Design and Implementation of MOVES:
EPA's New Generation Mobile Source Emission Model

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ABSTRACT

EPA's Office of Transportation and Air Quality (OTAQ) is currently working on a new modeling system termed the **M**ulti-scale m**O**tor **V**ehicle and equipment **E**mission **S**ystem (MOVES). MOVES will be a modeling framework which can be applied from very fine scales (e.g., intersections) to national-scale inventories for generating estimates of precursor, criteria, greenhouse, and toxic pollutants from on and off-road mobile sources. This paper gives an overview of the proposed MOVES design. First, use cases for MOVES were determined, based on extensive expert consultation and following the recommendations of the National Research Council (NRC). From these use cases, a design framework was developed to allow flexibility for modeling across analysis scales, pollutants, and sources and to provide for ease of customization and update based on new or user-supplied data. New concepts of characterizing emission sources and their operation are introduced as part of the design. A phased implementation plan is also described, beginning with release of a greenhouse gas implementation for on-road sources by the end of 2003.

INTRODUCTION

The Clean Air Act requires EPA to develop and regularly update emission factors for all emission sources. Pursuant to this charge, EPA's Office of Transportation and Air Quality (OTAQ) has developed a number of emission and emission factor estimation tools for mobile sources, including MOBILE (for highway vehicles) and NONROAD (for off-road mobile source pollutants). EPA is proposing to update these tools with the **M**ulti-scale m**O**tor **V**ehicle and equipment **E**mission **S**ystem (MOVES), which is intended to include and improve upon the capability of these tools and, eventually, to replace them with a single, comprehensive modeling system.

The National Research Council (NRC) published a thorough review of EPA's mobile source modeling program in 2000.[1] The NRC provided several recommendations for improving EPA's mobile source modeling tools, including: (a) the development of a modeling system more capable of supporting smaller-scale analyses; (b) improved characterization of emissions from high-emitting vehicles, heavy-duty vehicles, and off-road sources; (c) improved characterization of particulate matter and toxic emissions; (d) improved model evaluation and uncertainty assessments; and (e) a long-term planning effort coordinated with other governmental entities engaged in emissions modeling.

A particular focus of the NRC report was the need to provide emission factors and tools that will allow the estimation of emissions at finer analysis scales. Historically, EPA's mobile source emission estimation tools and underlying emission factors have been focused on the estimation of mobile source emissions based on average operating characteristics over broad geographical areas. Examples of this scale of analysis are the development of SIP inventories for urban nonattainment areas and the estimation of nationwide emissions to assess overall trends. In recent years, however, analysis needs have expanded in response to statutory requirements that demand the development of finer-scale modeling approaches to support more localized emission assessments. Examples include "hot-spot" analyses for transportation conformity and evaluation of the impact of specific changes in transportation systems (e.g., signalization and lane additions) on emissions.

We have adopted most of the NRC's recommendations as our objectives in designing MOVES. This paper presents an overview of the proposed MOVES design and implementation plan and includes our analysis of "use cases," the design and implementation plan proposed to meet these use cases, data input requirements to implement this design, and software choices which are proposed to implement the design. The full design and implementation plan for MOVES has been published in draft form as "Draft Design and Implementation Plan for EPA's Multi-Scale Motor Vehicle and Equipment Emission System (MOVES)", referred to as the MOVES design plan for brevity. The MOVES design plan was published in October 2002 and has since undergone public and formal peer review. The final version will be published in Summer 2003. This paper includes some updates to the draft design plan based on comments received and thinking which has evolved.

The current implementation schedule for MOVES is to first release a greenhouse gas implementation for on-road sources termed MOVES GHG. The first iteration of MOVES GHG would support development of national inventories and projections for Fuel Consumption, CO_2, N_2O, and CH_4, by the end of 2003. The next phase in implementing MOVES, planned for Fall 2005, would add HC, CO, NOx, SO_2, PM, NH_3, and air toxics for on-road sources and would allow the estimation of emissions at all analysis scales. This implementation would replace the current MOBILE6 model. Inclusion of updated off-road emissions would be incorporated into MOVES following the on-road implementations, replacing the current NONROAD model.

USE CASES

In developing a design for MOVES, we first assessed the many ways in which the model would be used, informed by the NRC report and interviews with subject-matter experts. This included formal interviews of expert users, as well as consulting with researchers and users within EPA and the FACA Modeling Workgroup (comprised of experts from industry, academia, government, and consulting firms). The result of this assessment was a list of fundamental use cases, shown in Table 1, which have driven the MOVES design.

In addition to these broad model purposes, we also, through consultation with model users, addressed use cases from the perspective of user interaction:

- A powerful and versatile GUI and a batch, command-line interface.
- Flexibility of input and output formats.
- Multiple options for output processing
- Ease of comparison of results from multiple model runs
- Ease of transition from MOBILE/NONROAD to MOVES

Table 1. MOVES use cases

Use Cases	Specific Applications
National inventory development for EPA reports and regulations	National Emissions Inventory (NEI) Inventory of U.S. Greenhouse Gas Sources and Sinks International Reporting Regulatory analyses
Local inventory development	SIP development Conformity NEI input Trading programs
Hot-spot and project level analysis	PM and CO Conformity Toxic exposure analysis
Model interaction	Air Quality Pre-Processors Travel Models • Travel Demand Models • Microscopic Models • TRANSIMS Dispersion Models
Policy evaluation	Cleaner vehicles Cleaner fuels Less travel Reducing in-use emissions Modifying vehicle operation Environmental justice
Model Analysis	Validation Uncertainty analysis Sensitivity
Model updates and expansion	Updating emission rates based on new data Updating base year fleet and activity (e.g., VMT) inputs

DESIGN CONCEPTS

The MOVES design has been developed to satisfy the use cases listed in Table 1. The design is modular, general purpose, data driven, easy-to-use, and high performance. All emission scales and processes are incorporated into a flexible framework of time spans and locations. MOVES emission rates and activity information are derived from databases, easily updated as needed.

The MOVES design introduces some new concepts related to the characterization of emission sources, their activity, and the resulting emissions (or fuel consumption). The term *source* is used to encompass both on-road vehicles and off-road equipment pieces. A *source use type* is a specific class of on-road vehicles or off-road equipment defined by unique activity patterns. *Source bins* are a subset of use types: subcategories that differentiate emission levels within a use type, covering categorizations such as weight class, fuel type, technology, standard, horsepower range, etc. *Total activity* is defined for a given use type as the product of the population of that use type and the per-source activity by time and location. We subdivide total activity into categories that differentiate emissions, known as *operating* *mode bins*; the intersection of source bins and operating mode bins results in a unique *source and operating mode bin*. By *emission rates,* we mean the most disaggregated rates the model produces internally by source and operating mode bins. By *emission factors,* we mean emission rates aggregated in various ways over source and/or operating mode bin and normalized by some activity basis, such as mass of pollutant per time or per mile.

An *emission process* is a unique emissions pathway. The proposed emission processes for MOVES are shown in Table 2. These processes are being defined the same as they are in MOBILE6 and NONROAD, except that resting loss emissions would now include estimates of offgassing, or hydrocarbons escaping from car materials such as upholstery. Three new processes have been added since the publication of the draft MOVES design plan:

1) **Extended Idle** added to enable MOVES to explicitly account primarily for overnight idle ("hoteling") for heavy-duty long-haul trucks, although there may be some applicability to light-duty vehicles as well (e.g., extended idle warm-up in cold climates)
2) **Well-To-Pump** added to account for upstream energy use and emissions associated with the fuel used by a source
3) **Manufacture/Disposal** added to account for energy use and emissions associated with the manufacture and disposal of the source

Together the Well-To-Pump and Manufacture/Disposal processes will enable full life-cycle analysis capability in MOVES.

Table 2. MOVES emission processes

Combustion Products	Hydrocarbon Evaporation	Other
Running Exhaust	Diurnal	Brake Wear
Start Exhaust	Hot Soak	Tire Wear
Crankcase	Resting Loss	Well-To-Pump
Extended Idle	Running Loss	Manufacture/Disposal
	Refueling	

These emission processes are generally associated with different source bins and operating modes and they may also produce different pollutants. Therefore, each emission process is generally handled separately from the others, using common data when appropriate. From a design perspective, this separation creates several submodels within MOVES. For example, running exhaust emissions are affected by a different set of fleet and activity characteristics than are diurnal evaporative emissions.

Three basic analysis scales are defined for MOVES. *Macroscale* analyses are appropriate for developing large-scale (e.g., national) inventories, for which the basic spatial unit would be the county. *Mesoscale* analyses are appropriate for generating local inventories at a finer level of spatial and temporal resolution, using as spatial units roadway links and traffic analysis zones or using vehicle trips consistent with output from standard travel demand models. *Microscale* analyses allow the estimation of emissions for specific corridors and/or intersections, which is appropriate for assessing the impact of transportation control measures and for performing project-level analyses.

DESIGN FRAMEWORK

We have established two fundamental design principles, which have guided the development of the MOVES design, as follows:

- The model design needs to be flexible enough to accommodate the calculation of emissions from a wide variety of emission sources (e.g., on-road and off-road), over multiple scales, and multiple emission processes using a similar design framework.
- The model must be developed in a modular way to allow ease of update and input of customized data by the user.

To address the first principle, a generic framework has been developed which provides significant flexibility for applying the model across emission source, scale, and process. The basic concept of this generic framework is the following: for a given time, location, use type, and emission process, total emissions can be calculated by the following four steps:

1) Calculate the **Total Activity**, expressed in units of the activity basis (explained in following section) for the given emission process.
2) Distribute the total activity into **Source and Operating Mode Bins**, which are defined as having unique emissions for that emission process.
3) Calculate an **Emission Rate**, which characterizes emissions for a given process, source bin, and operating mode bin and which accounts for additional effects such as fuel and meteorology.
4) Aggregate emission rates across these modes using the source bin and operating mode distribution from Step 2.

These steps are characterized mathematically as follows:

$$TotalEmissions_{UseType} = TotalActivity_{UseType} \times \sum_{n=1}^{Number\ of\ Bins} EmissionRate_{UseType,\ Bin} \times BinDistribution_{UseType,\ Bin}$$

In this equation, *bin* refers to source and operating mode bin. A discussion follows of total activity and the distribution of this activity into source and operating mode bins. A discussion of emission rates as characterized in MOVES is provided in a separate report published in December 2002 entitled "Draft Emission Analysis Plan for MOVES GHG."

The second design principle listed above, modularity to allow ease of update, has been addressed by designing MOVES to rely on a relational database. This is covered briefly later in this paper and in much more detail in the MOVES design plan.

CHARACTERIZING SOURCES AND THEIR ACTIVITY

Understanding the MOVES design requires understanding the design concepts previously identified. Three terms are discussed in more detail here, with more information available in the draft MOVES design plan.

Total Activity

For a given use type, time, and location, total activity is the product of population and per-vehicle activity. How *activity* is defined will depend on the emission process being modeled. For most processes, we propose to characterize total activity by source-time; i.e., source hours operating (SHO) or source hours parked (SHP). Source-time is the product of the population of vehicles/equipment and the analysis time span. Source-time is an attractive way of characterizing activity because it is common to all emission processes and operating modes. For on-road vehicles, source-time is more broadly applicable than the more conventional Vehicle Miles Traveled (VMT), since diurnal or idle emissions are produced when a vehicle is not moving. For non-transportation equipment, such as bulldozers and cranes, SHO and SHP can be applied as with on-road sources, while VMT cannot. Important to note, however, is this use of source-time mainly applies to the calculation of emissions within MOVES and does not preclude the use of VMT to express the activity of on-highway vehicles. The model design accepts a wide variety of inputs, including VMT, and produces a wide variety of outputs, including emission factors in grams/mile.

Some processes have total activity for which non-time based activities is more directly estimated. Specifically, start exhaust will use number of starts per time and location as the total activity basis and vehicle refueling will use the amount of fuel consumed. The total activity basis proposed for each process is shown in Table 3.

Table 3. Total activity basis by process

Emission Process	Total Activity Basis
Running Exhaust, Brake Wear, Tire Wear, Running Loss, Crankcase, Extended Idle	Source Hours Operating (SHO)
Start Exhaust	Number of Starts
Diurnal, Hot Soak	Source Hours Parked (SHP)
Resting Loss, Manufacture/Disposal	Source Hours (SH)
Refueling, Well-To-Pump	Energy (Fuel) Used

In MOBILE6, a single definition of vehicle (source) groupings was developed and each was assumed to have the same emission rate and activity patterns. One shortcoming of this approach is that categories which are important for distinguishing unique emission rates (e.g., vehicle weight class) may not be the best category descriptions in terms of activity or may not match available fleet and activity data. Therefore, we are proposing to approach source categorization in MOVES from the viewpoint of both activity and emissions, which will enable MOVES to take into account what is important for activity separately from what is important for distinguishing unique emission rates.

For characterizing activity, we are proposing MOVES categories known as *source use types*, which are more closely aligned with vehicle use patterns. For on-road vehicles, we propose that MOVES use types be subsets of Highway Performance Monitoring System (HPMS) vehicle classes, which are important to retain in the MOVES design because VMT data is provided from the Federal Highway Administration (FHWA) by these classes. The VMT data provided by HPMS form the basis of macroscale on-road activity estimates for all emission processes in the MOVES design and, hence, drive the structure of activity generation in MOVES.

Table 4 shows a breakdown of the HPMS vehicle classes and the proposed MOVES use types for on-road sources. The use types shown have been defined based on analysis of classification schemes in available data sources, most notably national registrations databases and the Vehicle In-Use Survey (VIUS), published by the U.S Census Bureau. A subset of source use type which will be accounted for in MOVES, but is not shown in Table 4, is source age, because activity does vary by age. Specifically, older vehicles accrue fewer annual miles than newer vehicles, an activity characteristic modeled in MOBILE6.

Table 4. HPMS class and corresponding MOVES use type.

HPMS Class	MOVES Use Type
Passenger Cars	Passenger Cars
Other 2-axle / 4-tire Vehicles	Passenger Trucks Light Commercial Trucks
Single Unit Trucks	Refuse Trucks Single-Unit Commercial Trucks Single-Unit Delivery Trucks Motorhomes
Buses	Interstate Buses Urban Buses School Buses
Combination Trucks	Combination Commercial Trucks Combination Delivery Trucks
Motorcycles	Motorcycles

Source Bins

Source bins are defined as subsets of use types defined by unique emission characteristics. The link between use types and the emission-based source bins will be made by the source bin distributions, to enable total activity from the use types to be distributed across the source bins. The important distinction between use types and source bin parameters is that activity is assumed to be constant across the source bin parameters. For example, under this approach diesel and gasoline passenger cars would be assumed to accrue mileage at the same average rate and travel at the same average speed for a given roadway type.

MOVES differs from the previous MOBILE series of models in that it is explicitly designed to use the same set of emission rates at a very large scale (such as national-level inventories) and at a very small scale (such as intersection modeling). It also combines into a single modeling framework the ability to generate (1) emissions for a wide range of pollutants and processes and (2) emissions from both on-road and off-road vehicles and equipment.

To handle this diversity of use and to enable ease of updates, we propose that MOVES store emission rates as average emissions within discrete source and operating mode bins. Each discrete bin will be dictated by factors that are found to result in unique emissions, based on subcharacteristics of the use type and operating modes. Parameters which define source bins could be based on fuel type, accumulated use (which accounts for deterioration), vehicle weight (on-road), horsepower range (off-road), technology types, and standard levels.

To maintain flexibility, specific definitions of source bins and operating modes will depend on emission process and pollutant. Source bins have been proposed for MOVES GHG for fuel consumption, methane, and nitrous oxide as shown in Table 5. Source bins fields that do not apply for a given pollutant (e.g., model year group for CH_4) would be considered “null”

Table 5. Source bin fields for MOVES GHG

Fuel Type (Fuel, CH_4, N_2O)	**Engine Technology** (Fuel, CH_4, N_2O)	**Model Year Group** (Fuel)	**Loaded Weight** (Fuel)	**Engine Size** (Fuel)	**Emission Technology** (CH_4, N_2O)
Gas Diesel CNG LPG Ethanol (E85/95) Methanol (E85/95) Gas H_2 Liquid H_2 Electric Note: fuel subtypes such as RFG, Biodiesel, E10 etc. would be handled through corrections to "base" fuel types	Null Conventional (IC) Direct Injection (DI) Hybrid Electric-IC A Hybrid Electric-IC B Hybrid Electric-IC C Hybrid Electric-DI A Hybrid Electric-DI B Hybrid Electric-DI C Fuel Cell Hybrid Electric-Fuel Cell A Hybrid Electric-Fuel Cell B Hybrid Electric-Fuel Cell C Note: Hybrid A/B/C provides placeholders for different hybrid strategies.	Null LD 80 and earlier LD 81-85 LD 86-90 LD 91 and later HD 90 and earlier HD 91 and later Note: LD use types are passenger car, passenger truck, and light commercial truck. HD use types are single unit truck, bus and combination truck. Motorcycles are "Null"	Null <= 2000 lbs. 2001-2500 2501-3000 3001-3500 3501-4000 4001-4500 4501-5000 5001-6000 6001-7000 7001-8000 8001-9000 9001-10,000 10,001-14,000 14,001-16,000 16,001-19,500 19,501-26,000 26,001-33,000 33,001-40,000 40,001-50,000 50,001-60,000 60,001-80,000 80,001-100,000 100,001-130,000 >=130,001	Null < 2.0 liters 2.1-2.5 liters 2.6-3.0 liters 3.1-3.5 liters 3.6-4.0 liters 4.1-5.0 liters > 5.0 liters Note: Would only apply to use types: passenger car, passenger truck and light commercial truck. Other use types would be "null".	Null Pre-control Non-catalyst Oxidation catalyst Tier 0 Tier 1 LEV Tier 2

Operating Mode Bins

Operating modes are defined as breakdowns of total activity necessary to reflect differences in emission rates. The Emission Rate Database will contain emission rates broken down by operating mode bin. Table 6 shows our proposed operating mode parameters for emission processes requiring further activity breakdown. Emission processes not listed will not require the breakdown of total activity into modes.

Table 6: Operating mode parameters by emission process

Emission Process	**Operating Mode Parameter(s)**
Running Exhaust, Brake Wear, Tire Wear	Average Speed, Vehicle Specific Power (VSP)
Start Exhaust, Hot Soak	Soak Time
Diurnal	Tank Pressure
Running Loss	Time Since Start

A central feature of MOVES is that the design has been developed such that the same definition of operating modes and the same operating mode-based emission rates will be applied at all three analysis scales of the model. The Operating Mode Distribution Generator and processes within the generator will function independent of scale.

To maintain flexibility, specific definitions of operating modes will depend on emission process and pollutant. Operating mode bins have been proposed for MOVES GHG for fuel consumption, methane, and nitrous oxide as shown in Table 7. Source bins fields that do not apply for a given pollutant (e.g., model year group for CH4) would be considered "null."

Table 7. Operating mode fields for MOVES GHG

Running Exhaust		**Start Exhaust**	**Extended Idle**	**Fuel/Vehicle Cycle**
Vehicle Specific Power (kw/metric ton) (Fuel)	**Average Speed** (CH_4)	No Operating Mode Bins		
VSP<-2	Null			
-2<=VSP<0	Low			
0<=VSP<1	High			
1<=VSP<4				
4<=VSP<7				
7<=VSP<10				
10<=VSP<13				
13<=VSP<16				
16<=VSP<19				
19<=VSP<23				
23<=VSP<28				
28<=VSP<33				
33<=VSP<39				
39<=VSP				

SOFTWARE ARCHITECTURE CONCEPTS: CORE MODEL AND IMPLEMENTATIONS

Two basic components of the MOVES design have evolved from the generic framework: the core model and implementations. The core model would perform the four-step calculation outlined in the previous section for the times and locations being modeled, resulting in outputs of emission factors and total emissions. At the heart of the core model is the emission calculation function, a large part of this function being a direct database lookup of emission rates by source and operating mode bin.

We refer to the "implementations" as the body of applications, controls, and utilities that would use the core model to address many of the use cases presented in Table 1. For example, macroscale inventory generation would operate the core model in conjunction with a database of fleet and activity information and front-end applications, which produce necessary core model inputs from these data.

Fundamental to the implementations is the concept of "data generators," which would convert data from a multitude of sources to the standard input form acceptable to the core model. For each emission process, the core model would be developed to use a standard input form for total activity and operating mode distributions regardless of analysis scale or the ultimate source of that information.

With this system any number of implementations could be addressed through the development of specific data generators to work with the myriad sources of fleet and activity data, empirical or modeled. To define a manageable scope, however, we propose to develop total activity and operating mode generators for the following implementations:

- Macroscale on-road inventory development at two levels: the national level or a user-defined domain level
- Mesoscale on-road inventory development at the user-defined domain level
- Microscale on-road analysis in conjunction with CAL3QHC at the user-defined domain level
- Macroscale off-road inventory development at the national level

We also believe that the advanced transportation model TRANSIMS will be linked to MOVES through the development of specific generators. TRANSIMS is a specific implementation that can be thought of as the “microscale” implementation expanded to a regional basis.

As stated earlier, a primary objective of the MOVES design is to develop a generic framework that can apply to different analysis scales and emission processes. To maintain this design objective, a generic approach to addressing the three analysis scales is required. The core model design is based on the idea of time and location, without regard to what the times and locations are; this is the generic feature of the core model. What primarily defines the difference between macroscale, mesoscale, and microscale are the definitions of time and location prior to implementation by the core model.

Location is defined by two elements: the “Domain,” which is the entire area being modeled, and “Zones,” which are subdivisions of the domain. MOVES will be flexible enough to work with any definition of domains and zones, as long as the user can supply necessary information to support that definition. Typical Domain/Zone combinations could be Nation/County, Region/Grid Cell, or County/Traffic Analysis Zone. For certain on-road emission processes, a third location element is also required: “Links,” which can either be assigned to a Domain or a Zone. Links are defined more concretely depending on the scale being modeled, but the core model will fundamentally apply the concept of links across all scales.

An overview of the primary implementations are shown in Table 8, which highlights the definitions of *domain*, *zone* and *link* for each implementation.

The total activity and operating mode generators will require significant mathematical processing and input data to convert from standardly available input data (e.g., VMT data) to the inputs necessary by the core model. Indeed, given the simplicity of the core model structure, the generator steps represent the most significant mathematical formulation elements of MOVES.

DATA GENERATORS

A large part of the architecture of MOVES will be relational databases containing the necessary information regarding the sources, their activity, and the fuel consumption or emissions of that activity. Emission data will be stored in an emission rate database and employed by the core model in the calculation steps given in the Design Framework discussion. Fleet and activity data will be stored in a variety of databases, primarily to support the calculation of total activity in the Total Activity Generator and the distribution of this activity into operating modes in the Operating Mode Distribution Generator. A discussion of these generators follows.

Total Activity Generator

The macroscale on-road inventory implementations (national default and domain-specific) use estimates of vehicle miles traveled (VMT) as a starting point for generating total activity for most emission processes. This approach recognizes that emission production in a given location depends on the activity in that location, which may not be captured by what is registered in that location. This is particularly true of heavy-duty vehicles, for which the registered fleet and the on-road fleet can be quite different for a given location.

Table 8. On-road implementations proposed for MOVES

Implementation	Description	Use Cases Applications	Domain	Zone Locations	Link Locations
Macroscale Inventory (National Default)	Produces county-level inventory for entire nation.	National Inventory Development Policy Evaluation AQ Pre-Processor Interaction	U.S plus territories	Counties	HPMS Roadway Types
Macroscale Inventory (Domain-Specific)	Produces inventory for user-defined domain	Local Inventory Development (e.g., SIP/Conformity analysis) Policy Evaluation AQ Pre-Processor Interaction	User-defined; likely examples are counties, MSA, nonattainment areas, states	User-defined; likely examples are grid cells, zip codes, census blocks	HPMS Roadway Type
On-Road Mesoscale Inventory	Produces inventory for user-defined domain at link/zone level	Local Inventory Development Policy Evaluation Travel Demand Model Interaction	User-defined; likely examples are counties, MSA, nonattainment areas, states	User-defined; likely example is Transportation Analysis Zones (TAZ)	User-defined on-Network links Off-network HPMS road way types
On-Road Microscale Analysis w/ CAL3QHC	Produces necessary emission factor inputs for microscale analysis using CAL3QHC	Hot Spot Analysis Dispersion Model Interaction	CAL3QHC analysis area	N/A	Idle and non-idle links as defined in CAL3QHC input file
TRANSIMS	Produces inventory for user-defined domain in conjunction with TRANSIMS	Model Interaction: TRANSIMS	TRANSIMS analysis area (user-defined)	Activity locations as defined by TRANSIMS	30 meter segments
Off-road Macroscale Inventory (National)	Produces county-level off-road inventory for entire nation.	National & Local Inventory Development Policy Evaluation AQ Pre-Processor Interaction	U.S plus territories	Counties	N/A

The basic process of total activity generation is the same for the national default and domain-specific implementations. The primary difference is that for the national case, total activity will be generated for the entire country (the default domain) and allocated to the county level (default zone location) using default geographic allocation factors. For the domain-specific case, total activity will be generated for the modeling domain based on user-supplied VMT data, which would override activity calculated from the default geographic allocation factors.

The mesoscale level of analysis proposed to be supported by MOVES requires that the user supply sufficient information to calculate bottom-up emissions at the link/zone level for running exhaust, start, brake wear, and tire wear processes. The most likely source of this information would be output from a traditional travel demand model. All other processes are handled using macroscale allocation approach down to the zone level, including off-network emissions for running exhaust and brake and tire wear processes. All fleet inputs are applicable across the entire modeling domain. The user must define the modeling domain, the road network (i.e., which roadways will be modeled as individual links), and analysis zones. More disaggregated approaches to the mesoscale model, such as the MEASURE framework developed by Georgia Tech and EPA's Office of Research and Development,[2] could be run in MOVES with direct interface with the core model, but would not be supported as a specific implementation of MOVES.

The microscale level of analysis proposed to be supported by MOVES is based on necessary input for the dispersion model CAL3QHC, EPA's recommended model for intersection analysis,[3] applicable primarily to CO, PM, and air toxics. Through the CAL3QHC input file, the user would supply sufficient information to calculate emission rates for running exhaust, brake wear, and tire wear at the link and intersection level. Other processes would need to be modeled through direct interface with the core model. All fleet inputs are applicable across the entire modeling domain. The user must define the modeling domain and the road network (i.e., which roadways will be modeled as individual links) through the CAL3QHC input file.

A listing of all of the steps necessary for total activity generation at the macroscale, mesoscale, and microscale levels is contained in the draft MOVES design plan.

Operating Mode Distribution Generator

For on-road emissions, the second generator requiring significant mathematical processing to calculate core model input is the Operating Mode Distribution Generator. The output of this generator is the distribution of operating modes as defined for each emission process, for those emission processes which will break total activity into modes. A significant design feature of MOVES is that the same operating mode distribution generation process can be applied to each of the analysis scales.

We are proposing that MOVES use Vehicle Specific Power (VSP) to characterize "modal" emission rates for the running exhaust emission process. The primary benefit of this metric is that it combines into a single parameter numerous physical factors influential to vehicle fuel consumption and emissions: vehicle speed, acceleration, road grade, and road load parameters such as aerodynamic drag and rolling resistance. By normalizing the vehicle weight, we can directly calculate VSP knowing only the driving pattern of a vehicle and road grade, if assumptions are made for road load coefficients. An in-depth evaluation of the merits of using VSP is presented in "Draft Emission Analysis Plan for MOVES GHG."

As detailed in the MOVES GHG emission analysis plan, we are investigating whether further binning variables are required to improve model accuracy; but these VSP bins are fundamental to defining operating modes in MOVES. The operating mode distribution generator would produce the distribution of time spent in each of these bins for a given roadway link. Default driving cycles will be used to calculate these distributions within MOVES. We are proposing to base the calculation of VSP bin distributions for light-duty vehicles in MOVES on the MOBILE6 framework for facility-specific driving patterns, and we plan to produce a parallel set of facility-based cycles for application to heavy-duty vehicles. MOBILE6 uses driving cycles to reflect varying Levels of Service by aggregated facility type: freeway, arterial, and local roads. MOVES would extend these cycles to represent travel on the 12 HPMS roadway types. With this approach, the user would interface with MOVES at the level of average speed and facility type, which maintains consistency with the MOBILE6 input structure. These driving cycles (expressed as second-by-second vehicle speed) can be converted to VSP in each second, along with input factors such as road grade, rolling resistance, and wind speed. We can then determine the distribution of time falling in the average speed and VSP bins, which would be passed to the core model.

Off-Road Implementation

The fundamental underpinnings of the core model apply to off-road sources as well as on-road sources: all sources have total activity, a distribution of that activity into specific modes, and emission associated with those modes. The differences between on-road and off-road sources will be handled through unique total activity and operating mode distribution generators. We are proposing, as an initial step, that these front-end generators be developed specifically to support macroscale analysis of off-road sources (including commercial marine, aircraft, and locomotives), at the same two sublevels applied for on-road. The national default level would function similar to the current NONROAD model, producing county-level emissions for the entire country. The domain level would allow users to model specific areas, but would require the input of domain-specific inputs for calculating total activity. Finer scale analyses of nonroad would be possible with direct interaction of the core model, if the user had fleet and activity data for the area being modeled. Some options for approaching off-road generators are presented in the draft MOVES design plan.

SOFTWARE DEVELOPMENT TOOLS SELECTED FOR MOVES

We have made a preliminary decision to program MOVES with the Java programming language as defined by SUN's Java System Development Kit (SDK). It is a state-of-the-art, widely used, object-oriented, programming language, which has enjoyed considerable success over the last several years and appears to have a promising future, independent of the fate of any particular company. With its "write once, run anywhere" philosophy, it offers the highest degree of platform independence of any language available. Java comes with a set of associated tools, such as Javadoc, which lead to relatively uniform coding and documentation practices.

As earlier described, MOVES is data driven, meaning that its emission rates are primarily determined by looking them up in a database. Input and output data are also in databases. Furthermore, it is a fundamental objective of MOVES that it be able to incorporate new vehicle population, vehicle activity, and emission measurement data easily. The complexity of such data and the limited input/output capability of the Java and C++ programming languages requires that MOVES include relational database management software (RDBMS) for the loading, storage, and (especially) retrieval of information. For this RDBMS to be state-of-the-art, platform independent, and in widespread use further dictates that it allow the use of SQL (Structured Query Language) for database operations. MySQL, one of two principal open-source RDBMS in widespread use, appears to meet all of our relevant software requirements and is the tool we have selected. It is available in a form that would allow the entire MOVES model to run on the EPA desktop platform and is written in C++, making it reasonably platform-independent. Run time performance has been given major consideration in MySQL, so it might be able to compensate for the relatively slow performance of Java programs.

Another important aspect of MOVES software implementation is distributed processing, a method used to speed model execution by dividing up a lengthy calculation and distributing separate portions of it to multiple computers or computing systems. The multiple separate results are then collected together into a final, collated result. In MOVES, some important use cases require thousands of time-location runs. Fortunately, the calculation for any time-location combination is completely independent of all the other time-location combinations, making it straightforward to divide these calculations between many computers. Two methods under consideration for distributed processing in MOVES are *grid computing* and *Beowulf clusters.* Because both of these methods for distributed processing are widely used, we plan to program MOVES to be able to use either one or both of them together. A master MOVES would reside on analysts' desktop machines and would set up and initiate the run, collect and collate the results, and produce final output. The master would also divide up the calculation and distribute it to worker MOVES via a shared hard drive on a server. The workers would perform the calculations and return the results to the shared drive.

CONCLUSION

EPA's new generation mobile source emission model MOVES has been designed to satisfy a variety of use cases recommended by the National Research Council and a wide array of model users, from national inventory generation to intersection-level analysis. At the core of the design is a simple framework that can be applied across analysis scale, pollutant, and emission process. This simple "core model" will be driven by specific "implementations" to address the specific MOVES use cases. Implementations will be developed for macroscale, mesoscale, and microscale applications, including the emerging transportation model TRANSIMS. These implementations will rely on data "generators," which transform readily available fleet and activity data into the inputs needed by the core model. MOVES will be programmed in Java and will use the open-source relational database system MySQL extensively, to meet the objective of modularity and ease of update based on new data.

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REFERENCES

1 National Research Council. *Modeling Mobile Source Emission*; National Academy Press; Washington, D.C; 2000.

2 Bachman , William H. "A GIS-Based Modal Model of Automobile Exhaust Emissions;" EPA-600/R-98-097, Prepared for OTAQ by the School of Civil and Environmental Engineering, Center for Geographic Information Systems, Georgia Institute of Technology, Atlanta, Georgia 30332, under EPA Cooperative Agreement CR823020, August 1998.

3 U.S. EPA. User's Guide to CAL3QHC Version 2.0: A Modeling Methodology for Predicting Pollutant Concentrations Near Roadway Intersections, Office of Air and Radiation, Research Triangle Park, NC, September, 1995; EPA-454/R-92-006.

BIBLIOGRAPHY

Bachman , William H. August 1998. *A GIS-Based Modal Model of Automobile Exhaust Emissions*.EPA-600/R-98-097. Prepared by School of Civil and Environmental Engineering, Center for Geographic Information Systems, Georgia Institute of Technology, Atlanta, Georgia 30332, under EPA Cooperative Agreement CR823020.

Barth, M.; An, F.; Younglove, T.; Scora, G.; Levine, C. April 2000. *Development of a Comprehensive Modal Emissions Model: Final Report.* Prepared for National Cooperative Highway Research Program under NCHRP Project 25-11.

Beck, Kent 2000.. *Extreme Programming Explained.* Addison-Wesley, New York.

Frey, H. Christopher; Unal, Alper; Chen, Jianjun; Li, Song; and Xuan, Chaoting. August 31, 2002. *Methodology for Developing Modal Emission Rates for EPA's Multi-scale mOtor Vehicle & equipment Emission System*. Prepared for OTAQ, U.S. EPA by Department of Civil Engineering, North Carolina State University, Raleigh, NC.

Houghton, J.T.; Meira Filho, L.G.; Lim, B.; Treanton, K.; Mamaty, I.; Bonduki, Y.; Griggs, D.J.; Callendar, B.A.; editors. 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual.* Intergovernmental Panel on Climate Change (http://www.ipcc.ch/pub/guide.htm).

National Research Council. 2000. *Modeling Mobile Source Emissions.* National Academy Press; Washington, D.C.

U.S. EPA. April 2001. *EPA's New Generation Mobile Source Emssions Model: Initial Proposal and Issues*. EPA420-R-01-007. Office of Air and Radiation, Ann Arbor, MI.

U.S. EPA. September, 1995. *User's Guide to CAL3QHC Version 2.0: A Modeling Methodology for Predicting Pollutant Concentrations Near Roadway Intersections.* EPA-454/R-92-006. Office of Air and Radiation, Research Triangle Park, NC.

KEY WORDS

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