Introducing MOVES2004, the initial release of EPA's new generation mobile source emission model

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ABSTRACT

MOVES2004 is the first release of EPA's new generation mobile source modeling framework, and will enable national inventories and projections at the county-level for on-road energy consumption, CO_2, N_2O, and CH_4. The model will also include an integration with Argonne National Laboratory's GREET model, for the ability to account for life-cycle (i.e., well-to-pump) effects in the estimate of energy consumption and emissions. The release of MOVES2004 serves several purposes: a) it fulfills the recommendations of the Intergovernmental Panel on Climate Change (IPCC) guidelines recommending development of a bottom-up greenhouse gas inventory model; b) it provides a means of validating the underlying model data and structure against top-down energy consumption estimates; and c) it gives the broader user community an opportunity to work with MOVES while the full-scale version of the model (with regulated pollutants and multiple analysis scales) is developed. This report provides an overview of the three primary components of MOVES2004: 1) the design of the software and data structure, 2) the data and underlying analyses used to populate default inputs for fleet and activity components to enable nationwide inventory estimates; and 3) the data and underlying analysis used to develop energy consumption and emission rates for the entire on-road fleet. A brief demonstration of the user interface and discussion of input data requirements will also be included.

INTRODUCTION

MOVES2004 is the initial release of the MOVES series, which will progress towards replacement of the current MOBILE and NONROAD models. The background and objectives of MOVES are covered extensively in previous documentation,[1] which the reader is referred to if desiring a full discussion of these items.

The scope of MOVES2004 is as follows:

- **Output:** Energy consumption (divided into total energy, petroleum-based energy and fossil fuel-based energy) and greenhouse gas emissions (CO_2, N_2O, CH_4 and CO_2 equivalent)

- **Sources:** All on-road sources, divided into 13 "use types"
- **Geography:** The entire U.S. (plus Puerto Rico and the U.S Virgin Islands) at the county level, with options to run at a more aggregate state or national level.
- **Emission Processes:** running, start, extended idle (e.g. heavy-duty truck "hoteling"), well-to-pump (via integration with an updated version of Argonne National Laboratory's GREET model)
- **Time Spans**: Energy/emission output by hour of the day, day of the week, month for calendar years 1999 through 2050, with options to run at a more aggregate day, month or year level.

As discussed in the referenced background reports, one of the primary features of the MOVES design is the ability to function at multiple analysis scales: macroscale, mesoscale and microscale. The MOVES2004 operates solely at the macroscale level. The mesoscale and microscale applications will be implemented as regulated pollutants are added to future versions of the model.

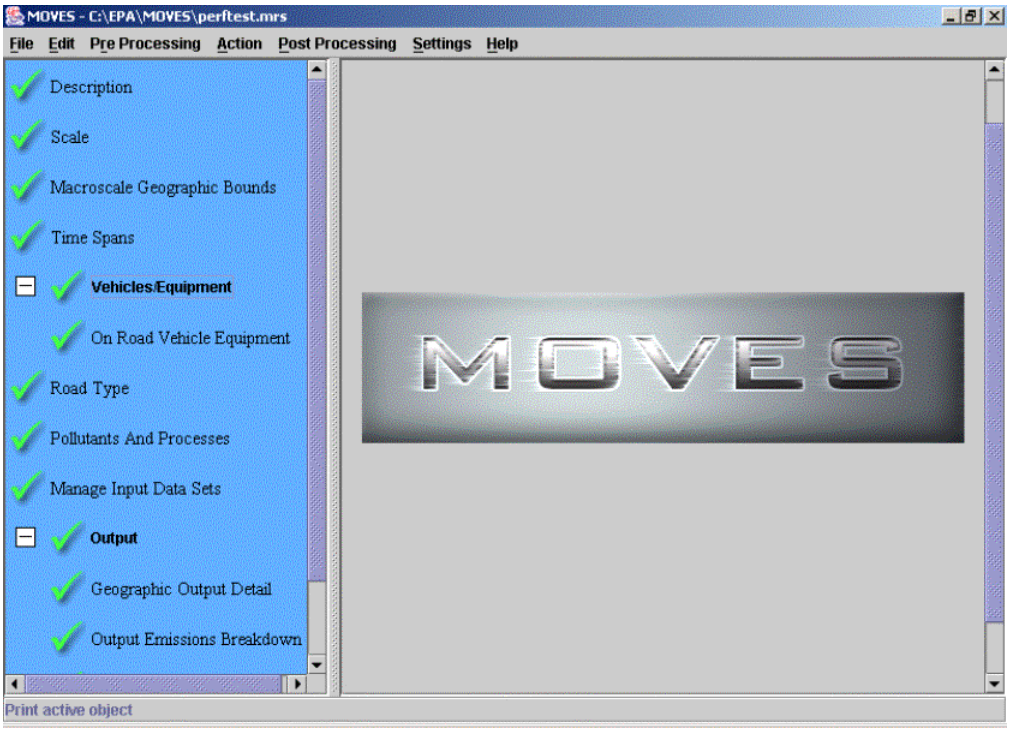
While MOVES2004 is only a step towards the stated objective of having a model that includes all mobile sources, all pollutants at any analysis scale, there are several reasons for releasing it at this stage. First, the focus of the model on energy consumption allows for validation against top-down energy consumption estimates produced by DOE, thus fulfilling one of the main recommendations laid out in the National Research Council's review of EPA's mobile source models.[2] This validation will provide assurance that the aspects of bottom-up inventory common to all pollutants – namely, fleet characteristics and activity patterns – are adding up correctly. Second, we expect that MOVES2004 will be a useful research tool in the energy and climate change arenas, given the ability to generate total inventories broken down by region, as well as a broad range of "what-if" capability. Finally, MOVES2004 will begin to give users a sense of the "look and feel" of MOVES, so that they may provide early feedback to EPA on likes and dislikes.

WORKING WITH MOVES

MOVES2004 is an open-source program written in Java and the relational database program MySQL. In addition to the software code, an extensive MySQL database structure is used to store model input and output data. MOVES2004 will be made available with a comprehensive installation package, which includes the MOVES software code, and underlying database structure populated with default data; Java and the necessary utilities to run it; and MySQL.

MOVES2004 uses a graphical user interface (GUI) to allow users to establish the specifications for a model run. The GUI is made up of several panes, which guide the user through selections of geography, time spans, vehicle classes, pollutants, emission processes, alternative input data, and output options (Figure 1). Run specifications can be saved for later use and editing as well.

Figure 1 - MOVES GUI main interface window



MOVES is designed for transparency. Although populated with a full suite of default data, the relational database design provides maximum flexibility for providing alternate input data, working with different levels of output aggregation, or even changing fundamental elements of the design implementation such as vehicle classifications or operating mode definitions. Whereas in the past MOBILE users wishing to alter underlying data would commonly need to alter FORTRAN code, MOVES users wishing to operating at a similar level will likely not need to alter the Java code at all. All changes the user might wish to influence in term of subject matter content would be done in the MySQL database. Thus, users wishing to work at the database level will need to be familiar with relational database manipulation in general, and MySQL in particular. MySQL can be worked with directly or can be set up to port to commonly available commercial database or analysis packages such as MS Excel, MS Access or FoxPro.

MOVES DESIGN CONCEPTS

Understanding how MOVES2004 operates, and why the input and output databases are set up as they are, requires an understanding of some basic design concepts. Fundamental aspects of the MOVES design are the characterization of emission sources, emission processes, and characterizing the activity of these sources.

Characterizing Emission Sources

A long-standing challenge in the generation of on-road mobile source emission inventories is the disconnect between how vehicle activity data sources characterize vehicles and how emission or fuel economy regulations characterize vehicles. The crux of this issue is that there is a fundamental difference between factors influencing how vehicles are used, and their fuel consumption and emission performance. An example of this is how vehicles are characterized by the Highway Performance Monitoring System (HPMS) – by a combination of the number of tires and axles – and EPA's weight-based emission classifications such as LDV, LDT1, LDT2 etc.

This disconnect is fundamental to matching activity data and emissions data, and generally requires some "mapping" of activity data to emission data. The MOBILE series of models have traditionally grouped vehicles according to the EPA emission classifications, and provided external guidance on mapping these categories to the sources of activity data, such as HPMS. MOVES is designed to take these mappings into account internally, so that the casual user of MOVES will not have to deal with external mapping. Doing this, however, requires some complexity in the design. Vehicles are characterized both according to activity patterns and energy/emission performance, and are mapped internal to the model. Thus the model uses data for both the activity and energy/emission methods of characterization. On the activity side, vehicles are grouped into "Source Use Types", or Use Types, defined as groups expected to have unique activity patterns. Because HPMS data is a fundamental source of activity, the MOVES use types are defined as subsets of HPMS vehicles classifications. These use types are shown in Table 1.

Activity patterns which may differ between the use types are: annual mileage, distribution of travel by time of day or day of week, driving schedule (i.e. real time speed/accel profile), average speeds, or distribution of travel by roadway type. For example, refuse trucks are separated out because their activity patterns are expected to vary significantly from other single-unit trucks, and accurately accounting for these vehicles requires accounting for their unique activity.

Source use types are the method of vehicle characterization seen by the MOVES user. The user selects which use types and fuel combination to model in the user interface, and output results are reported by use type. However, emission rates contained in the model are not broken down by use type, for two (related) reasons: first, emission and fuel consumption data are not gathered according to use types or other activity-based classifications (e.g. HPMS). Second, the factors that influence fuel consumption and emission production are different from how vehicles are used. For example, with regard to fuel consumption, loaded vehicle weight is a predominant influence; a 2000 lb compact car and 5000 lb SUV will have very different fuel consumption levels, although these vehicles may have similar use patterns. It is necessary to account for these differences in fuel consumption and emission generation, separate from activity pattern. To do this, the MOVES design has implemented the concept of "Source Bins". Unique source bins are defined by those characteristics with the largest influence on fuel (energy) consumption and

emissions – and because these vary by pollutant, they are allowed to vary by pollutant in MOVES. Table 2 shows the source bins fields used in MOVES2004, which vary by pollutant. For energy (and hence CO_2, which is calculated from energy), source bins are defined by fuel type, engine type, model year group, loaded weight and engine size. For CH_4 and N_2O, source bins are defined by fuel type, engine type, model year group (notice the definition of model year group can vary by pollutant, which is necessary to account for trends which vary by pollutant), and regulatory class.

Source bins are defined completely separate from use types, but are mapped to source types internal to MOVES by the Source Bin Distribution Generator, discussed in the Software Design section.

Table 1 – MOVES Source Use Type Definitions

HPMS Class	MOVES use type	Description
Passenger Cars	Passenger Car	
Other 2-axle / 4-tire Vehicles	Passenger Truck	Minivans, pickups, SUVs and other 2-axle / 4-tire trucks used primarily for personal transportation
	Light Commercial Truck	Minvans, pickups, SUVs and other trucks 2-axle / 4-tire trucks used primarily for commercial applications. Expected to be Unique from passenger trucks in terms of annual mileage, operation by time of day
Single Unit Trucks	RefuseTruck	Garbage and recycling trucks Expected to be unique from other single unit trucks in terms of drive schedule, roadway type distributions, operation by time of day
	Single-Unit Short-Haul Truck	Single-unit trucks with majority of operation within 200 miles of home base
	Single-Unit Long-Haul Truck	Single-unit trucks with majority of operation outside of 200 miles of home base
	Motorhome	
Buses	Intercity Bus	Buses used primarily by commercial carriers for city-to-city transport.
	Transit Bus	Buses used within an urban area
	School Bus	
Combination Trucks	Combination Short-Haul Truck	Combination trucks with majority of operation within 200 miles of home base
	Combination Long-Haul Truck	Combination trucks with majority of operation outside of 200 miles of home base
Motorcycles	Motorcycle	

Table 2 – MOVES Source Bin Definitions

Fuel Type (Energy, CH_4, N_2O)	**Engine Technology** (Energy, CH_4, N_2O)	**Model Year Group**		**Loaded Weight** (Energy)	**Engine Size** (Energy)	**Regulatory Class** (CH_4, N_2O)
		Energy	(CH_4, N_2O)			
Gas Diesel CNG LPG Ethanol (E85) Methanol (E85) Gas H_2 Liquid H_2 Electric	Conventional IC (CIC) Advanced IC (AIC) Hybrid - CIC Mild Hybrid - CIC Full Hybrid - AIC Mild Hybrid - AIC Full Fuel Cell Hybrid - Fuel Cell (See Table X for combinations of fuel type and engine type used in MOVES2004)	1980 and earlier 1981-85 1986-90 1991-2000 2001-2010 2011-2020 2021 and later	1972 and earlier 1973 1974 1975 . . . 1999 2000 2001-2010 2011-2020 2021 and later	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	Null Motorcycle LDV LDT HDT

Emission Processes

On-road vehicles consume energy and produce emissions through several mechanisms. For hydrocarbons, for example, this includes tailpipe exhaust, raw fuel evaporation and refueling. These mechanism are known as "processes" within MOVES, and are accounted for and reported out (if desired by the user) separately. The mechanisms for "pump-to-wheel" energy consumption and greenhouse gas emissions are limited to operation of the engine and emissions from the tailpipe. However, certain aspects of operation are so different in terms of their activity and affect on emissions, they merit treatment as separate processes. The processes for MOVES2004 are as follows:

- **Running**, meaning the energy consumed or emissions produced during operation over freeways and surface streets while the engine is fully warmed up.
- **Start**, meaning energy consumed or emissions produced during the period immediately following vehicle start-up. An important note is that this quantifies the energy consumed or emissions produced *in addition* to "running" energy/emissions that would be produced immediately following start-up. In other words, how much incremental emissions are produced following vehicle start-up, after the baseline running emissions are accounted for?

- **Extended Idle**, meaning energy consumed during long periods of idle off of the roadway network. This process applies mainly to combination long-haul trucks in MOVES, and is meant to account for the emerging issue of overnight "hoteling" at truck stops, although it could be applied to idling of passenger vehicles in drive-thru lanes, etc. This process is implemented only for energy consumption/CO_2 in MOVES2004.
- **Well-To-Pump**, meaning the energy and emissions produced from processing and distributing vehicle fuel in the process of getting from raw feedstock to the fuel pump. These energy use and emission rates are produced by Argonne National Laboratory's GREET model.

An additional process, manufacture/disposal, would account for energy and emissions from vehicle production and disposal. This could not be ready for inclusion in MOVES2004, but is planned for inclusion in a later version.

Characterizing Activity

The cornerstone of estimating total energy usage and emission inventories is vehicle activity. Vehicle activity centers on two fundamental questions: what is the total amount of vehicle activity, and how is this activity subdivided into modes that are unique to energy and emissions? The first question is quantified in MOVES by the metric Total Activity. Total Activity, as the name implies, is the total amount of vehicle activity for source use types in the given location and time which the user has selected in the run specification. The basis of total activity depends on the emission process, as shown in Table 3. In MOVES2004 Total Activity is estimated by the Total Activity Generator discussed in the Software Design section, generally using vehicle miles traveled (VMT) as the primary input.

Table 3 - Total Activity Basis by Process

Emission Process	Total Activity Basis	Description
Running	Source Hours Operating (SHO)	Total hours, of all sources within a source type, spent operating on the roadway network for the given time and location of the run spec. The same as number of sources * per-source hours operating
Start	Number of Starts	Total starts, of all sources within a source type, for the given time and location of the run spec. The same as number of sources * per-source starts
Extended Idle	Extended Idle Hours	Total hours, of all sources within a source type, spent in extended idle operation for the given time and location of the run spec.
Well-To-Pump	Pump-To-Wheel Energy Consumed	Total energy consumed, of all sources within a source type, for the given time and location of the run spec. The sum of running, start and extended idle.

The second piece of activity characterization is to define how total activity is subdivided into operating modes which produce unique energy consumption and emission rates. In the MOVES design these operating modes are allowed to vary by emission process and even pollutant, although for MOVES2004, discrete operating modes are only employed for running energy consumption, based on combinations of vehicle specific power (VSP) and instantaneous vehicle speed. These operating modes are shown in Table 4.

Table 4 – Operating Mode Bin definitions for MOVES2004 (running energy consumption)

Braking (Bin 0)			
Idle (Bin 1)			
VSP \ Speed	**0-25mph**	**25-50**	**>50**
< 0 kw/tonne	Bin 11	Bin 21	-
0 to 3	Bin 12	Bin 22	-
3 to 6	Bin 13	Bin 23	-
6 to 9	Bin 14	Bin 24	-
9 to 12	Bin 15	Bin 25	-
12 and greater	Bin 16	Bin 26	Bin 36
6 to 12	-	-	Bin 35
< 6	-	-	Bin 33

The operating mode concept is central to MOVES multi-scale analysis capability, and will be expanded with the criteria pollutant version of the model.

MOVES SOFTWARE DESIGN

The primary elements of the MOVES design are known conceptually as the Core Model, Generators, and Control Strategies. The Core Model calculates energy and emissions using as input:

- Total Activity
- Operating Mode Distribution
- Source Bin Distribution
- Meteorology Data
- Fuel Supply Data

These inputs, contained in a body of MySQL tables known as Core Model Input Tables, are provided for the time and location specified in the run specification. The core model is designed for the user to provide these data directly, for maximum flexibility in customizing the model. In the absence of user-supplied data to these tables, the inputs are produced by a series of Generators that take more readily available input data and produce the core model inputs. A summary of the Generators, their primary inputs and outputs are shown in Table 5.

Table 5 - Generators

Name	Primary Inputs	Outputs
Total Activity Generator	VMT, source populations, age distributions, sales growth rates, survival rates, VMT growth rates, temporal VMT allocation factors, roadway allocation factor geographic allocation factors	SHO, Starts, Extended Idle Hours by time, location, road type, source type, age
Operating Mode Distribution Generator	Average speed, drive schedules, VSP coefficients	Operating Mode (VSP and speed) distribution by time, location, road type, source type
Source Bin Distribution Generator	Engine size/loaded weight distribution, fuel/engine technology distribution, regulatory class distribution, model year groupings	Source Bin distribution by source type, model year (uniform over modeling domain)
Meteorology Generator	Hourly temperature and relative humidity	Hourly heat index

Another element of the MOVES design, Control Strategies, provide the user an easier interface for "what-if" analysis. Internal control strategies are accessed through the MOVES GUI and serve as a "wizard" for making changes that are translated to the underlying database. External control strategies generally require pre-processing of specific code (e.g. MySQL scripts) to affect the underlying MOVES database for a forthcoming run. While several control

strategies are envisioned as MOVES expand, MOVES2004 includes one internal and one external control strategy. The internal control strategy is known as the Alternative Vehicle & Fuel Control Strategy, which lets the user specify the market penetration mix of advanced technology vehicles, by source use type and model year, through a separate GUI screen. The fuel and engine technologies supported by MOVES2004 are shown in Table 6.

Table 6 – Fuel & Engine Technologies in MOVES2004*

Engine Technology → / Fuel Type ↓	Conventional Internal Combustion	Advanced Internal Combustion	Mild Hybrid (Conventional Internal Combustion)	Mild Hybrid (Advanced Internal Combustion)	Full Hybrid (Conventional Internal Combustion)	Full Hybrid (Advanced Internal Combustion)	Fuel Cell	Fuel Cell Hybrid
Gas**	✓	✓	✓	✓	✓	✓		
Diesel***	✓	✓	✓	✓	✓	✓		
CNG	✓							
LPG	✓							
E85	✓							
M85	✓							
Liquid H_2							✓	✓
Gas H_2		✓					✓	✓
Electric	Electric							

* Some source types do not support all fuel/engine technology combination
** Gasoline fuel subtypes: Conventional, RFG, E10
*** Diesel fuel subtypes: Conventional, FT, Biodiesel (B20)

The one external control strategy in MOVES2004 is the Future Emission Rate Generator. This a stand-alone MySQL script and MySQL table containing adjustment factors which, when run, updates emission rates used by MOVES for the 2001 and later model years, for all of the fuel and engine technology combinations listed in Table 6 above. This enables "what-if" assessment of energy and emission performance for specific technologies.

DEFAULT DATA

The MOVES2004 database is populated with a wealth of default data to enable the estimation of energy consumption and CO_2, CH_4, and N_2O emissions for calendar years 1999 through 2050, for each county in the U.S (plus territories) at the roadway level, by hour, day or month. In MOVES2004, 1999 is considered the base year, from which all projections are made; hence the bulk of default data is centered on this year. The default data covers information about the on-road fleet, vehicle activity patterns, emission rates, as well as localized meteorology and fuel supply. The derivation and sources of default data will be the subject of two reports to be published shortly after model release. An overview of the primary data inputs and their sources are shown in Table 7.

Table 7 – Selected Default Data and Data Sources in MOVES2004

Default Data	Sources
1999 Source use type Populations and Age Distribution	R.L. Polk, 1997 Vehicle In-Use Survey (VIUS)
1999 Vehicle Miles Traveled	Highway Statistics 2000
Sales and VMT Growth Rates	2004 Annual Energy Outlook
VMT allocations by month, day, hour, roadway type	1995 FHWA Study
Geographic activity allocations	EPA National Emission Inventory 1999
Average speed distribution	MOBILE6
Drive schedules by roadway and average speed	MOBILE6 plus new work for high speed, MD/HD, bus schedules
Energy and Emission rates by Source Bin (running, start, extended idle)	Multiple emission research programs, Physical Emission Rate Estimator (PERE), new analysis
Well-to-Pump Energy and Emission Rates	GREET
Meteorology (hourly temperature and humidity) by county	NOAA
Fuel supply (fuel subtype market share) by county	EPA National Emission Inventory 1999

CUSTOMIZING MOVES2004

Although a full range of default data is available in MOVES2004, the model was designed for the ability for users to customize the model to meet their specific needs. The primary ways users would be interested in customizing MOVES would be a) to better represent a local area better than the defaults, and/or b) to alter inputs for "what-if" analysis, for example with regard to different advanced technology and fuel scenarios.

Local Customization

A user would customize MOVES2004 for a specific area first by re-defining the modeling domain that the input data pertains, as well as the zones that make up the domain if sub-domain analysis was desired. The default modeling domain for MOVES2004 is the entire U.S. plus territories, with counties defined as zones. The minimum level of data required in tailoring input data to a re-define domain would be VMT and geographic (zone-level) allocation factors, since the current defaults only apply to the entire nation. All other fleet and activity inputs only serve to allocate these total activity measures, hence if not changed the national default allocations by time, roadway type, age, source type, etc. would be applied to the user-supplied VMT and geographic allocation data.

Beyond this basic requirement local customization could proceed on many levels. On the simpler end, it may involve using local vehicle age distribution or meteorology data, similar to what many users currently undertake with MOBILE. On the more complex end, the level of local customization could extend to specific driving schedules culled from in-use driving surveys. In the end the more specific data for an area, the better the model will be for that

area; but given the array of choices a user faces in using local data, a sensitivity analysis will be performed on MOVES2004 to shed light on the most important factors to focus on.

"What-if" Analysis Customization

MOVES2004, with integrated GREET, will provide a very broad range of "what-if" analysis capability for looking at different future scenarios. "What-if" capability extends to four dimensions: fuel and vehicle technology penetration, energy and emission performance of these technologies, upstream fuel pathway options, and activity patterns. How the user would make changes in each of these dimensions is elaborated below:

- **Fuel and Vehicle Technology Penetration:** As discussed earlier, the Alternative Vehicle & Fuel Control Strategy has been developed to provide a convenient graphically-driven mechanism for the user to input different penetration rates of the vehicle and fuel combinations listed in Table 6, by source type and model year. This allows the user to address the question "what is the impact of having X percent of advanced technology Y in the fleet, in year Z?" The control strategy is designed to make the necessary changes to the underlying MOVES database tables feeding into the Source Bin Generator
- **Energy and Emission Performance:** the external control strategy Future Emission Rate Generator has been developed to allow the user to input alternative assumptions regarding the relative benefit of energy and emission performance of individual technologies. This allows the user to address the question "what is the impact of varying the energy consumption and emissions of advanced technology Y?"
- **Fuel Pathway Options:** The integration with the Argonne National Laboratory well-to-wheel model GREET will enable the user to select different pathway options, or mixes of options, for specific fuel subtypes in MOVES. It will also allow the user to alter inputs at each step of a given pathway. This allows the user to address the question "what is the impact of varying the source of fuel for advanced technology Y?"
- **Activity Patterns:** MOVES2004 provides unprecedented flexibility in varying activity patterns of the fleet, for more real-world estimation. This pertains to many parameters related to VMT growth and allocation, as well as driving patterns themselves. Specifically, MOVES2004 estimates energy and emissions using real-world driving patterns culled from in-use driving surveys. The user can look at differences between real-world urban vs. freeway driving or congested vs. uncongested conditions, across source use types. The user would alter such inputs directly in the underlying MySQL database, through use of the "Manage Input Data Sets" screen on the MOVES2004 graphical user interface. The intent for future versions of MOVES is to develop in internal control strategy, or perhaps several, to address alternate activity inputs.

CONCLUSION

MOVES2004 is the first generation of EPA's MOVES series. It includes integration with Argonne National Laboratory's GREET model, providing complete well-to-wheel analysis capability. The scope of the model is on on-road vehicle energy consumption and greenhouse gas emissions (CO_2, CH_4, N_2O), with the ability to estimate these quantities for any county in the nation from 1999 through 2050. A significant body of default data is included with the model to enable estimation of these parameters; however, the MOVES design is focused on allowing users to customize input data for better local estimation, of for "what-if" research analysis. "What-if" analysis extends to four dimensions: fuel and vehicle technology penetration, energy and emission performance of these technologies, upstream fuel pathway options, and activity patterns.

REFERENCES

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