Development of an International Version of MOVES

E. Glover[1], J. Koupal[1], J.Warila[1], S. Kishan[2], S. Fincher[2], A. Stanard[2], and W. Faler[3]*

[1]U.S. EPA, 2000 Traverwood Dr., Ann Arbor, MI 48105
[2]Eastern Research Group, Inc., 3508 Far West Blvd., Suite 210, Austin, TX 78731, sandeep.kishan@erg.com
[3]Fluid and Reason, LLC, 3319 Greenfield Rd #352, Dearborn, MI 48120

Introduction

The U.S. EPA has taken the next step to modify and extend the MOtor Vehicle Emissions Simulator (MOVES) model's capabilities to allow estimation of on-road vehicle emissions inventories and rates in other countries. This revised model will allow users to create a set of custom inputs for a specific country or region, reflecting the specific emission standards and phase-in schedules applicable to that region. In the initial phase of the project, alternate emission rate data tables were developed to reflect international emissions standards (e.g., European, Asian, and other such standards) that are prevalent in non-U.S. jurisdictions. The model is being designed to accept appropriate fleet penetration and implementation dates for the use of these standards in any country through a pre-processor being developed as part of this work. Initial research into development of an international MOVES framework was previously been conducted by USEPA staff [Koupal et al, 2010].

Overview of MOVES2010

EPA's MOVES model is a comprehensive vehicle emission modelling software package used to estimate emission inventories and rates from on-road motor vehicles in all U.S. states and territories. MOVES can be applied at a variety of geographic scales, from national and regional emission inventories, to specific locations such as intersections, for project-level or "hot-spot" analyses. Fundamental to the MOVES design is the implementation of modal emission rates, which are sensitive to vehicle speed, acceleration and road grade, allowing the model to better account for differences in real-world traffic patterns. MOVES was developed to allow customization using local vehicle fleet, activity and emission patterns, to better facilitate international application.

Analysis Scales

The overall goal of this study is to create a *generalized* process for modifying the MOVES model, so that it can be used for a variety of local conditions in an international setting. Development of such a process is desired so that international users can adapt their own local data for inclusion in the model (as opposed to re-programming model code and modifying database structures to support usage in many different countries). Because the complexity involved in developing a generalized process is substantial, EPA wishes to create a framework for MOVES expansion that will identify the primary steps of transitioning from a U.S. based model to an international basis, and begin applying those steps to the existing MOVES code base. The code changes and database modifications produced during this project will be focused on these initial steps, with the intention that the draft version of MOVES International produced can be used in certain limited analysis situations for *light duty vehicles*, with the potential for additional improvement (e.g., inclusion of additional vehicle classes) in the future.

As described in Koupal et al (2010), a "tiered" approach to MOVES International customization is recommended. This is due to the fact that full customization of MOVES for use in other countries would require intensive data collection and analysis efforts. Use of a tiered approach allows for application of currently available foreign data sets for the purpose of developing regional emissions estimates (not project level estimates) through usage of the existing MOVES Custom Domain option. Having established such a domain for international areas of interest, MOVES could be modified using the following EPA-suggested tiers:

Tier 1: Use of the MOVES County Data Manager (CDM) for input of local data. By using the CDM to import localized activity data, fleet characterization data, fuel properties, and other parameters into MOVES, international users can customize inputs to more closely reflect the makeup of their local fleets. However, MOVES would still use its internal emission rates, drive cycles, vehicle classes, road types, and other information, all of which are based on data collected in the U.S., to calculate modeled emission estimates.

Tier 2: Implementation of international emissions standards. Under this tier, alternate emission rate data tables could be developed to reflect international emissions standards (e.g., Euro, Asian, and other such standards) along with appropriate fleet penetration and implementation dates. Development of these emission rate tables might be based, for example, on mapping of European standards to U.S standards. Another approach might involve processing of localized fleet emissions data across technology strata to develop entirely new rate tables for a particular area. Using newly developed rate tables, along with local fleet characterization data discussed under Tier 1, would allow for more accurate estimation of emissions; however drive cycles, vehicle classes, road types and so forth would still be derived from U.S.-based defaults currently contained in MOVES.

Tier 3: Implementation of alternate data via MySQL and Java code changes. In order to completely transform MOVES for use in international application, MySQL database updates and associated Java code changes could be developed to reflect customized vehicles classes, road types, and/or drive cycles. While this approach would allow for calculation of highly customized estimates for a given area, it would require the greatest amount of effort and research in MOVES model adaptation.

Customizing MOVES for International Use

This project is an attempt to create, as described in Tier 2 above, a framework that could be easily adapted to any jurisdiction for analysis of local fleets, in which technology penetration and implementation dates are accurately represented within MOVES. Localized data will still be needed to fully customize the model for a particular area, but the updates to MOVES developed here should serve as a good starting point for future model refinement.

The MOVES model is primarily a data driven model, and uses a default MySQL database extensively in its calculations. Thus, a major task of this study is to provide guidance and software tools to enable international users to develop a custom database that can be used with MOVES to model their particular country.

MOVES currently contains an input option called the Custom Domain, which allows users to specify a custom geographic domain and provide most of the local data required to model it. It is EPA's intention to extend the Custom Domain to allow for modelling of international areas of interest. Users would supply local activity, fleet distribution, and fuel parameters through the CDM interface. Guidance for international users will be developed to address how to create a customized database for their country using the Custom Domain option and CDM, along with additional inputs that may be required. We anticipate that this guidance will mainly be concerned with mapping of international vehicle classes to MOVES source types, and mapping international road types/classifications to existing MOVES road types. Other topics of interest may include aggregation of regional VMT, adaptation of fuel formulation and supply, and meteorological inputs.

Emission Rate Converter

The current US version of MOVES bases its calculations on emission rates that are stored as ratios of each different vehicle type back to Tier I emissions levels. All of the Tier II vehicles in MOVES are modeled based on their ratio to Tier I emissions levels. Because of this, emission rates for vehicles that meet international standards can be integrated into the model based on their ratios to Tier I emissions levels as well.

In order to relate international emissions standards to EPA standards, we needed a way to create equivalence between the different drive cycles that vehicles are tested over when initially certified for sale. For EPA standards, the chassis dynamometer test cycle used for certification is the FTP-75, which is an approximately 30 minute cycle that covers about 11 miles at an average speed of 21 mph. Vehicles certified to EURO standards are tested over the New European Driving Cycle (NEDC), which is an approximately 20 minute cycle that travels about 7 miles with an average speed of 21 mph. While the average speeds are almost identical, the NEDC consists of more steady-speed driving and also has a higher top speed than the FTP-75.

Because data relating FTP to EURO emissions standards is rare, ERG chose to follow a procedure for portable emissions measurement system (PEMS) data in order to estimate the inherent emissions differences between the test cycles used for each set of standards. We used a vehicle specific power (VSP) approach in order to bin different modes of operation that occurred during on-road testing. VSP refers to the amount of engine power that is being used to propel the vehicle at any instant, divided by the weight of the vehicle. Engine power was

estimated using estimates of vehicle road load coefficients, instantaneous speed and acceleration, as well as road grade if available. Each second of operational data was binned based on VSP and speed into 23 different operational bins in 3 speed ranges. For each of these bins, the emission levels were then averaged for each vehicle.

For support of MOVES International, ERG used various sources of PEMS data in order to conduct the VSP-bin analysis in order to have as wide a variety of vehicles as possible. There were three general data sources. The first was data from the EPA Kansas City PEMS test program, in which 500 light-duty vehicles were PEMS tested both on the road and on a chassis dynamometer [Kishan et al. 2006]. The second was data from the Hong Kong Environmental Protection Department's PEMS measurements of various vehicle types in support of their Hong Kong emissions inventory [Wong 2012]. This source provided data for about 25 vehicles. The third source was from the European Union's Joint Research Centre, which provided PEMS test results for 11 light duty vehicles which were tested in support evaluating current Euro standards [Bonnel 2012].

With the average PEMS-test emission level in each VSP bin for each vehicle, we could then reconstruct the NEDC and FTP test cycles for comparison. Each test vehicle was simulated over the NEDC and FTP cycles and the VSP required at every second to follow each cycle was calculated and binned as before. The number of counts in each bin were multiplied by the average emission rate for that bin, and summed to find the total emission level that would have been produced had the vehicle been driven over the dynamometer cycle. FTP-emission results were weighted 43%/57% as given in the actual test procedure. For some test vehicles, cold-start data was collected and binned separately, and the cold start average bin emissions were used for the first 200 seconds of the two test cycles in order to make the comparison more accurate. Using this method, ratios between the NEDC and FTP-75 could be found for each test vehicle, and these ratios could be averaged based on vehicle type and model year period. The process was performed for CO_2, CO, NO_x, and HC.

For an example test vehicle, VSP bin emission levels of NO_x along with the distribution for each bin are presented in the figures below. The emission levels are the filled circles, and the number of seconds of time spent in each bin are the open squares. Note that for both cycles, the emission rates in each bin are the same, only the number of seconds of operation changes between the two different cycles.

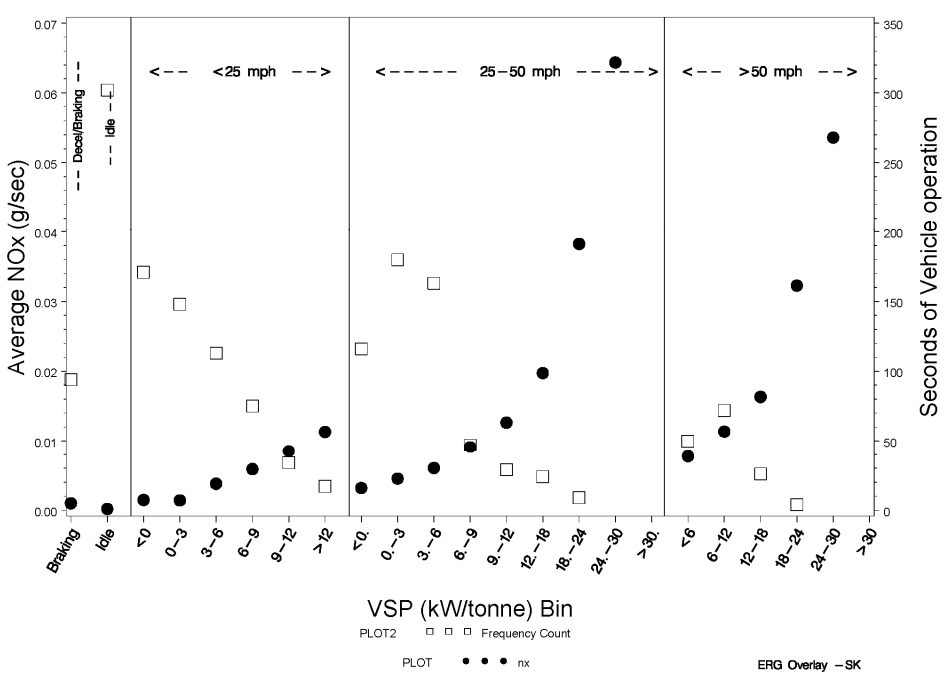


Figure 1.FTP Equivalent Distributions – 0.878 g/mi

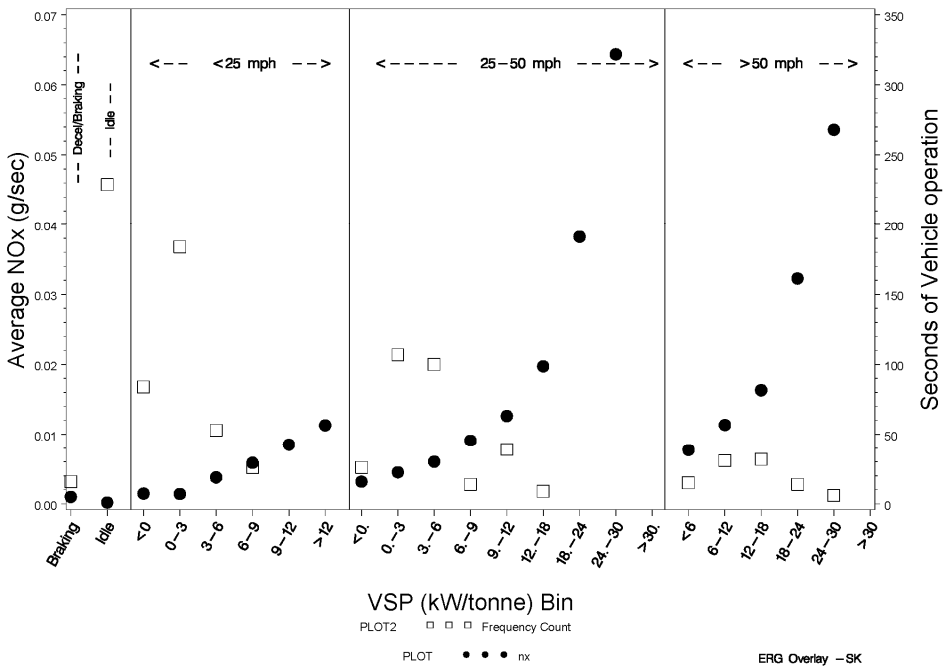


Figure 2. NEDC Equivalent Distributions – 0.979 g/mi

We were then able to find the ratio of NEDC to FTP emission levels based on the above reconstructions. Subsequently, we plotted the results for the different test vehicles to get a sense of the variation in the different pollutant ratios. Those values are presented in the following figures, first for hydrocarbons, then for NO_x. The ratio for each vehicle is shown as a plus symbol, and the two wider lines in the middle of each range represent the averages for both cars and trucks. The results are presented by bins of model years, pre-1980, 1981 to 1990, 1991 to 1995, and then 1996 and newer. By binning the years like this, there is a fairly steady increase in the average ratios of emissions over the two cycles as model year bin progresses.

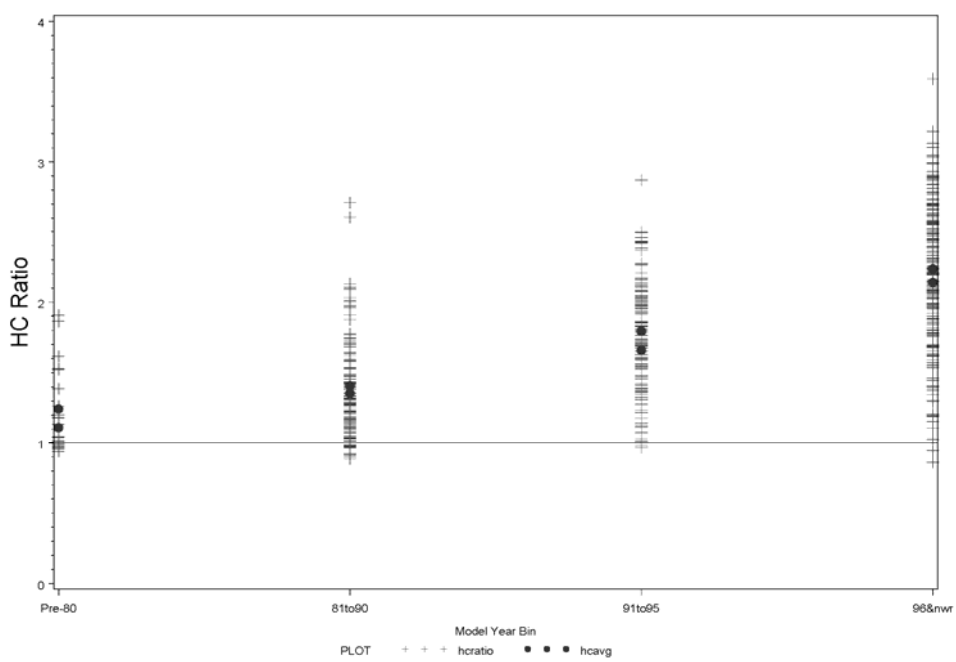


Figure 3. HC g/mi NEDC/FTP by model year group, both cars and trucks

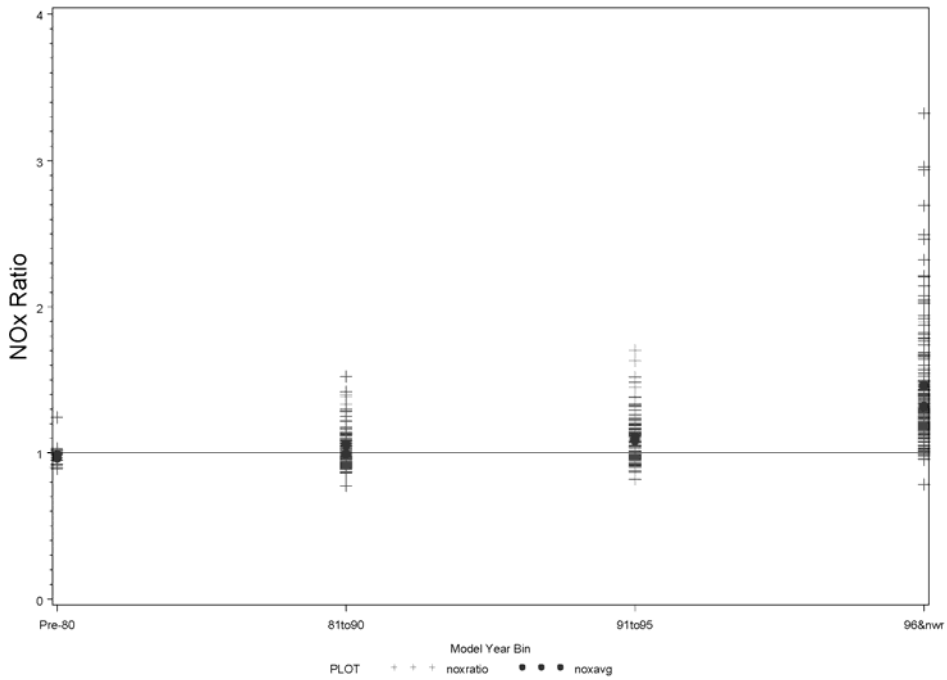


Figure 4. NO_x g/mi NEDC/FTP by model year group, both cars and trucks

The average ratios of NEDC to FTP equivalent emissions levels for each vehicle type from each dataset are presented in the following table. Note that the vehicles from the Hong Kong dataset do not have any cold-start data. It is apparent that they have much lower CO and HC ratios than the other vehicles, and it is likely that the lack of cold-start data is the cause.

Table 1: Average ratios of NEDC/FTP grams per mile for different vehicle types and different data sources.

Vehicle Type/Source	Model Year	CO	NOx	HC
Car-gas (KC)	Pre-83	1.14	1.00	1.11
Car-gas (KC)	83to92	1.21	1.02	1.28
Car-gas (KC)	93to98	1.48	1.14	1.64
Car-gas (KC)	99&nwr	1.99	1.56	2.23
Car-gas, (JRC)	99&nwr	2.32	1.48	.
Car-gas, (HK)*	93to98	0.84	0.91	0.90
Car-gas, (HK)*	99&nwr	0.99	0.91	0.91
Truck-gas (KC)	Pre-83	1.04	0.96	1.05
Truck-gas (KC)	83to92	1.29	0.98	1.24
Truck-gas (KC)	93to98	1.45	1.07	1.49
Truck-gas (KC)	99&nwr	1.97	1.40	2.25
Car-Diesel, (JRC)	99&nwr	1.44	1.07	--
Truck -Diesel (HK)*	83to92	0.88	0.92	--
Truck -Diesel (HK)*	93to98	0.89	0.96	0.87
Truck -Diesel (HK)*	99&nwr	0.95	0.90	--

*- The HK data did not include cold-start data, as such all operation is assumed to be warm

We performed a simple unit conversion from the g/km values specified in Euro emissions standards to g/mi as in the FTP. Multiplying by the average ratios above, we put the different Euro standards on an FTP basis. This has the effect of calculating what a vehicle that emits exactly the level of a Euro standard would emit over the FTP-75. Those values are presented along with EPA standards below, and sorted by emission level.

Table 2: Equivalent EPA and Euro Light Duty Emissions Standards, in grams per mile, estimated using the VSP-Bin Technique

CO		NOx		HC	
Euro 1	3.600	Euro 1*	0.654	Euro 1*	0.693
Tier I	3.400	Tier I	0.400	Euro 2*	0.279
Tier 2, B8	3.400	Euro 2*	0.304	Tier I	0.278
Tier 2, B6	3.400	Euro 3	0.154	Euro 3	0.143
Tier 2, B5	3.400	Tier 2, B8	0.140	Tier 2, B8	0.106
Euro 2	2.376	Euro 4	0.082	Tier 2, B6	0.080
Euro 3	1.852	Tier 2, B6	0.080	Tier 2, B5	0.080
Euro 4	0.805	Euro 5	0.062	Euro 4	0.071
Euro 5	0.805	Tier 2, B5	0.050	Euro 5	0.071

*- The Euro standard was for NOx+HC, split apart here based on subsequent ratios of separate NOx/HC standard levels

In this analysis, we assume that vehicles certified to one standard have an equivalent margin for meeting the standard, meaning that this equivalence is based on the assumption that if FTP-certified vehicles generally pass with a 30% margin, NEDC-certified vehicle would pass with that same margin.

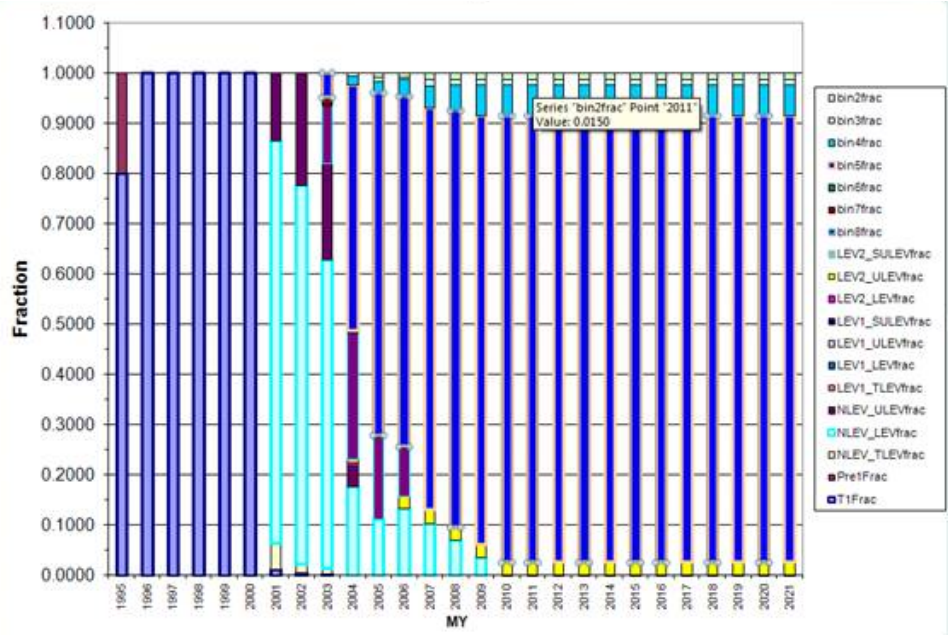
Technology Inputs by Model Year

In MOVES International, users will be able to provide modifications to fleet technology across two dimensions – technology penetration and calendar year. Technology penetration fractions will sum to 1.0, and vary from pre-Tier 1 technologies all the way through LEV2, with Euro technologies integrated (or, in some cases, perhaps completely replacing US standards) as necessary. Technology fractions can be provided for each model year to be analyzed, and will allow users to alter or delay introduction of certain technologies as appropriate for their fleet. An example of how such inputs might be provided is presented in Table 3, which shows a hypothetical variation in technology penetration fractions based on “default” model years.

Table 3. Technology Penetration Fractions by Year

US and Euro Stds			User's Technology Penetration %						
Year	US Std	Euro Std	T1	Pre1	NLEV	T2	LEV1	LEV2	Euro
1994	Tier 0, 40%	Euro 1	0.1	0.4	0.1	0.1	0.1	0.1	0.1
1995	Tier 0, 80%	Euro 1	0.1	0.4	0.1	0.1	0.1	0.1	0.1
1996	Tier 1	Euro 1	0.4	0.1	0.1	0.1	0.1	0.1	0.1
1997-2000	Tier 1	Euro 2	0.3	0.1	0.1	0.1	0.1	0.1	0.2
2001	Tier 1	Euro 3	0.3	0.1	0.1	0.1	0.1	0.1	0.2
2002	Tier 1	Euro 3	0.2	0.1	0.1	0.1	0.1	0.1	0.3
2003	Tier 1	Euro 3	0.2	0.1	0.1	0.1	0.1	0.1	0.3
2004	Bin 9 Avg	Euro 3	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2005	Bin 5/9 50% Flt Avg	Euro 3	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2006	Bin 5, 75% Flt Avg	Euro 4	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2007	All Bin 8, Flt Avg 5	Euro 4	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2008	All Bin 8, Flt Avg 5	Euro 4	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2009	All Bin 8, Flt Avg 5	Euro 4	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2010	All Bin 8, Flt Avg 5	Euro 4	0.1	0.0	0.1	0.3	0.1	0.1	0.3
2011	All Bin 8, Flt Avg 5	Euro 5	0.1	0.0	0.1	0.3	0.1	0.1	0.3
>=2012		Euro 5	0.0	0.0	0.2	0.1	0.1	0.1	0.5

As another example, consider the following graph that presents fractions of technologies introduced across vehicle model years. In this example, Tier 1 LDVs are phased out, beginning in the 2000 model year, in favor of NLEV-LEV technology, which is subsequently replaced by a mid-level Tier 2 bin starting in 2004-2005. Users of MOVES International would be able to provide technologies more representative of the fleet in their area, and vary the timeframe of technology introductions as appropriate.



Future Updates

In future updates to MOVES International, alternate MySQL tables, scripting, and Java code might be developed to add vehicle classes (e.g., taxis), road types, or driving patterns specific to a particular country. The resulting model might reflect the local situation to a large degree, but would likely require an extensive local research program to generate the data needed for these fundamental changes. This is consistent with the approach outlined under Tier 3 above.

As an example of the type of database alterations that might need to be made under this task, consider that an international version of MOVES must supply a customized *SampleVehiclePopulation* table. This table relates source type, model year, fuel, engine technology, regulatory class, engine size, weight class, and SCC vehicle type. Further, the combinations present in this table indicate the physical reality of what combinations can exist. A combination that cannot exist is not present in the table, whereas a combination that could physically exist but is not observed is in the table with a zero fraction. As jurisdictions other that the US have differing regulatory classes and fuel usage (akin to MOBILE6 diesel sales fractions), those jurisdictions must provide their own representative values for this table.

Other future updates might include broader, high-level customization changes, including provision of foreign language support for the GUI, as well as changing GUI units from English standard to metric.

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