emissions is not relevant for this type of application because the input parameters do not offer the appropriate level of detail to support dispersion modeling.

Freight Corridor

This application calculates freight emissions from a transportation corridor, which can fall within one jurisdiction (state), or cross multiple jurisdictional boundaries. Supply chain design is not relevant because the application does not intend to model a specific supply chain. Link and node characterization are critical because links and nodes along a corridor can have unique characteristics in terms of capacity, traffic volumes, congestion levels, and grade. Because freight activity can be determined from commodity flows, the processes regarding commodity flows, mode choice, and route choice are all relevant to this application. The determination of service levels also can be relevant because of the logistics requirements from different commodity types (e.g., higher-value commodities demand faster transit times). As in other applications, the subsequent processes are required, including equipment configuration, determination of loading patterns (to calculate payload), freight activity, and emission factors, as is the calculation of fuel consumption (if emissions are calculated from fuel consumption) and emissions. The spatial and temporal allocation of emissions is not relevant for this type of application because the input parameters do not offer the appropriate level of detail to support dispersion modeling.

Metropolitan

This application calculates freight emissions inventories within a metropolitan region. Supply chain design is not relevant because the application does not intend to model a specific supply chain. Link and node characterization are important because links and nodes within a metropolitan region can have unique characteristics that affect emissions. Because vehicle activity is provided as an external input parameter, the processes regarding commodity flows, service level, mode choice, route choice, and loading patterns are not relevant to this application. As in other applications, the subsequent processes are required, including equipment configuration, freight activity, and emission factors, as is the calculation of fuel consumption (if emissions are calculated from fuel consumption) and emissions. Spatial and temporal allocation of emissions can be relevant for this type of application because the input parameters can offer the appropriate level of detail to support dispersion modeling.

Facility

This application calculates freight emissions from freight facilities including truck terminals, railyards, marine and inland ports, and airports. Supply chain design is not relevant because the application does not intend to model a specific supply chain. Node characterization is possibly one of the most important processes given that the analysis is associated with a node itself. Link characterization can be used if the system boundaries associated with the analysis include surrounding transportation links (or if links within the facility can be identified). The determination of service levels is not relevant to this application because mode choice is more a function of infrastructure availability. If freight activity is determined from commodity flows, the processes regarding commodity flows, service level, and mode choice are relevant to this application. Route choice is generally not relevant because the analysis is done at a facility level. As in other applications, the subsequent processes are required, including equipment configuration, freight activity, and emission factors, as is the calculation of fuel consumption (if emissions are calculated from fuel consumption) and emissions. Spatial and temporal allocation of emissions can be relevant for this type of application because the input parameters can offer the appropriate level of detail to support dispersion modeling.

Supply Chain

This application calculates the emissions associated with a specific supply chain. Supply chain design is required to determine the location of the relevant facilities involved in the supply chain. The level of link and node characterization will need to be commensurate with the level of detail and accuracy required by the analysis. Because freight activity will be determined from commodity flows, the processes regarding commodity flows, service levels, mode choice, and route choice are required. All of the subsequent processes are necessary, including equipment configuration, determination of loading patterns (to calculate payload), freight activity, and emission factors, as is calculation of fuel consumption (if emissions are calculated from fuel consumption) and emissions. The spatial and temporal allocation of emissions is not relevant for this type of application because the effects of an individual supply chain are not likely to have significant local impacts.

4.4 Case Study

This section presents a case study that illustrates a possible application of the Conceptual Model. The case study involves the comparison of different supply chain configurations for importing products from Asia to Chicago.

Many product supply chains—from automotive to retail—rely on imports of parts or finished products from Asia. These shipments are typically consolidated before reaching an Asian outbound marine port, then shipped to an inbound marine port in North America. Most ocean containers are then either transloaded directly onto double-stack trains, or deconsolidated at transloading facilities, where shipments are transferred to trucks for final delivery.

In this specific case study, the goal is to quantify emissions associated with transporting 100 lbs of product X from Shanghai to Chicago via three supply chains: ocean/rail via Long Beach, ocean/truck via Seattle, and ocean/rail via Prince Rupert, BC. Other objectives of the analysis are as follows to:

- Assist in incorporating emissions in the planning and operations of logistics activities,
- Identify which parameters are responsible for changes in emission outputs (e.g., facility location, mode choice, route choice, equipment configuration),
- Track trends in freight emissions over time, and
- Compare company performance against best-in-class through a benchmarking analysis.

The most likely audience for this type of analysis will be manufacturers sourcing raw materials, parts, or finished products from Asia. The results of the analysis are likely to be one of the criteria for designing or modifying a supply chain, given that other considerations such as economics and reliability also need to be taken into account.

Input parameters include facility location, shipment characteristics, mode choice, route choice, inventory levels, packaging, delivery patterns, equipment characteristics, and timeframe. Outputs from this analysis include freight emissions associated with the transportation necessary to manufacture and distribute product X under different scenarios in each of the three supply chains. All objects described in Exhibit 4-7 will be used in this analysis. The following sections define the processes required for this analysis.

Supply Chain Design

Users need to define the logistics facilities involved in a product supply chain, as well as the product flows between these facilities. In this case study, the following supply chains will be considered:

- Shanghai to Chicago via Long Beach, with double-stack intermodal service from Los Angeles to Chicago;
- Shanghai to Chicago via Seattle, with trucking service from Seattle to Chicago; and
- Shanghai to Chicago via Port of Prince Rupert, with double-stack intermodal service from Port of Prince Rupert (PPR) to Chicago.

Exhibit 4-14 illustrates the logistics facilities (nodes) and the product flows between facilities.

For freight transportation demand, it can be assumed that calculations will be based on a product that weighs 100 lbs and weighs out. It also will be assumed that the user has enough volume to fill an entire ocean container.

Because the functional unit for this analysis is one product and the modes are already pre-selected, the processes for deter-

Exhibit 4-14. Logistics facilities and flows by supply chain.

Supply Chain	Logistics Facilities/Nodes	Product Flows
Long Beach	• Port of Shanghai • Port of Long Beach (POLB) • Intermodal facility in Los Angeles • Intermodal facility in Chicago	• Port of Shanghai to POLB (ocean) • POLB to intermodal facility in Los Angeles (rail) • Intermodal facility in Los Angeles to intermodal facility in Chicago (rail)
Seattle	• Port of Shanghai • Port of Seattle • Trucking distribution center in Seattle • Trucking distribution center in Chicago	• Port of Shanghai to Port of Seattle (ocean) • Port of Seattle to trucking distribution center in Seattle (drayage truck) • Trucking distribution center in Seattle to trucking distribution center in Chicago (long-distance truck)
PPR	• Port of Shanghai • Port of Prince Rupert (PPR) • Intermodal facility in Chicago	• Port of Shanghai to PPR (ocean) • PPR to intermodal facility in Chicago (rail)

mination of commodity flows, determination of service level, and mode choice are not required for this analysis.

Node Characterization

Nodes represent freight facilities, including trucking terminals, railyards, and marine/inland ports. The Exhibit 4-15 characterizes all nodes included in this analysis. For the simplest analysis, all nodes can be characterized as freight facilities (i.e., no virtual nodes). However, virtual nodes can be used to separate links on the same route with different activity profiles (e.g., road grade, rail grade, congestion levels). Nodes will not be characterized in terms of equipment availability (due to lack of detailed information from a shipper's perspective) and geographic area (because shippers are not interested in that type of information).

Link Characterization

A link is a transportation facility connecting two nodes. In this analysis, the links considered will be the following:

- Ocean routes from the Port of Shanghai to the ports of Long Beach, Seattle, and Prince Rupert;
- Alameda (rail) corridor between the Port of Long Beach to a rail intermodal terminal in downtown Los Angeles;
- Rail corridor between a rail intermodal terminal in downtown Los Angeles to a rail intermodal terminal in Chicago;
- Rail corridor between PPR and a rail intermodal terminal in Chicago;
- Truck corridor between the Port of Seattle and a trucking distribution center in Chicago;
- Truck corridor between trucking distribution centers in Seattle and Chicago.

Depending on the level of detail required for the analysis, these corridors can be broken down in multiple sublinks to reflect different operational characteristics of different ocean, rail, and road sections. For example, ocean routes can be broken down depending on the ships' activity profiles: cruise, speed reduction zones, and maneuvering (hotelling emissions should be associated with a node). Truck and rail routes can be subdivided into multiple links, if detailed information about capacity, grade, average speed, and congestion level are available. All links need to be characterized as outlined in Exhibit 4-9.

Equipment Configuration

This process consists of the determination of equipment characteristics for all routes included in this analysis. The following equipment types should be characterized based on the parameters included in Exhibit 4-10: OGVs, double-stack trains, drayage trucks, and long-distance trucks. Depending on the level of sophistication of the analysis, users can either rely on industry defaults for vehicles or they can customize to the specific vehicles they utilize. For example, if a firm is a SmartWay partner, they might choose to configure a long-distance truck that has a better-than-average rating for fuel efficiency due to the use of aerodynamic devices.

Determination of Loading Patterns

The main importance of this process is to determine the payload associated with each type of equipment on each link. This will determine the share of vehicle emissions that need to be allocated to the product. Because the product in question weighs out, the equipment utilization (payload as a share of total weight capacity) needs to be determined. For example, if the capacity of a truck trailer is 80,000 lbs, the user can assume that a truck would carry 72,000 lbs (i.e., 90% utilization), and that 1/720 of total vehicle emissions would be allocated to a product that weighs 100 lbs.

Determination of Freight Activity

Freight activity can be calculated separately by scenario, mode, activity profile, transportation equipment, link/node,

Exhibit 4-15. Parameters for node characterization.

Node	Link Connectivity	Mode Availability	Equipment Availability	Geographic Area
Port of Shanghai (POS)	SEA, PPR, LBE	Ocean, truck, rail	N/A	N/A
Port of Long Beach (LBE)	POS, LA_INT	Ocean, truck, rail	N/A	N/A
Port of Prince Rupert (PPR)	CHI_INT	Ocean, rail	N/A	N/A
Intermodal facility in Los Angeles (LA_INT)	LBE, CHI_INT	Rail, truck	N/A	N/A
Intermodal facility in Chicago (CHI_INT)	PPR, LA_INT	Rail, truck	N/A	N/A
Trucking distribution terminal in Seattle (SEA_TRK)	SEA, CHI_TRK	Truck	N/A	N/A
Trucking distribution terminal in Chicago (CHI_TRK)	SEA_TRK	Truck	N/A	N/A

and time period. The specific formulas that will be used to calculate freight activity will depend on the type of analysis and the exact input parameters. The following provide some examples of calculations of freight activity at the link level.

- Intermodal rail service: rail activity can be initially measured in ton-miles of revenue freight and then converted into fuel consumption. In this example, the product weighs 100 lbs, the rail link is 50 miles long, and rail activity will be equal to $100 \times 50/2000 = 2.5$ ton-miles. Rail activity in ton-miles will be divided by a fuel efficiency factor (ton-miles/gallons) that is representative of the rail link and equipment in question to determine the fuel consumption allocated to the product on that specific link. In this example, the fuel consumed to transport this load on this link will be 2.5 ton-miles/400 ton-miles/gallons = 0.00625 gallons.

$$ACT_{SCE,MOD,PRO,EQP,LNK,TIM} = \frac{COM_{SCE,MOD,PRO,EQP,LNK,TIM} \times Link\_Length_{LNK}}{Fuel\_Efficiency_{EQP,PRO,LNK}}$$

(Equation 35)

- Drayage and long-distance trucks: truck activity can be measured in VMT on each link allocated to the specific product. For example, if a product weighs 100 lbs, the link is 50 miles long, and the amount that can be loaded onto a truck is 72,000 lbs (90% of 80,000 lbs), the VMT allocated to this product on this link will be 100 lbs × 50 miles/72,000 lbs/vehicle = 0.0694 VMT.

$$ACT_{SCE,MOD,PRO,EQP,LNK,TIM} = \frac{COM_{SCE,MOD,PRO,EQP,LNK,TIM} \times Link\_Length_{LNK}}{Pay_{SCE,MOD,EQP}}$$

(Equation 36)

Since empty equipment activity will affect emissions, they will also need to be included and allocated to the load.

Determination of Emission Factor

The determination of emission factors needs to be commensurate with the level of detail required by the analysis. In the simplest analysis, a user can rely on default emission factors by mode independently of the vehicle activity profile. For example, a single emission factor can be used for an entire ocean, rail, or truck route. For more sophisticated analyses, emission factors can be determined separately by transportation equipment, activity profile, and link. For example, different emission factors will be determined for different ship types for the following operational modes: cruise, reduced speed zone, maneuver, and hotelling.

Calculation of Emissions

As previously indicated, freight emissions are generally the product of freight activity (e.g., fuel consumed, energy generated, or VMT), and emission factors (in grams of pollutant per measure of freight activity). Emissions will be calculated for each pollutant, scenario, mode, link/node, and time period, as shown previously in Equations 27 and 28.

This analysis does not involve the spatial or temporal allocation of emissions.

Model Calibration

It is possible that the user might have information from carriers (on fuel consumption, for example), which will enable the application of user-specific fuel efficiency factors instead of model defaults.

Analysis of Scenarios

Scenarios can be differentiated based on any parameter in the model. For example, freight emissions can be evaluated over time to examine emission changes based on changes in facility locations, production outputs, and service levels, as well as mode choice and/or equipment decisions. Sensitivity analyses can be performed to evaluate the effects of given parameters on emissions, and this can assist users in their decision-making process.

The emissions associated with a mode in one scenario are calculated as shown previously in Equation 31. Subsequently, total emissions associated with one scenario are calculated as shown previously in Equation 32.

CHAPTER 5

Recommended Research Areas

This chapter provides five recommended areas for research that offer great promise for improving freight emissions estimates. Although these five research statements are mode-specific, the link between modes can be addressed with the implementation of the Conceptual Model.

Each of these areas will improve the Conceptual Model and modeling of these modes in general. The descriptions of these research areas have been written as research statements with sections describing background, objectives, description of tasks, and funding requirements. This will provide the basis for NCFRP to develop statements of work and requests for proposals for future work.

5.1 Improving the Allocation of National Transportation Emissions

Background

The transportation sector accounts for a large portion of the nation's emissions inventory, resulting in significant local health and public welfare impacts as well as nationwide greenhouse gas emissions (GHGs). These emissions are the subject of public policy at the national, state, and local levels, in which regulatory agencies and industry organizations work together to minimize transportation emissions in a cost-effective manner. Calculations of both the current emissions impacts and the benefits of mitigation strategies rely on the accurate allocation of national emissions estimates to individual geographic regions, transportation modes, and vehicle types.

On the national scale, criteria air pollutant (CAP) and hazardous air pollutant (HAP) emissions are calculated by the EPA in the National Emissions Inventory (the NEI), (*2*) which is completed every 3 years. The NEI provides emissions data on the county level by SCC, representing the on-road, nonroad, locomotive, marine, and air transportation modes, as well as subcategories within each mode.

In addition, nationwide GHG emissions are calculated by EPA in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (the EPA GHG Inventory) annually. (*1*) This study allocates GHG emissions to each sector of the economy, including transportation, and within the transportation sector allocates emissions to each transportation mode, including on-road and nonroad vehicles, locomotives, aircraft, and marine vessels. Additionally, for several modes including on-road vehicles, the GHG Inventory further divides emissions by vehicle type. The allocations are based on share of fuel consumption and fuel type.

For both the NEI and the GHG Inventory, the methodology used to allocate emissions varies by mode, depending on available data sources. In some modes, such as rail, the NEI uses a "top-down" methodology, in which national-level fuel consumption data are allocated to specific regions and modes, in proportion to a measure of activity level. Calculations for other modes, such as on-road and nonroad, rely on a "bottom-up" methodology, in which activity data reported on the county level are aggregated and modeled using the National Mobile Emissions Model (NMIM), with resulting emissions allocated to each region. The EPA GHG Inventory methodology uses both top-down and bottom-up approaches simultaneously, in which a top-down calculation of fuel consumption by sector and mode based on fuel statistics is reconciled with a bottom-up modal analysis of fuel consumption by industry activity measures. Although the NEI focuses on regional allocation and the EPA GHG Inventory focuses on modal allocation, the accuracy of both methodologies depends on the quality of regional and activity data and the allocation method used, which vary across modes.

There are both known and unknown limitations to the data used for regional and modal allocation, leading to uncertainty in the resulting emissions allocations. Research is needed to determine the sources and magnitude of uncertainty in emissions allocation, and to develop more accurate methods and data sources for allocating national transportation emissions by region.

This research statement builds on prior work completed by the Transportation Research Board and other regulatory agencies. The analysis of data sources continues research completed by transportation sector (such as this effort) and mode (*ACRP Report 11: Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories*). (*37*)

EPA has analyzed transportation emissions in depth, both in terms of GHG inventories (3) and in terms of evaluating uncertainty in emissions results. (*195*)

The subjects and results of this research may impact agencies at the national, state, and regional level. The NEI is conducted by the EPA Office of Air Planning and Standards. The GHG Inventory is conducted by the EPA Climate Change Division of the Office of Atmospheric Programs. Emissions of CAPs and hazardous air pollutants (HAPs) within transportation modes are regulated by EPA in nonattainment areas (NAAs) and in state implementation plans. Finally, transportation-related GHG emissions are under analysis by several state DOTs either for inventory or policy purposes.

Objectives

The objective of this research is to analyze current methods and data sources for allocating national CAP, HAP, and GHG emissions by region and mode, and to identify opportunities for improving the accuracy of such allocations. To thoroughly evaluate the issues involved, this research will include a review of sources of uncertainty in the data and methodologies used, an evaluation of the magnitude of uncertainty in regional emissions inventories, and an identification of improvements to minimize uncertainties in regional emissions estimates. Finally, since the GHG Inventory allocates emissions by mode but not region, the research will analyze potential methods to allocate regional GHG emissions. The research and results should span pollutant types including CAP, HAP, and GHG, as well as transportation modes including on-road, nonroad, locomotive, marine, and aircraft.

Description of Tasks

Task descriptions are intended to provide a framework for conducting the research. NCFRP is seeking the insights of proposers on how best to achieve the research objective. Proposers are expected to describe research plans that can realistically be accomplished within the constraints of available funds and contract time. Proposals must present the proposers' current thinking in sufficient detail to demonstrate their understanding of the issues and the soundness of their approach to meeting the research objective.

Task 1: Conduct Kick-Off Call

Conduct a conference call with the panel 30 days after contract initiation to discuss the revised work plan developed in response to the panel review of the research plan in the agency's original proposal.

Task 2: Describe the Current Methodologies

Describe the current methodologies used to allocate national emissions to regions and transportation modes. Identify sources of uncertainty in data sources and methodologies used in allocation.

Task 3: Analyze the Limitations of Current Methodologies

Building on Task 2, describe the limitations of current allocation methods, and evaluate the magnitude of uncertainty both in the data and methodologies used to allocate emissions to the regional level. Submit an interim report to the panel describing the results of Tasks 2 and 3.

Task 4: Identify Options for Reducing Uncertainty

Identify and evaluate options for reducing uncertainty and increasing accuracy in regional and modal emissions estimates by pollutant and transportation mode. The analysis of options should include the extent of data or modeling requirements, the ease or complexity of data collection, and any institutional or industry barriers to implementing the proposed strategy. Recommend opportunities for strategy implementation that would reduce uncertainty in regional emissions estimates considering budget and time constraints.

Task 5: Analyze Allocation Strategies

Analyze strategies for extending the allocation of GHG emissions to the state and regional level, with consideration of accuracy and implementation issues.

Task 6: Prepare Final Report

Prepare a final report providing the results of the entire research effort.

Funding Requirements

A funding level of $200,000 is allocated to this research. The contract will be completed within 12 months of acceptance of proposal, including 1 month for NCFRP review and approval of the interim report and 1 month for NCFRP review and contractor revision of the final report. It is anticipated that the research will not require fieldwork, laboratory testing, or travel in addition to meetings with the project panel.

5.2 Refining Road Project-Level Emission Estimates Methodologies

Background

Previous research has indicated the importance of accurately reflecting the effects of local parameters on vehicle emissions, especially at the project or corridor level. These parameters can include road grade, road capacity, congestion, and vehicle aerodynamic coefficients, among others. Although there have been many advances in methodologies to capture such effects, there still is no clear guidance on the best methods for different types of applications. With the release of the final version of MOVES, scheduled for the end of 2009, EPA is indicating that MOVES will be the required model for SIP and conformity analyses. However, it is unclear how MOVES should be utilized for project-level analyses.

MOVES employs a "modal" emission rate approach as a prelude to finer-scale modeling. It relies primarily on second-by-second vehicle emissions data to develop emissions rates, and better represents the physical processes from vehicles, including the ability to model cold starts and extended idling, which is especially critical for heavy-duty trucks. Although the modal approach taken by MOVES seems appropriate to capture some local impacts, other tools, such as the Comprehensive Modal Emissions Model, developed by UC Riverside under an EPA contract, provide a more direct and transparent way to account for factors such as vehicle aerodynamics, pavement quality, and road grade. As a result, it is unclear as to whether it will the best tool for all applications, or how local traffic and vehicle data will need to be collected for use in MOVES or other applicable emission models.

Although this research does not strictly apply to heavy-duty trucks, the evaluation of truck emissions would greatly benefit from this research project. Despite the fact that some trucks can avoid congestion by traveling during off-peak times, congestion is expected to worsen over time. Thus, the trend is that trucks will become more affected by congested roadways in the future. Additionally, voluntary programs such as EPA's SmartWay, have been advocating for the use of devices that improve either aerodynamic coefficients or rolling resistance coefficients, and these parameters need to be properly captured in emission calculations.

Objectives

This research aims to address the following objectives:

- Determine the best methods/models to capture the effects of local traffic and vehicle parameters on vehicle emissions for different types of application and
- Determine how to best capture local traffic activity and local vehicle characteristics for use in different emission models.

Description of Tasks

Task descriptions are intended to provide a framework for conducting the research. The panel is seeking the insights of proposers on how best to achieve the research objectives. Proposers are expected to describe research plans that can realistically be accomplished within the constraints of available funds and contract time. Proposals must present the proposers' current thinking in sufficient detail to demonstrate their understanding of the issues and the soundness of their approach to meeting the research objective.

Task 1: Conduct Kick-Off Call

Conduct a conference call with the panel within 30 days after contract initiation to discuss the revised work plan developed in response to the panel review of the research plan in the agency's original proposal.

Task 2: Review Effects of Local Parameters on Vehicle Emissions

Conduct a brief literature review on the effects of local parameters on vehicle emissions, aiming at selecting a list of parameters that should be included in the research (i.e., those with the most substantial effects on vehicle emissions). At a minimum, congestion, road grade, and vehicle aerodynamics should be considered. Other parameters such as pavement quality could also be included.

Task 3: Determine Accuracy Needs and Limitations

Determine the accuracy requirements and limitations for emissions analyses that aim at capturing the effects of local parameters on vehicle emissions.

This research needs to be framed by accuracy requirements. On one end of the spectrum, accuracy requirements for air quality analyses and emission estimation need to be determined. This will guide the selection of appropriate methods to quantify the effects of local parameters on emissions. At the other end of the spectrum, the limitations of methods (data collection, traffic modeling, emission modeling) need to be assessed. In other words, the right balance between how accurate methods *should be* and how accurate methods *can be* needs to be achieved.

This task will also consider the different types of applications that might require the evaluation of effects of local parameters on vehicle emissions. For example, projects that add road capacity, improve traffic operations, or manage travel demand could have impacts on road congestion, and consequently on vehicle emissions. It will be important to consider these different applications when evaluating accuracy requirements and limitations.

Task 4: Evaluate Current Methods

Conduct an evaluation of current methods to capture the effects of local parameters on emissions, including the tradeoffs between accuracy and data limitations.

Current methods to evaluate congestion effects can be roughly divided into three types: (1) speed correction factors, (2) customized driving cycles, and (3) vehicle-specific power. Currently MOBILE6 and EMFAC estimate the effects of congestion on emissions by using speed correction factors that differentiate emission factors by average speed. Previous research has indicated that this method might work reasonably well for uncongested freeways but it is ill-suited to assess the congestion effects on arterials and local roads or on congested freeways. The use of modal emission models such as CMEM can provide a more accurate representation of the effects of congestion on emissions, but they rely on the development of customized driving cycles that depend on heavy data requirements, and might not be representative of driving conditions other than those for which they were originally developed. Somewhere in between are methods such as those proposed by MOVES, where a binning approach could provide a more accurate representation of driving conditions by assigning the share of time in each combination of speed range and vehicle-specific power. However, it is uncertain how local input driving parameters will be used to feed into the binning approach. New methodologies need to be developed and tested to bridge the gap between traffic data availability and emission methodologies that provide an accurate representation of congestion.

Regarding other parameters such as road grade and vehicle aerodynamic coefficients, some models can consider them explicitly (CMEM), while others (MOVES) might require additional steps to convert these parameters into modified vehicle-specific power estimates. This research should examine the feasibility and levels of effort and technical expertise required to make such conversions, and describe whether the conversions would yield accurate estimates of the effects of such parameters on vehicle emissions.

Task 5: Provide Interim Report

Provide an interim report to panel members summarizing the findings from Tasks 2, 3, and 4. Panel members would review the report and provide supporting concurrence and/or recommendations for additional data gathering as needed.

Task 6: Improve Methods to Model Traffic Activity

Task 6 will improve the methods to model traffic activity to reflect congestion impacts on vehicle emissions more accurately. This will be accomplished by (1) the development of new congestion metrics that can be used in emissions calculations and (2) the development of new methods for traffic data collection to gather the right type of information for emissions calculations, including information on vehicle mix.

The modeling of traffic activity needs to be conducted in such a way that it fulfills the needs of emissions and air quality analyses that aim to incorporate the effects of congestion. In such a context, traffic modeling relies on three elements: congestion modeling, traffic data, and vehicle configuration.

Congestion has traditionally been represented in terms of road level of service (LOS) or total vehicle delay, and there are concerns about the use of such metrics as inputs in emissions models. LOS is a discrete measure of traffic conditions, while the estimation of emissions depends on continuous variables. Although LOS can be represented by an “average” driving cycle, there are criticisms associated with representing a level of service by a single driving cycle, given that an LOS represents a wide variety of traffic conditions. As a result, there is a need to develop new congestion metrics that can be used in emissions estimation.

Traffic data need to be collected in a way that enables the calculation of such new congestion metrics. The basic concepts of traffic theory, which model traffic based on traffic flow, traffic density, and average speed, currently determine traffic data collection processes. New methods for traffic data collection need to be developed and implemented to gather the right type of information for emissions estimation. For example, new technologies (e.g., GPS, cell phones) can collect traffic data in real time, and methods to aggregate traffic data could both protect drivers’ privacy and provide the appropriate inputs for emission models.

The VMT share by vehicle type is a key input to emission models, but information on vehicle type is rarely collected on site. Instead, it typically relies on vehicle registration data, which can be a poor proxy for local traffic mix, especially for heavy-duty trucks. With the requirements of emission models in mind, new methods could be developed to capture data on traffic mix.

Task 7: Evaluate Methodologies for Local Data Collection

Task 7 will evaluate different methodologies to collect local data, including traffic data, infrastructure data (e.g., road grade, pavement quality), and vehicle characteristics data (e.g., aerodynamics).

The use of GPS devices could provide enough information for the development of real-time driving cycles, which could be linked with modal emission models for emissions estimation on a second-by-second basis. GPS devices could also transmit vehicle information for proper characterization of fuel type, engine and transmission characteristics, and vehicle gross vehicle weight rating (GVWR). Road grade information can be obtained by superimposing such driving cycles with grade information for relevant road networks.

Task 8: Prepare Final Report

Task 8 will compile the results from previous tasks in a clear and concise document that will serve as support for future emissions analyses.

Funding Requirements

A funding level of $200,000 is allocated to this research. The contract will be completed within 12 months of acceptance of proposal, including 1 month for review and approval of the interim report and 1 month for review and contractor revision of the final report. It is anticipated that the research will not require fieldwork, laboratory testing, or travel in addition to meetings with the project panel.

5.3 Improving Rail Activity Data for Emission Calculations

Background

Current practice for estimating freight rail emissions is often based on EPA's methodology, which relies on fuel consumption data to determine emissions. Detailed fuel consumption data are typically considered sensitive information by railroads. However, aggregate fuel consumption data, which are based on 100% reporting for Class I railroads, are available from industry or government agencies (i.e., Association of American Railroads, Energy Information Administration, state agencies, private companies via surveys). Streamlined, or "top-down," methods determine emissions based on publicly available data on fuel consumption at the national or state level, and apportion emissions to the state or county level using an available activity metric, such as traffic density or mileage of active track. Detailed, or "bottom-up," methods calculate fuel consumption either by measuring freight movements or surveying individual railroad companies. Typically, there is little or no published information on railroad activity available for a specific region. Thus, state and regional air quality agencies must obtain railroad activity data directly from the railroad companies.

Objectives

The objective of this research project is to improve rail activity data for emission calculations through the development of alternative methods for railroad data reporting and the comparison of different methods to disaggregate rail fuel consumption data.

Description of Tasks

Task descriptions are intended to provide a framework for conducting the research. The panel is seeking the insights of proposers on how best to achieve the research objectives. Proposers are expected to describe research plans that can realistically be accomplished within the constraints of available funds and contract time. Proposals must present the proposers' current thinking in sufficient detail to demonstrate their understanding of the issues and the soundness of their approach to meeting the research objective.

Task 1: Conduct Kick-Off Call

Conduct a conference call with the panel within 30 days after contract initiation to discuss the revised work plan developed in response to the panel review of the research plan in the agency's original proposal.

Task 2: Develop Alternative Methods for Railroad Data Reporting

Three factors drive the need for new methods of railroad fuel data reporting. First, there are large uncertainties associated with the use of aggregated fuel data for regional and local emission analyses. Second, disaggregated data can only be obtained directly from the railroads. Because of concerns about releasing sensitive information, railroads are sometimes reluctant to share detailed operational activity. Third, there are concerns about the accuracy of county-level gross ton-miles data provided by the railroads. As a result, this task should (1) examine the concerns presented by railroads, (2) determine the most critical information necessary to improve the accuracy of emission estimates, (3) determine the most effective ways to increase the cooperation between public agencies and private railroads, and (4) develop new methods for collecting railroad data.

Task 3: Compare Methods to Disaggregate Rail Fuel Consumption Data

Many regional and local emission analyses rely on different methods to disaggregate rail fuel consumption data. Depending on the chosen method, high levels of uncertainties are involved, and this task will determine how such methods can be improved through the collection of local and regional data. The research should consider the tradeoffs between improved accuracy and additional resources needed to collect and report local and regional data.

Task 4: Prepare Final Report

Compile the results from previous tasks in a clear and concise document that will serve as a support for future rail emissions analyses.

Funding Requirements

A funding level of $100,000 is allocated to this research. The contract will be completed within 12 months of acceptance of proposal. It is anticipated that the research will not require fieldwork, laboratory testing, or travel in addition to meetings with the project panel.

5.4 Improving Parameters and Methodologies for Estimating Marine Goods Movement Emissions

Background

Numerous issues arise in the calculation of emissions at and near marine transport and goods movement terminals. Emissions at these port areas include activity from ocean-going vessels (OGVs), commercial and non-commercial harbor craft (H/C), and cargo handling equipment (CHE). Each mode has unique calculation methodologies and input data, as well as resulting uncertainties.

Emissions from marine goods movement are a significant share of the nation's total freight emissions. For example, the EPA GHG Inventory estimated that 14% of the nation's 2005 total freight transportation-related CO_2 emissions are due to domestic waterborne commerce alone. The share of other pollutants is likely to be higher given the relatively uncontrolled emissions from this sector. At a global scale, the marine transport sector emits 1.2–1.6 million metric tons (Tg) of PM_{10}, 4.7–6.5 Tg of SO_x, and 5–6.9 Tg of NO_x annually. That is, approximately 15% and 5%–8% of global NO_x and SO_x emissions, respectively, are attributable to ocean-going ships, and approximately 60,000 annual cardiopulmonary and lung cancer deaths are related to PM emissions from marine shipping. However, all emission estimates from marine shipping are uncertain.

Current best practices in preparing individual port emission inventories have advanced considerably since the first attempts at quantifying national port-related emissions. Generally, there are insufficient data to confidently and quantitatively assess marine emission uncertainties. Although overall accuracy and uncertainty associated with different methods and models to estimate freight emissions are not generally quantified, sources of these uncertainties have been identified.

For example, emissions from OGVs are usually determined at and around ports only, as these are the entrances and clearances of cargo into the regions of modeling interest, using information on number of calls at a particular port, engine power, load factors, emission factors and time in like modes. These data are often incomplete or of insufficient quality. Although a wide range of commercial harbor craft (H/C) operate in the vicinity of ports, many of these vessels serve purposes other than just direct goods movement and their activities and vessel parameters are often unknown. The diversity of types, the number, and fleet parameters of CHE in use is related to the diversity and amount of freight handled at a port. Even in cases where cargo data are available, CHE data are often estimates.

Further uncertainty arises when aggregating marine freight emissions regionally or nationally. For example, emissions at a national scale are computed in EPA's National Emission Inventory (NEI) with a reliance on a combination of distinct methodologies for each source category and aggregation to the county level. Furthermore, data in the 2002 and 2005 NEI are based on an inventory of marine engines conducted in 1998. Emissions estimates appropriate at two scales—local and national—should be estimated and appropriately joined.

To improve the emissions estimate from this critical sector of the nation's freight transport infrastructure, these issues need to be addressed.

Objectives

The goal of the following objectives is to improve the estimation of emissions from marine freight-related (OGV, H/C, and CHE) activities near ports, and their impact on national emissions:

- OGV
  - Develop updated and more accurate marine vessel emission factors and load factors,

  - Improve information and emissions factors associated with auxiliary engines, and
  - Improve emission factors for methane, nitrous oxide, and black carbon.
- H/C
  - Improve input parameters for HC emission estimation, especially emission factors and load factors.
- CHE
  - Develop updated emission parameters for CHE engines, especially emission factors and load factors, and
  - Develop idling emission factors for CHE and idling time estimates.
- National Scale
  - Conduct updated marine inventory for future NEI publications.

The objective of this research statement is to address and implement these recommended changes. To best achieve this objective, the recommendations have been reorganized and distilled here into three primary objectives based on theme rather than source category. Each objective applies to several of the source categories active at ports.

Objective 1: To Improve Emission Inputs for Marine and Port-Related Emissions

Current OGV and H/C emission factors are still based on limited test data and provide only a rough estimate of emissions from newer vessels. Several new emissions testing programs funded by the California Air Resources Board, EPA, and Environment Canada, among others, have involved OGVs, H/C, and CHE. These new data need to be reviewed and compared against currently accepted emission factors. Results of this current testing of emissions should be compiled.

Specifically for OGVs, PM emission factors for slow- and medium-speed engines need further review, evaluation of impact of previous emission factors, development of emission factors specifically for $PM_{2.5}$, and advancement in the ability to relate PM and SO_X emissions to fuel sulfur level. Emission factors need to be improved for non CO_2 GHGs, including methane, nitrous oxide, and black (elemental) carbon. Improved emission factors also are needed for incinerators and boilers. In addition, emissions at low loads need to be examined since emission factors tend to increase rapidly when engine load drops below 20% maximum continuous rating (MCR).

Current emission factors for CHE are based on limited test data, often for on-road engines, and need to be updated to represent emissions from the current fleet of CHE engines. Especially for CHE, emission factors should be developed that separate idling from active-engine emission factors.

Better emissions input characteristics for other parameters also need to be developed. For OGV auxiliary engines and H/C, there is little consistent information on the number and size of the engines on vessels. Information needs to be developed including number, load factors, types of operation, and fuel used. Current H/C load factors differ from one another by a factor of two or more; this variance should be reduced by studies of H/C activity and engine load profiles. Separate profiles need to be developed for in-port versus inland river cargo movements. Duty cycles for nonroad engines should also be examined more fully and selected to provide CHE-specific load factors.

Objective 2: To Improve Modeling Methodologies for Port-Related Emissions

There are numerous improvements that should be made to activity and other emission modeling parameters for OGV, H/C, and CHE.

Data on vessel activity should be improved. For OGVs, domestic ship movements within the United States are currently not reported except in detailed inventories. H/C movement data at ports and on rivers also are generally not well documented. Additional data is needed for CHE activity profiles, specifically as used at ports and incorporating idle time. A suggested method to estimate these activity data needs to be developed.

Emission models should be improved to better estimate nonroad emissions. NONROAD will eventually be replaced by the MOVES model; it is unknown if OFFROAD will be similarly updated. Both should be improved to specifically handle CHE, H/C, and OGV engines, although MOVES should be able to calculate emissions at smaller spatial scales than either current model. Testing of the model is required once available.

Objective 3: To Implement Advances to Update Regional/National Scale Estimates for Port-Related Emissions

As advances are made in Objectives 1 and 2, they should be implemented to improve estimates in both local and regional/national scale emission inventories. Typically, detailed inventories are made at the scale of individual ports and are scaled to other areas to estimate regional and/or national emissions. The advances in port emission inventory practices should be implemented first to improve local emission inventories.

Simultaneously, national inventories should be updated that will incorporate the advances from Objectives 1 and 2. As more ports complete detailed emission inventories, guidance on port matching should be updated in order to better estimate emissions at small, poorly characterized ports. As this mapping between more and less detailed ports is developed and more ports produce updated, detailed emission inventories, the calculation of national and regional marine emissions should be updated to reflect—not only changes in equipment type and number—but also changes in age distribution and usage (load factor) of CHE, H/C, and OGV at the port. This will result in a more comprehensive National Emission Inventory (NEI) for the marine freight sector.

Description of Tasks

Task descriptions are intended to provide a framework for conducting the research. NCFRP is seeking the insights of proposers on how best to achieve the research objective. Proposers are expected to describe research plans that can realistically be accomplished within the constraints of available funds and contract time. Proposals must present the proposers' current thinking in sufficient detail to demonstrate their understanding of the issues and the soundness of their approach to meeting the research objective.

Task 1: Conduct Kick-Off Call

Conduct a conference call with the panel within 30 days after contract initiation to discuss the revised work plan developed in response to the panel review of the research plan in the agency's original proposal.

Task 2: Conduct Literature Review

Conduct a literature review and analysis to determine appropriate emission factors, load factors, duty cycles, and other parameters to represent the current fleet of engines used in CHE, H/C, and main, auxiliary, and boiler engines for OGV, and compare them to currently accepted factors.

Task 3: Develop Activity Methodology

Develop methodologies to estimate OGV, H/C, and CHE activities missing from current data sets. Once available, evaluate MOVES for performance in the marine sector.

Task 4: Update Emission Inventories

Update local scale marine freight emission inventories with best-practice data and methodologies. Develop enhanced port matching routine and update national marine-freight emission inventory.

Task 5: Provide Interim Report

Provide an interim report to panel members summarizing the findings from Tasks 2 and 3. Panel members would review the report and provide supporting concurrence and/or recommendations for additional data gathering as needed.

Task 6: Prepare Final Report

Prepare a final report providing results of the entire research effort.

Funding Requirements

A funding level of $250,000 is allocated to this research. The contract will be completed within 18 months of acceptance of proposal, including 1 month for review and approval of the interim report and 3 months for review and contractor revision of the final report. It is anticipated that the research will not require fieldwork, laboratory testing, or travel in addition to meetings with the project panel.

5.5 Improving Air Freight Emission Calculations

Background

Demand for air freight transportation is projected to return to strong growth in North America in the near future. OAG Aviation projects an annual growth rate of 5.6% per year by 2011 and an overall international 10-year annual average growth rate of 6.1% over the period from 2008 to 2017. Although increased fuel efficiency from new aircraft will partially mitigate increased air freight emissions, it is not expected to fully offset greenhouse gas emissions (GHGs) and will have minimal reductions on particulate matter and NO_x emissions. Current methods used to estimate air transportation emissions have focused on passenger aircraft because they are the major share of air transportation emissions. However, with the projected growth in air freight, the contribution of air freight needs to be more clearly determined, especially in light of the mixed-mode use of aircraft to move both passengers and air cargo. Further, limited data exists on emission indices for air freight aircraft as well as air freight performance data.

Current tools used to assess environmental impacts from air transportation are FAA's AEDT/EDMS. The focus to date has been with passenger aircraft, and default values have been developed with this as the basis. However, these default values may not always be appropriate for air cargo aircraft. Continued growth at major airports and regional hubs are leading to increased congestion and the use of alternative/secondary regional airports to avoid delays. This may include movement to airports mainly servicing air cargo needs. Nearby communities may be impacted, particularly as these operations may have significant activity during the nighttime period. Research is needed to clearly evaluate air freight emissions consistent with the knowledge level of air passenger aircraft as well as to develop a consistent scheme for allocating emissions associated with mixed air freight and air passenger operations. Better assignment of air passenger and air freight emissions will enable decision makers to make informed decisions about the impacts from future airport expansions for both air passenger and air cargo operations.

The research will need to be incorporated into FAA models because these are used to evaluate air quality impact assessments as required in state implementation plans and environmental impact assessments. Coordination with FAA and EPA will be needed to ensure that the research results can be incorporated into the modeling tools, both in terms of analysis of the results and the quality of information gathered.

Objective

The objective of this research is to develop an improved basis for generating emissions associated with air freight transportation. The research should examine the current usage and assignments made specific to air cargo freight within EDMS and the future AEDT modeling system. Some, but not all of the assignments would include: (1) aircraft/engine combinations, (2) assumptions and basis for takeoff weight, (3) glide slope angle, (4) time in mode, and (5) disaggregation of freight emissions for air passenger emissions. The research should evaluate the appropriateness of the current assignment practices, evaluate the limitations with the current approach, and provide recommendations for better assignments.

The proposed project comes at a critical time when research garnered from this study could be incorporated into the current development of the AEDT 2.0 Modeling System. Current assignment practices for mixed-mode air freight and passenger mode are probably not representative of the air freight transportation contribution. It is likely that emission reduction targets near airports will be needed at many of the nationwide airports as they are, or soon will be, located in air quality nonattainment areas due to the recently revised 24-hour $PM_{2.5}$ ambient air quality standard (65 $\mu g/m^3$ lowered to 35 $\mu g/m^3$) and the newly proposed 1-hour NO_2 standard of between 80–100 ppb to be finalized by January 2010.

Description of Tasks

Task descriptions are intended to provide a framework for conducting the research. NCFRP is seeking the insights of proposers on how best to achieve the research objective. Proposers are expected to describe research plans that can realistically be accomplished within the constraints of available funds and contract time. Proposals must present the proposers' current thinking in sufficient detail to demonstrate their understanding of the issues and the soundness of their approach to meeting the research objective.

Task 1: Conduct Kick-Off Call

Conduct a conference call with the panel within 30 days after contract initiation to discuss the revised work plan developed in response to the panel review of the research plan in the agency's original proposal.

Task 2: Describe Current Methods

Describe the current method used to estimate air freight emissions as implemented in EDMS. This would include details on the underlying assumptions, data sets used to support these assumptions and the extent to which the assumptions are justified, their relative importance, and the current limitations with the method and supporting databases.

Task 3: Identify Data Needs

For those data set or underlying assumptions that were identified as critical to improving the characterization of air freight emissions, provide recommendations on the additional data needed to support development of a more robust data set to better characterize freight emissions. This could include both activity data as well as emission indices.

Task 4: Provide Interim Report

Provide an interim report to panel members summarizing the findings from Task 2 and Task 3. Panel members would review the report and provide supporting concurrence and/or recommendations for additional data gathering as needed.

Task 5: Conduct Additional Data Gathering

Conduct additional data gathering as reached in discussion with panel members. This could include gathering existing data sets for further analysis or additional data gathered from field studies. Analyze the data for use in support of the EDMS/AEDT Modeling System.

Task 6: Develop Methodology for Disaggregating Freight Emissions

Develop an improved methodology for disaggregating freight emission fractions between air freight and air passengers when a plane operates in mixed mode. Include characterizations of potential impacts on time in mode, engine performance, and takeoff weight.

Task 7: Address Air Cargo Issues in AEDT Model Development

Currently, development of FAA's AEDT lacks participation from the air freight community. This effort is being sponsored by FAA using supporting contractors and the academic community. External oversight and guidance are provided on a once per year basis as part of the Design Review Group. Actively participate in at least one, and preferably two, stakeholder meetings as a representative of the air freight community to assure that issues relevant to air cargo transport are addressed as part of the model development process.

Task 8: Determine Impact of New Aircraft Technology in Modeling Methodology

New aircraft technology including very light jets (VLJs) and unmanned aerial vehicles (UAVs) will be used increasingly in future air freight transportation, particularly UAVs, in an effort to reduce labor costs. Identify how these technologies will change aircraft operations such as takeoff weight, glide slope, and emission indices, and the resulting likely change in air freight emissions.

Task 9: Prepare Final Report

Prepare a final report providing results of the entire research effort.

Funding Requirements

A funding level of $150,000 to $200,000 is allocated to this research. The contract will be completed within 18 to 24 months of acceptance of proposal, including 1 month for review and approval of the interim report and 1 month for review and contractor revision of the final report. It is anticipated that the research will not require fieldwork, laboratory testing, or travel in addition to meetings with the project panel.

The budget depends upon the additional data gathering effort involved in Task 5. The low-end estimate assumes existing data are available from the literature to support the analysis, while the high-end estimate allows for the need to collect field data in the case that published data are not available.

APPENDIX A

Pedigree Matrix

Criteria	Indicator Score				
	1	2	3	4	5
Impact on Final Result	Parameter contribution is unknown	Parameter is not likely to affect final results significantly	Parameter is within the top 10 contributors to final result	Parameter is within the top 5 contributors to final result	Parameter is the top contributor to final result
Acquisition Method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Nonqualified estimate
Independence of Data Supplier	Verified data, information from public or other independent source	Verified information from enterprise with interest in the study	Independent source, but based on nonverified information from industry	Nonverified information from industry	Nonverified information from the enterprise interested in the study
Representativeness	Representative data from sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but for shorter periods	Data from adequate number of sites, but for shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or for shorter periods
Temporal Correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area of study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological Correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology
Range of Variation	Estimate is a fixed and deterministic number	Estimate is likely to vary within a 10% range	Estimate is likely to vary within a 50% range	Estimate is likely to vary more than 50%	Estimate is likely to vary within unknown range or vary significantly among methods

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Acronyms

AAR	Association of American Railroads
ACES	Air Consulting and Engineering Solutions
AEDT	Aviation Environmental Design Tool
AEM	Advanced Emission Model
AIS	Automatic Identification System
APCD	Air Pollution Control District
APEX	Air Pollution Exposure Model
ARB	Air Resources Board
ASPEN	Assessment System for Population Exposure Nationwide
ATM	Air Traffic Management
ATRS	Air Transport Research Society
BADA	Base of Aircraft Data
BFFM2	Boeing Fuel Flow Method 2
BNSF	Burlington Northern Santa Fe Railroad
BSFC	Brake-Specific Fuel Consumption
BTS	Bureau of Transportation Statistics
Btu	British Thermal Unit
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CAEP	Committee on Aviation Environmental Protection
CAMx	Comprehensive Air quality Model with Extensions
CAP	Criteria Air Pollutant
CARB	California Air Resources Board
CASAC	Clean Air Scientific Advisory Committee
CDA	Continuous Descent Approach
CE	Categorical Exclusion
CEQ	Council on Environmental Quality
CEQA	California Environmental Quality Act
CF	Control Factor
CFD	Computational Fluid Dynamics
CH_4	Methane
CHE	Cargo Handling Equipment

CMAQ	Community Multiscale Air Quality
CMEM	Comprehensive Modal Emissions Model
CMV	Commercial Marine Vessel
CNG	Compressed Natural Gas
CNS	Communication, Navigation, and Surveillance
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2 Eq.	CO_2 Equivalent
COG	Council of Governments
CRC	Coordinating Research Council
DEOG	Diesel Exhaust Organic Gases
DF	Deterioration Factor
DMV	Department of Motor Vehicles
DPM	Diesel Particulate Matter
DWT	Dead Weight Tonnage
EDMS	Emissions and Dispersion Modeling System
EA	Environmental Assessment
EEA	Energy and Environmental Analysis, Inc.
EEZ	Exclusive Economic Zone
EF	Emissions Factor
EIA	Environmental Impact Analysis
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
EMD	Electro-Motive Diesel, Inc.
ERG	Eastern Research Group
ETMS	Enhanced Traffic Management System
FAF	Freight Analysis Framework
FESG	Forecasting and Economics Sub Group
FTP	Federal Test Procedure
GHG	Greenhouse Gas
GIFT	Geospatial Intermodal Freight Transportation
GIS	Geographic Information System
GM	General Motors
GPS	Global Positioning System
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GSE	Ground Support Equipment
GTM	Gross Ton-Miles
GVWR	Gross Vehicle Weight Rating
H/C	Harbor Craft
HAP	Hazardous Air Pollutant
HAPEM	Hazardous Air Pollutant Exposure Model
HARP	Hotspots Analysis and Reporting Program
HC	Hydrocarbon
HDDTC	Heavy-Duty Diesel Test Cycle

HDDV	Heavy-Duty Diesel Vehicle
HDT	Heavy-Duty Truck
HDV	Heavy-Duty Vehicle
HEATS	Houston Exposure to Air Toxics Study
HEM	Human Exposure Model
HFC	Hydrofluorocarbon
HHDT	Heavy Heavy-Duty Truck
HOV	High Occupancy Vehicle
HP	Horsepower
HPMS	Highway Performance Monitoring System
HRA	Health Risk Assessment
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IFTA	International Fuel Tax Agreement
IFTA	International Fuel Tax Association
I/M	Inspection and Maintenance
IMO	International Maritime Organization
INM	Integrated Noise Model
IPCC	International Panel on Climate Change
ITS	Intelligent Transportation System
IVL	IVL Swedish Environmental Research Institute
LEV	Low-Emission Vehicle
LF	Load Factor
LHDT	Light Heavy-Duty Truck
LNG	Liquefied Natural Gas
LOS	Level of Service
LPG	Liquified Petroleum Gas
LTO	Landing and Takeoff
MARAD	Maritime Administration
MATES	Multiple Air Toxics Exposure Study
MCR	Maximum Continuous Rating
MEPA	Marine Exchange or Port Authority
MPO	Metropolitan Planning Organization
MS	Maximum Speed
MSAT	Mobile Source Air Toxic
MVSTAFF	Motor Vehicle Stock Travel, and Fuel Forecast
N_2O	Nitrous Oxide
NAA	Nonattainment Area
NAAQS	National Ambient Air Quality Standards
NATA	National Air Toxics Assessment
NCAP	Non-Criteria Air Pollutant
NEI	National Emissions Inventory
NEPA	National Environmental Policy Act
NEVES	Nonroad Engine and Vehicle Emission Study
NMHC	Non-Methane Hydrocarbon

NMIM	National Mobile Inventory Model
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
NTAD	National Transportation Atlas Database
O_3	Ozone
OAG	Official Airline Guide
O/D	Origin-Destination
OGV	Ocean-Going Vessel
PATA	Portland Air Toxics Assessment
Pb	Lead
PERE	Physical Emission Rate Estimator
PGM	Photochemical Grid Model
PiG	Plume in Grid
PM	Particulate Matter
PM_{10}	Particulate Matter smaller than 10 µg
$PM_{2.5}$	Particulate Matter smaller than 2.5 µg
PMT	Passenger-Miles Traveled
POLA	Port of Los Angeles
POLB	Port of Long Beach
PPR	Port of Prince Rupert
PWD	Pier/Wharf/Dock
REMSAD	Regional Modeling System for Aerosols and Deposition
RIA	Regulatory Impact Analysis
ROG	Reactive Organic Gases
RSZ	Reduced Speed Zone
RVP	Reid Vapor Pressure
RVSM	Reduced Vertical Separation Minimum
SAE	Society of Automotive Engineers
SAGE	System for Assessing Aviation's Global Emissions
SCAG	Southern California Association of Governments
SCC	Source Classification Code
SCR	Selective Catalytic Reduction
SI	Spark-Ignition
SIP	State Implementation Plan
SO_2	Sulfur Dioxide
SO_X	Sulfur Oxides
SSD	Slow Speed Diesel
STB	Surface Transportation Board
STEEM	Ship Traffic, Energy, and Environmental Model
T&M	Tampering and Mal Maintenance
TAC	Toxic Air Contaminant
TAF	Transient Adjustment Factor
TAZ	Traffic Analysis Zone
TEM	Train Energy Model
TEU	Twenty-foot Equivalent Unit

Tg	Million Metric Tons
THC	Total Hydrocarbon
TIM	Time-in-Mode
TIUS	Truck Inventory and Use Survey
TOG	Total Organic Gases
TRU	Transport Refrigeration Unit
UAV	Unmanned Arterial Vehicles
UC	University of California
UL	Useful Life
UN	United Nations
UP	Union Pacific Railroad
U.S. ACE	United States Army Corps of Engineers
VALE	Voluntary Airport Low Emissions
VIUS	Vehicle Inventory and Use Survey
VLJ	Very Light Jets
VMT	Vehicle-Miles Traveled
VOC	Volatile Organic Compound

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation