# Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES201X

Draft August 11, 2017

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# Glossary of Acronyms

| | |
|---|---|
| A/C | Air Conditioning |
| ACCF | Air Conditioning Correction Factor |
| ASM | Acceleration Simulation Mode |
| CO | Carbon Monoxide |
| EPA | Environmental Protection Agency |
| F | Fahrenheit |
| FID | Flame Ionization Detection |
| FTP | Federal Test Procedure |
| g/mi | Grams per Mile |
| GVWR | Gross Vehicle Weight Rating |
| HC | Hydrocarbons |
| LHDT | Light Heavy-Duty Truck |
| I/M | Inspection and Maintenance |
| LDT | Light-Duty Truck |
| LDV | Light-Duty Vehicle |
| LLDT | Light Light-Duty Truck |
| MDPV | Medium-Duty Passenger Vehicle |
| MOVES | MOtor Vehicle Emission Simulator |
| MSAT | Mobile Source Air Toxics |
| NMHC | Non-Methane Hydrocarbons |
| NOx | Oxides of Nitrogen |
| OBD | On-Board Diagnostic |
| PM | Particulate Matter |
| RSD | Remote Sensing Device |
| SFTP | Supplemental Federal Test Procedure |
| THC | Total Hydrocarbons (FID detection) |
| VIN | Vehicle Identification Number |
| VOC | Volatile Organic Compounds |

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# 1 Introduction

The United States Environmental Protection Agency's Motor Vehicle Emission Simulator—commonly referred to as MOVES—is a set of modeling tools for estimating air pollution emissions produced by onroad (highway) and nonroad mobile sources. MOVES estimates the emissions of greenhouse gases (GHGs), criteria pollutants, and selected air toxics. The MOVES model is currently the official model for use for state implementation plan (SIP) submissions to EPA and for transportation conformity analyses outside of California. The model is also the primary modeling tool to estimate the impact of mobile source regulations on emission inventories.

MOVES calculates emission inventories by multiplying emission rates by the appropriate emission-related activity, applying correction and adjustment factors as needed to simulate specific situations, and then adding up the emissions from all sources and regions. The highway vehicle emission rates in the MOVES model represent emissions under a single (base) scenario of conditions for temperature, humidity, air conditioning load and fuel properties. MOVES is designed to adjust these base emission rates to reflect the conditions for the location and time specified by the user. MOVES also includes the flexibility to adjust the base emission rates to reflect the effects of local Inspection and Maintenance (I/M) programs. This report describes how these adjustments for temperature, humidity, I/M, and air conditioning were derived. Adjustments for fuel properties are addressed in a separate report.[1]

This report describes MOVES201X adjustments that affect running exhaust, start exhaust, and extended idling emissions. The crankcase emission processes are chained to running exhaust, engine start, and extended idling emissions, and thus are similarly affected by the temperature adjustments described in this report. The impact of fuels, temperatures, and I/M programs on vapor venting, permeation, and liquid leaks is addressed in a separate report on evaporative emissions.[2]

This report replaces the MOVES2014 adjustment report.[3] Updates for MOVES201X were minor. They include removing the running exhaust temperature effect for particulate matter, updating the humidity effects, and correcting an error in the I/M adjustments. This report also includes an appendix describing temperature and humidity in MOVES defaults.

# 2 Temperature Adjustments

Emission rates in MOVES are adjusted by the ambient temperature to account for temperature effects that impact emissions such as inefficient oxidation of emissions at cool catalyst temperatures and additional fuel needed to start an engine at cold temperatures. In MOVES, exhaust emissions are adjusted relative to their base rates at 75 degrees Fahrenheit based on:

1. Ambient temperature[4]
2. The latent engine heat from a previous trip, applied as an adjustment based on the length of the soak time[5,6]

This report contains the adjustment based on ambient temperature. The second point regarding soak time and start emissions is addressed in the light-duty[6] and heavy-duty[7] emission rates reports.

This report addresses temperature sensitivity of emissions from gasoline vehicles in Sections 2.1 through 2.3. All the gasoline emissions data used to estimate temperature effects are obtained from light-duty gasoline vehicles. However, the gasoline temperature effects developed based on light-duty vehicles are applied to all gasoline vehicles in MOVES, including motorcycles, heavy-duty gasoline vehicles, and light-duty vehicles fueled on ethanol-gasoline blends.

Section 2.4 discusses the temperature effects derived for diesel vehicles. The data used to derive temperature effects is based on light-duty diesel vehicles, but are applied to all diesel vehicles in MOVES due to a lack of temperature effect data on heavy-duty diesel vehicles. The diesel temperature effects are also applied to CNG buses as discussed in Section 2.5. Section 2.6 discusses the temperature effects for energy consumption for all vehicle types in MOVES.

## *2.1 Data Sources for Gasoline Temperature Effects for HC, CO, and $NO_X$ emissions*

For the analysis of the temperature effects on start emissions, the data consists of Federal Test Procedure (FTP) and LA-92 tests. For running emissions, analysis includes the Bag 2 emissions of FTP tests as well as US06 tests (without engine starts). Measurements from both the Federal FTP and California Unified Cycle (3-phase / 3-bag tests) are used to determine the effect of temperature on vehicle emissions. Within each test cycle, the first and third phases are identical driving cycles, but the first phase begins with a cold-start (cold engine and emission control equipment) while the third phase begins with a hot-start (relatively warm engine and control equipment). The difference between Bag 1 and Bag 3 (in grams) are the emissions attributed to the cold start of the vehicle.

Some second-by-second test data were also used, but only to validate the effects of temperature on running emissions (HC, CO, and $NO_X$). The data used in these analyses are from the following sources:

**Table 2-1 Summary of Data Sources**

| Data Source | Test | Temperatures Tested (deg. F) | # of Vehicles | MY Range |
|---|---|---|---|---|
| MSOD | FTP + | 15-110 | Hundreds | Pre-2005 |
| ORD | FTP, IM240 | -20, 0, 20, 40, 75 | 5 | 1987-2001 |
| MSAT | FTP | 0, 20, 75 | 4 | 2005 |
| OTAQ | FTP, US06 | 0, 20, 75 | 9 | 2010 |

- **MSOD -** EPA's Mobile Source Observation Database (MSOD) as of April 27, 2005. Over the past decades, EPA has performed or acquired data representing emissions measurements over various cycles (often the FTP) on tens of thousands of vehicles under various conditions. EPA has stored those test results in its Mobile Source Observational Database (MSOD).

For the data stored in MSOD, we limited our analysis to those tests for which vehicles were tested at two or more temperatures. The subset of tests meeting this criterion covered a temperature range from 15 to 110°F. Note that the results acquired from MSOD were collected in aggregate or “bag” modes.

Information on EPA's MSOD is available on EPA's website:
https://www.epa.gov/moves/mobile-source-observation-database-msod

- **ORD Program -** EPA’s Office of Research and Development (ORD) contracted (through the Clean Air Vehicle Technology Center, Inc.) the testing of five cars (model years 1987 through 2001). Those vehicles were tested using both the FTP and the IM240 cycles under controlled conditions at temperatures of: 75, 40, 20, 0 and –20 ºF.[8]

- **MSAT Program -** Under a contract with EPA, the Southwest Research Institute (SwRI) tested four Tier 2 vehicles (2005 model year car and light-duty trucks) over the FTP under controlled conditions at temperatures of: 75, 20, and 0 ºF.[9]

- **OTAQ Cold Temperature Program -** EPA’s Office of Transportation and Air Quality (OTAQ) contracted the testing of nine Tier 2 vehicles (2010 model year car and light-duty trucks). Eight of the nine vehicles were Mobile Source Air Toxics (MSAT-2) rule compliant. Vehicles were tested on the FTP and US06 under controlled conditions 75, 20, and 0ºF. Information on the vehicle test design is located in Appendix A.

## *2.2 Temperature Effects on Gasoline Start Emissions*

When a vehicle engine is started, emissions can be higher than during normal operation due to the relatively cold temperature of the emissions control system. As these systems warm up to their ideal operating temperature, emissions from the vehicle can be dramatically reduced. The cold start effect can vary by pollutant, temperature, and vehicle technology.

The effects of ambient temperature on HC, CO, and $NO_X$ start emissions were developed using the following approach:

- No adjustment for temperatures higher than 75°F. 75°F is the midpoint of the allowable temperature range (68°F-86°F) per the FTP.

- Additive adjustments for temperatures below 75°F. These adjustments are added to the emissions that would occur at 75°F.

- Calculate the adjustments as either polynomial (Equation 2-1) or log-linear (Equation 2-2) functions:

$$Additive\ Grams = A*(T\text{-}75) + B*(T\text{-}75)^2 \qquad \textbf{Equation 2-1}$$

$$Additive\ Grams = Be^{A*(T\text{-}75)} + C \qquad \textbf{Equation 2-2}$$

This approach provides a value of zero change for the additive adjustment at 75° F (i.e., the temperature of the federal FTP test). The coefficients, A and B, for the adjustment equations are stored in the StartTempAdjustment table. This table contains temperature effect coefficients for each model year group and pollutant.

In MOVES, the temperature effects for older model year groups use polynomial function (Equation 2-1) and more recent model year vehicles use log-linear function (Equation 2-2). The data processing and the model fitting process differed for the polynomial and log-linear fits, and each is described separately below. Temperature effects in MOVES201X were retained from earlier versions of MOVES.

### *2.2.1 HC and CO Start Emissions for Gasoline-Fueled Vehicles*

In developing temperature adjustments for HC and CO start emissions, both polynomial and log-linear regression models were used to fit the data. Data anomalies were resolved by combining two or more model year groups to obtain a larger dataset, or by removing anomalous data points. We also distinguish temperature effects between pre-MSAT-2 (Mobile Source Air Toxics)[a] and MSAT-2 compliant vehicles, which began phase-in starting in 2010. The MSAT-2 rule included the first regulation on low temperature (20° F) non-methane hydrocarbon (NMHC) emissions for light-duty and some medium-duty gasoline vehicles.

#### *2.2.1.1 Polynomial Fits*

The coefficients for HC emissions for pre-2006 gasoline vehicles and CO emissions for pre-2001 gasoline vehicles were calculated with polynomial fits to data processed in the following steps. First, the cold start emissions (grams/start) were calculated as the difference between Bag 1 and Bag 3 emissions for each vehicle test. Next, the cold start emissions were stratified by model year groups. The data was initially grouped according to the following model year groups:

- 1960 to 1980
- 1981 to 1982
- 1983 to 1985
- 1986 to 1989
- 1990 to 1993
- 1994 to 1999

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[a] http://www.epa.gov/otaq/fuels/gasolinefuels/MSAT/index.htm

- 2000 to 2005

Then, the mean emissions at 75°F were subtracted from the mean emissions at the other temperatures to determine the change in emissions as functions of ambient temperature. Then, we modeled the changes in cold-start emissions as a polynomial function of temperature minus 75° F. The additive adjustments are set equal to zero for temperatures higher than 75° F. Thus, we did not use the changes in emissions from temperature above the FTP temperature range (68º to 86º F). The model year groups were aggregated to larger intervals when the less aggregated groups yielded non-intuitive results (e.g. older model year group had lower cold start emissions). Table 2-2 summarizes the coefficients used with Equation 2-1 (polynomial) to estimate additive start temperature adjustments for older model year gasoline vehicles.

**Table 2-2 Polynomial Model Coefficients for CO Temperature Effects for 2000 Model Year and Earlier Gasoline Vehicles and HC Temperature Effects for 2005 and Earlier Gasoline Vehicles**

| | CO | | HC | |
|---|---|---|---|---|
| **Model Year Group** | **A** | **B** | **A** | **B** |
| Pre-1981 | -4.677 | | -0.631 | |
| 1981-1982 | -4.631 | | -0.414 | |
| 1983-1985 | -4.244 | | -0.361 | |
| 1986-1989 | | | | 0.002 |
| 1986-2000 | | 0.023 | | |
| 1990-2005 | | | | 0.003 |

The HC test data for the 1986-1989, and 1990-2005 model year groups included the ORD program vehicles that were tested at an ambient temperature of -20° F. However, when this ultra-low temperature data was included, the "best fit" HC regression curves (linear, quadratic, and cubic) all exhibited poor fits for temperatures from zero through 20° F. We removed the five ORD vehicle tests conducted at -20° F, which improved the estimate of the cold-start HC emissions in the more common 0° F to 20° F range. Therefore, the coefficients in MOVES are based on the changes in cold-start emissions for temperatures from zero through 75°. However, these coefficients are applied to all ambient temperatures less than 75° F in MOVES.

For CO, the temperature effect for the 1994-2000 model years was applied to all model years from 1986-2000. The temperature effect for 1986-1993 vehicles was dropped because it led to cases where older model years were modeled with substantially lower CO emissions than newer model years. Note that the base CO emission rates still vary across this model year range.

#### *2.2.1.2 Log-linear Fits*

In estimating the HC temperature effect for model years 2006 and later and the CO temperature effect for model years 2001 and later[a], data from ORD, MSAT and OTAQ cold temperature programs[b] were used to fit regression models We used linear mixed models, with both continuous and categorical variables, to fit to the logarithm of the start emissions. Second-order polynomial models fit to the data exhibited non-intuitive behavior when fitted to the data (negative values, non-monotonically increasing emissions). Thus, we chose to fit the data with log-linear models because they provide monotonically increasing emissions at colder temperatures and can model the strong curvature evident in the cold start data (See Figure 2-1 and Figure 2-2).

The model parameters were fit using linear mixed models using the function *lme* within the R statistical package *nlme.*[10] Using random effects for vehicle, and the test temperature as a fixed effect, we accounted for the paired test design of the data set, yielding robust temperature effect estimates for the entire data set (e.g. not all vehicles were tested at the same set of temperatures which is evident at -20° F in Figure 2-1).

The linear mixed model had the following form:

$$\log(y) = \propto + \beta_1 \cdot Temp + Veh$$ **Equation 2-3**

Where: y = start emissions (grams), Temp = temperature in Fahrenheit, Veh = random effect for each individual vehicle. The mean model simply removes the random vehicle effects:

$$\log(y) = \propto + \beta_1 \cdot Temp$$ **Equation 2-4**

We then converted the mean logarithmic model to real-space, yielding:

$$y = e^{\propto + \beta_1 Temp}$$ **Equation 2-5**

We then changed the intercept to 75°F, by setting $T' = 75 - Temp$ , and substituting $Temp = 75 - T'$ into the above equation and rearranging. This yields equation:

$$y = e^{\propto + \beta_1 Temp}$$ **Equation 2-6**

Where A = $\beta_1$, and B= $e^{\alpha + 75 \cdot \beta_1}$. B is essentially the 'Base Cold Start' at 75°F, with units of (g/start). The $e^{A(Temp-75)}$ term is a multiplier which increases the cold start at lower temperatures.

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[a]The CO temperature effects for 2001-2005 model years were estimated using the log-linear fit because the temperature correction for these model years in previous versions of MOVES caused the model to estimate cold start CO emissions that were unrealistically high relative to older model year vehicles.

[b] We excluded the two GDI vehicles from the OTAQ cold temperature program from the model fit because were not deemed representative of the predominate technology in the 2010 vehicle fleet. In addition, they were believed to be transitional GDI technologies that were not necessarily representative of future GDI technology.

To convert the model to an additive adjustment, we calculated the additive difference from the cold start: y – y(75) = $Be^{A(Temp-75)} - B$. This model form can be used in the current MOVES temperature calculator for HC and CO, by setting C = -B, yielding Equation 2-2:

$$\textit{Additive Grams} = Be^{A*(T-75)} + C \qquad \textbf{Equation 2-2}$$

The initial estimated fixed effects (including p-values) for the linear model fit are displayed in Table 2-3. The model estimates that the Portable Fuel Injection (PFI) MSAT-2 compliant vehicles (2010) tested in the OTAQ 2012 test program have consistently lower start emissions than the pre-MSAT-2 vehicles (pre-2010), as shown by the positive pre-MSAT coefficient ($\alpha_2$). However, no statistically significant difference in the log-linear impact of temperature (coefficient β) was found between the 2001-2009 and the 2010 model year groups for CO emissions, as shown in Table 2-3 (p-value of the Temperature × pre-MSAT effect is >0.90).

**Table 2-3 Fixed Effects for the Initial CO Model Fit to Data from 2001+ Model Year Vehicles from the ORD, MSAT, and Cold Temperature Programs (13 vehicles, 95 observations)**

| | Value | Std.Error | DF | t-value | p-value |
|---|---|---|---|---|---|
| Intercept ($\alpha_1$) | 3.5502 | 0.1433 | 80 | 24.8 | 2.8E-39 |
| Temperature ($\beta_1$) | -0.0380 | 0.0022 | 80 | -17.5 | 4.3E-29 |
| pre-MSAT ($\alpha_2$) | 0.7378 | 0.2066 | 11 | 3.6 | 0.0044 |
| Temperature ($\beta_1$) × pre-MSAT ($\alpha_2$) | -0.0003 | 0.0032 | 80 | -0.1 | 0.9225 |

Because there was not a significant temperature effect between the pre- and post-MSAT-2 vehicles, we estimated the temperature effect ($\beta_1$) from a model fit where the pre-MSAT-2 and post-MSAT-2 vehicles are pooled together as shown in Table 2-4.

**Table 2-4 Fixed Effects for the Final CO Model Fit to Data from 2001+ Model Year Vehicles from the ORD, MSAT, and Cold Temperature Programs (13 vehicles, 95 observations)**

| | Value | Std.Error | DF | t-value | p-value |
|---|---|---|---|---|---|
| Intercept ($\alpha_1$) | 0.6914 | 0.1400 | 81 | 4.94 | 4.1E-06 |
| Temperature ($\beta_1$) | -0.038 | 0.0016 | 81 | -24.08 | 1.1E-38 |
| pre-MSAT ($\alpha_2$) | 0.7284 | 0.1815 | 11 | 4.01 | 0.0020 |

The data along with the final model fits are displayed in Figure 2-1. The MSAT-2 compliant group (2010+) has significantly lower base cold start (coefficient α), which causes the emissions to be lower across all temperatures for the newer model year vehicles. The CO model coefficients in the form of Equation 2-2 for use in MOVES are provided in Table 2-7. The 2009 and 2013 model year B values are derived from the linear mixed model for the pre-MSAT-2 and the MSAT-2 compliant groups, respectively. The 2010 through 2012 model year B values are derived by linearly interpolating the 2009 and 2013 values.

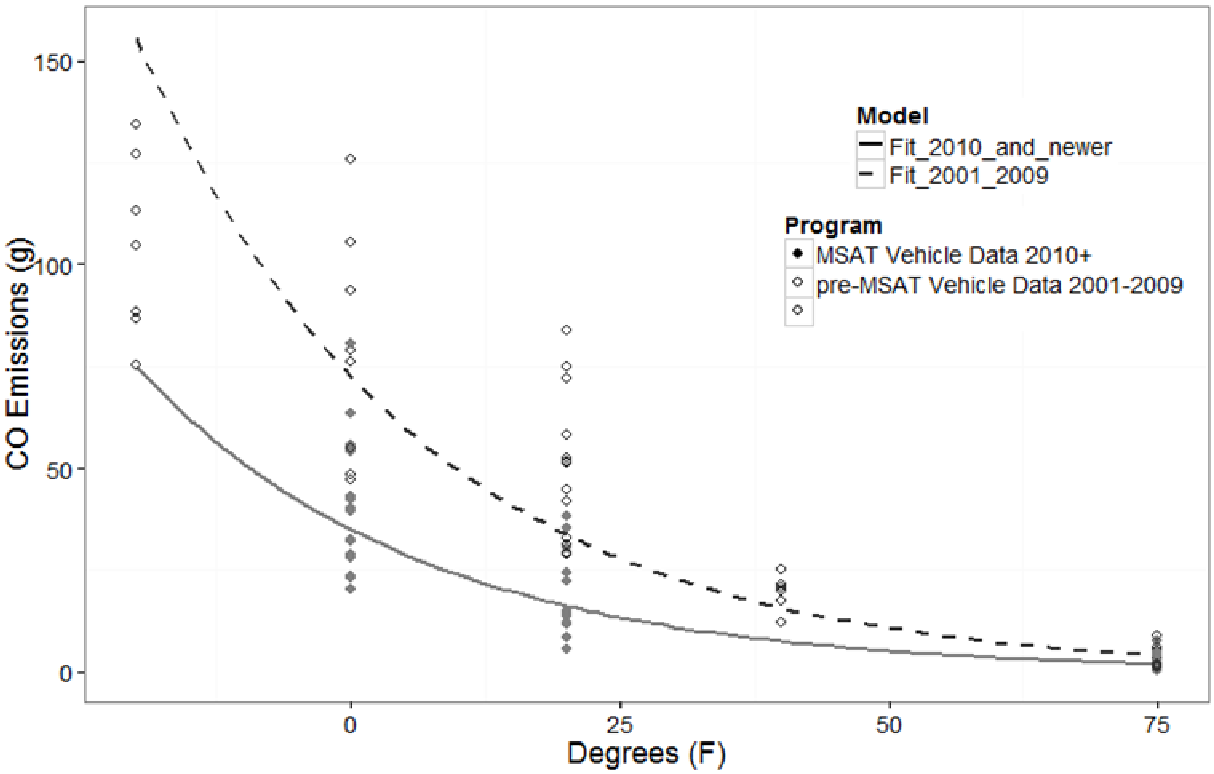


**Figure 2-1 FTP CO Start Emissions with Log-linear Model Fit**

For HC emissions, a statistically significant difference was detected in the log-linear temperature effect ($\beta_1$) between the pre-MSAT-2 and MSAT-2 compliant vehicles as shown in Table 2-5 (p-value of the Temperature × pre-MSAT term is much smaller than 0.05).

**Table 2-5. Fixed Effects for the Final HC Model Fit to Data from 2006+ Model Year Vehicles from the MSAT Program and the Cold Temperature Program (11 vehicles, 69 observations)**

| | Value | Std.Error | DF | t-value | p-value |
|---|---|---|---|---|---|
| Intercept ($\alpha_1$) | 1.8613 | 0.1321 | 56 | 14.1 | 4.6E-20 |
| Temperature ($\beta_1$) | -0.0394 | 0.0011 | 56 | -34.6 | 1.7E-39 |
| pre-MSAT ($\alpha_2$) | 0.7503 | 0.2254 | 9 | 3.3 | 0.0088 |
| Temperature ($\beta_1$) × pre-MSAT ($\alpha_2$) | -0.0111 | 0.0021 | 56 | -5.2 | 2.7E-06 |

The model fit to the cold start emissions data is graphed in Figure 2-2. As shown, the pre-MSAT-2 cold start emissions are much more sensitive to cold temperature than the MSAT-2 compliant vehicles.

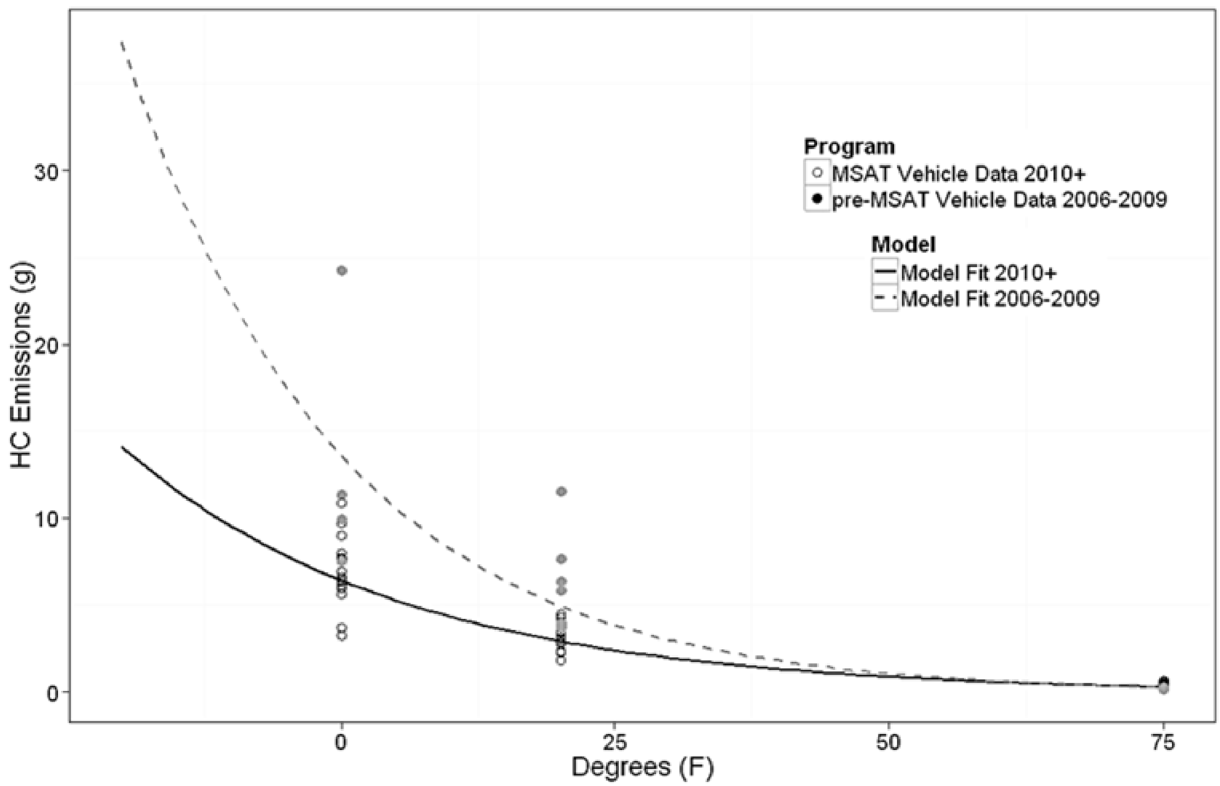


**Figure 2-2 FTP HC Start Emissions with Log-linear Model Fit**

The differences in the HC cold start temperature effect represent the impact of the Mobile Source Air Toxic (MSAT-2) rule. The MSAT-2 rule included a limit on low temperature (20° F) non-methane hydrocarbon (NMHC) emissions for light-duty and some medium-duty gasoline-fueled vehicles.[9] Specifically:

- For passenger cars (LDVs) and for the light light-duty trucks (LLDTs) (i.e., those with GVWR up to 6,000 pounds), the composite (combined cold start and hot running) FTP NMHC emissions should not exceed 0.3 grams per mile.

- For light heavy-duty trucks (LHDTs) (those with GVWR from 6,001 up to 8,500 pounds) and for medium-duty passenger vehicles (MDPVs), the composite FTP NMHC emissions should not exceed 0.5 grams per mile.

These cold weather standards are phased-in beginning with the 2010 model year, as shown in Table 2-6).

**Table 2-6 Phase-in of Vehicles Meeting Cold Weather HC Standard**

| **Model Year** | **LDVs / LLDTs** | **LHDTs / MDPVs** |
|---|---|---|
| 2010 | 25% | 0% |
| 2011 | 50% | 0% |
| 2012 | 75% | 25% |
| 2013 | 100% | 50% |
| 2014 | 100% | 75% |
| 2015 | 100% | 100% |

For the phase-in years, the coefficients for the HC temperature effect equation in the startTempAdjustment table were adjusted linearly according to the light-duty vehicle phase-in. Equation 2-7 shows how the temperature effect is calculated for a model year 2010 LDV, where $A_{2010}$ is the 2010 emissions rate:

$$A_{2010} = A_{2009}(1 - 0.25) + A_{2013}(0.25)$$ **Equation 2-7**

With this approach, the log-linear temperature effect (coefficient A) for HC emissions is reduced from 2009 to 2013 while the base 75° F HC cold start (coefficient B) is relatively constant.

Within the current MOVES design, temperature effects are applied by fuel types and model year vehicles, but not by regulatory class (e.g., LHDTS/MDPVs). As such, the light-duty rates, including the light-duty MSAT-2 phase in are applied to all the gasoline-fueled vehicles in MOVES. No data on LHDTs/MDPVs or heavy-duty temperature effects were available to assess this approach.

Table 2-7 summarizes the coefficients used with Equation 2-2 (log-linear) to estimate additive start temperature adjustments for newer model year gasoline vehicles.

**Table 2-7. Coefficients Used for Log-linear Temperature Effect Equation for All Gasoline Source Types**

| | **CO** | | | **HC** | | |
|---|---|---|---|---|---|---|
| Model Year Group | A | B | C | A | B | C |
| 2001-2009 | -0.038 | 4.136 | -4.136 | | | |
| 2006-2009 | | | | -0.051 | 0.308 | -0.308 |
| 2010 | -0.038 | 3.601 | -3.601 | -0.048 | 0.315 | -0.315 |
| 2011 | -0.038 | 3.066 | -3.066 | -0.045 | 0.322 | -0.322 |
| 2012 | -0.038 | 2.531 | -2.531 | -0.042 | 0.329 | -0.329 |
| 2013 & Later | -0.038 | 1.996 | -1.996 | -0.039 | 0.336 | -0.336 |

Figure 2-3 and Figure 2-4 graphically compare all the cold start temperature effects for gasoline vehicles by model year groups in MOVES. These include both the polynomial fits and the log-linear curve fits to the data.

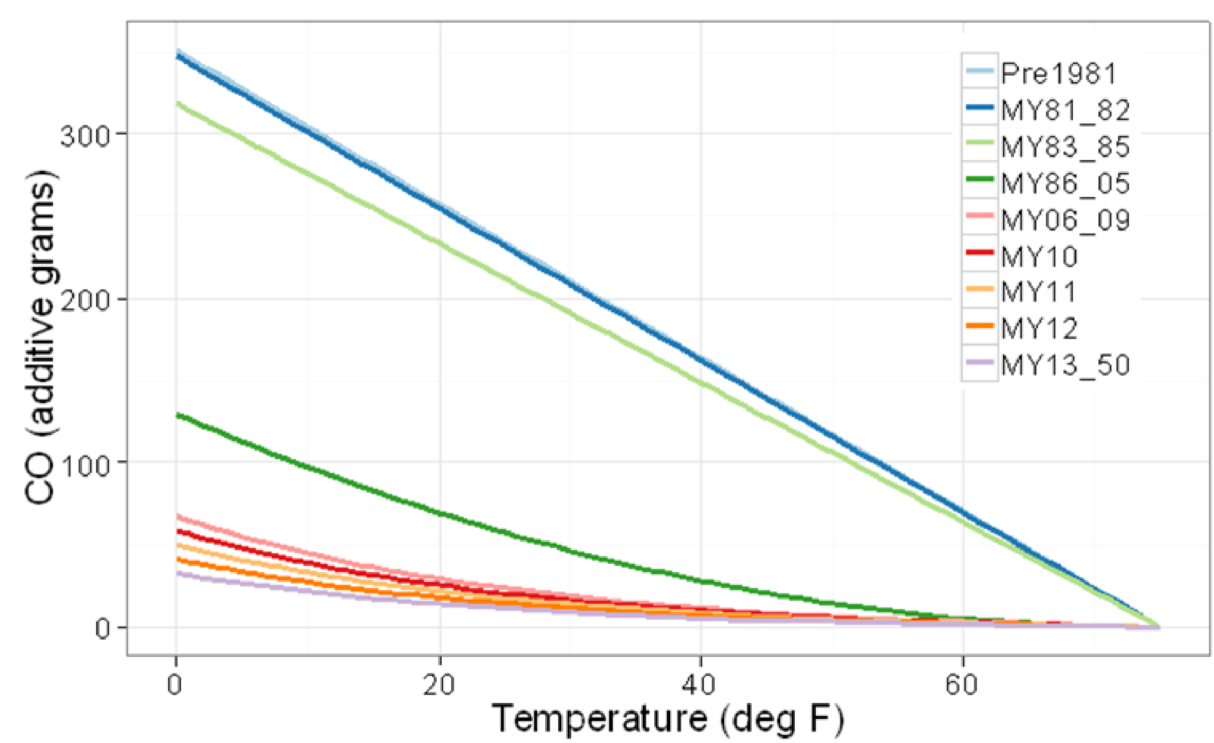


**Figure 2-3 CO Additive Cold Start Temperature Effects for Gasoline Vehicles by Model Year Groups**

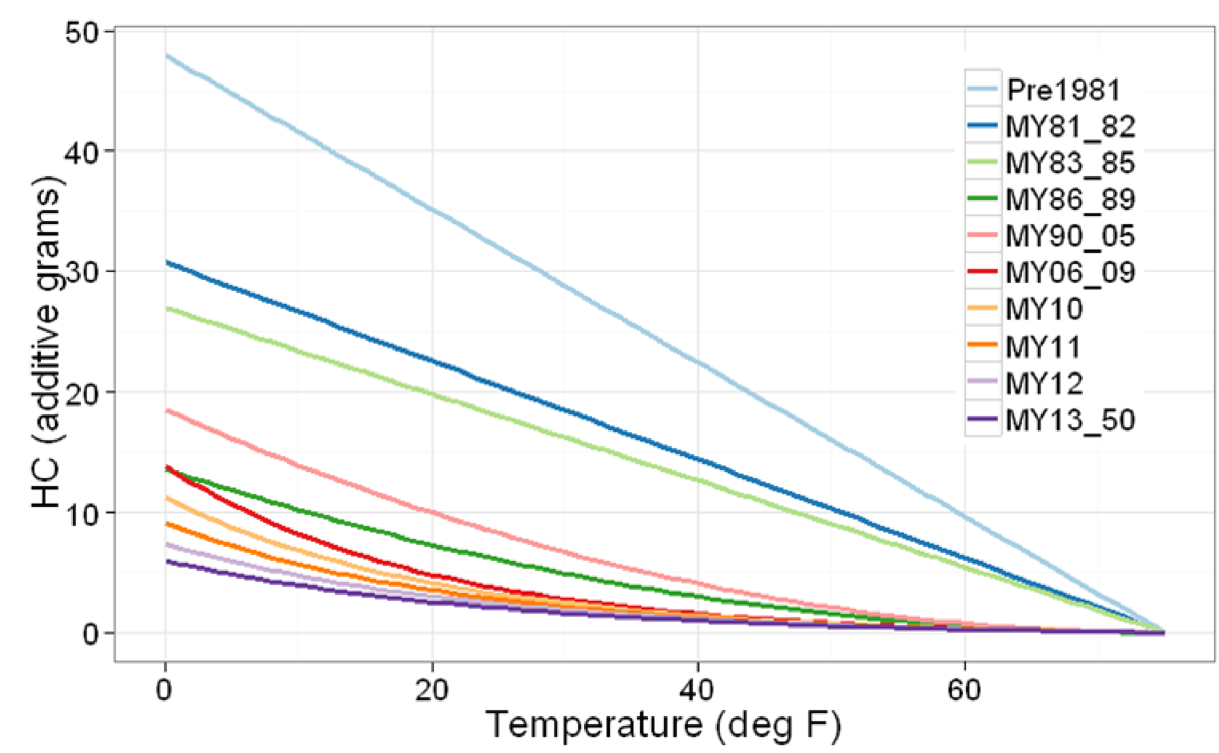


**Figure 2-4 HC Additive Cold Start Temperature Effects for Gasoline Vehicles by Model Year Groups**

### *2.2.2 Temperature Effects on Gasoline $NO_X$ Start Emissions*

Cold-start $NO_X$ emissions are not as sensitive to ambient temperature changes as HC and CO emissions, because the fuel-rich conditions at engine start favor incomplete combustion of fuel, forming CO and HC; $NO_X$ is favored under the lean burn, high temperature engine operation more typical of running emissions. However, $NO_X$ emissions are impacted by the inefficiencies of the three-way catalyst at low temperatures, and a small cold start temperature sensitivity is expected.

Due to the small temperature effects and the variability of the data, the $NO_X$ temperature effect was calculated in MOVES by averaging all the available $NO_X$ results (i.e. the 2005-and-earlier model year data) together across model year groups and then performing regression. The following table lists the average incremental cold start $NO_X$ emissions from the MSOD, ORD, and MSAT programs.

**Table 2-8. Average Incremental Cold Start $NO_X$ Emissions by Temperature for Gasoline Vehicles Calculated from the MSOD, ORD, and MSAT Programs**

| Temp F | Delta $NO_X$ (grams) |
|---|---|
| -20 | 1.201 |
| 0 | 1.227 |
| 19.4 | 0.202 |
| 20.7 | 0.089 |
| 22.4 | -0.155 |
| 31 | -0.007 |
| 40 | 0.876 |
| 48.8 | 0.127 |
| 49.8 | 0.333 |
| 51 | 0.325 |
| 54.2 | 0.438 |
| 76.3 | 0 |
| 95.3 | 0.225 |
| 97.1 | 0.37 |
| 105.8 | 0.543 |

Using the data above, we fit a linear regression to the emission averages for temperatures of 76.3 ̊F and lower, and obtained the following fit:

$$NO_X \textit{temperature additive adjustment} = A * (Temp. - 75)$$
$$\text{where: } A = -0.009$$
$$R^2 = 0.61$$

**Equation 2-8**

Although the value of $R^2$ is not as high as for the HC and CO regression equations, the fit is statistically significant.

Note that Equation 2-8 predicts a decrease in cold-start $NO_X$ emissions for temperatures greater than 75° F, while the data in Table 2-4 indicates an increase in cold-start $NO_X$ emissions as the ambient temperature rises above 90° F. The increase is small and may be an artifact of how these data were analyzed, since only a subset of vehicles were measured above 75° F. As with the other temperature adjustments, we have set the $NO_X$additive adjustment to zero in MOVES for temperatures higher than 75° F.

In addition, we investigated whether different $NO_X$ temperature correction is needed for vehicles subject to the MSAT-2 rule.   shows a comparison between $NO_X$ start emissions data from OTAQ Cold Temperature Program (all vehicles, PFI and GDI, 2006-2010 model year vehicles) and the emissions predicted using MOVES temperature effects. Because start emissions compose such a small percentage of total $NO_X$ emissions, the differences between the MOVES temperature effects and the $NO_X$ data from the OTAQ Cold Temperature Program were considered negligible. Thus, we applied the $NO_X$ temperature adjustment estimated in Equation 2-8 for all model years.

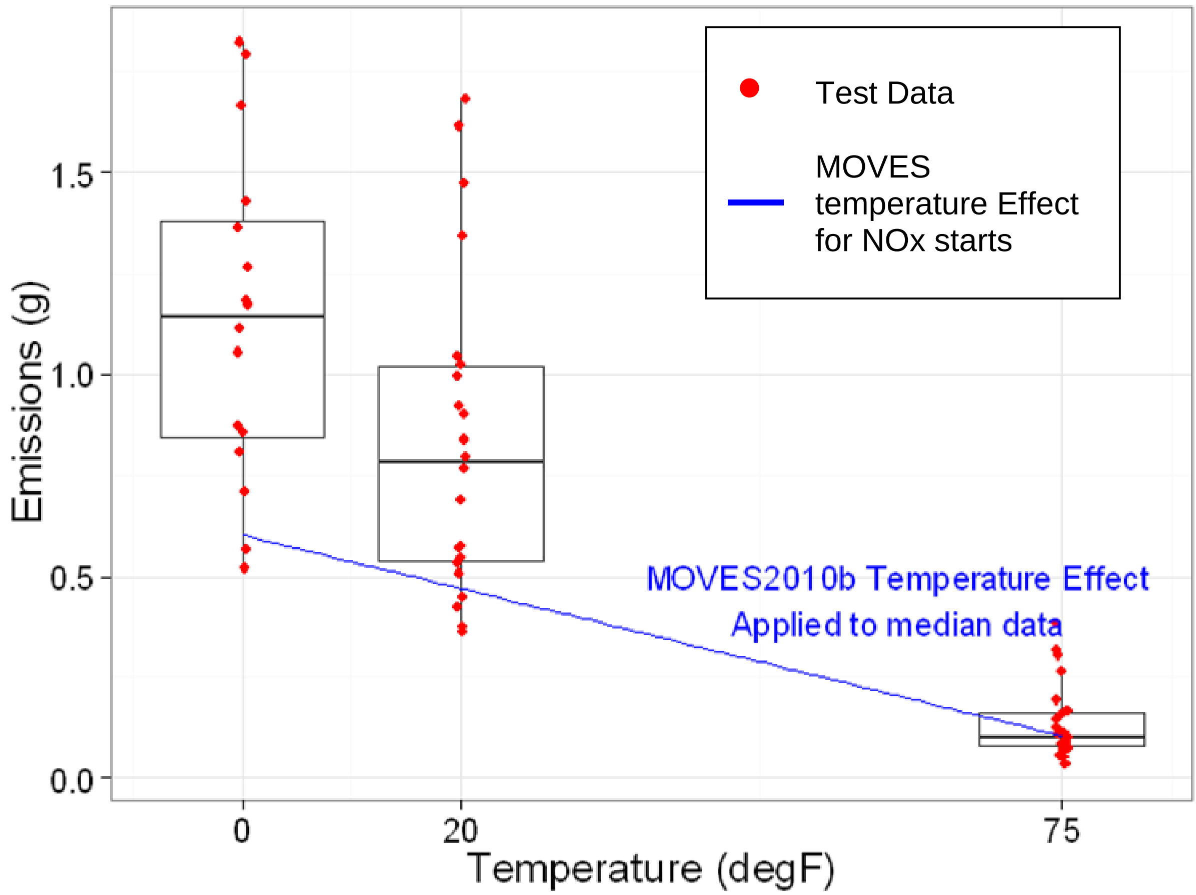


**Figure 2-5 FTP Start $NO_X$ Emissions, Bag 1 – Bag 3, Model Years 2006-2010**

### *2.2.3 Temperature Effects on Gasoline PM Start Emissions*

The temperature effects for particulate matter emissions from gasoline engines were obtained from the Kansas City Light-Duty Vehicle Emissions Study (KCVES)[11], conducted between 2004 and 2005. The KCVES measured emissions from 496 vehicles collected in the full sample, with 42 vehicles sampled in both the winter and summer phases of the program. The EPA conducted an analysis of the temperature effects of gasoline vehicles from the KCVES by estimating the temperature effect on PM emissions from 34 paired vehicle tests that were sampled in both winter and summer ambient conditions (10 paired vehicle tests were removed due to missing values and/or too small temperature differences between the phases) as derived in the EPA report[11] and Nam et al.[12]

The analysis of the KCVES data indicated that ambient temperature affects for start PM emissions is best modeled by (log-linear) multiplicative adjustments of the form:

$$\textit{Multiplicative Factor} = e^{A*(72-T)} \quad \textbf{Equation 2-9}$$

Where $T$ = Temperature
$A$ = log-linear temperature effect. $A$ = 0.0463 for cold starts from the KCVES analysis[11,12]

The log-linear temperature effect of 0.0463 is used in MOVES for gasoline vehicles of model year 2009-and-earlier (i.e., vehicles not affected by the MSAT-2 requirements).

The MSAT-2 rule (signed February 9, 2007) does not explicitly limit cold weather emissions of particulate matter (PM). However, the Regulatory Impact Analysis (RIA) document[9] that accompanied the rule noted there is a strong linear correlation between NMHC and $PM_{2.5}$ emissions based on the MSAT program discussed in Section 2.1. That correlation is illustrated in Figure 2-6 (reproduced from that RIA) as the logarithm of the Bag-1 $PM_{2.5}$ versus the logarithm of the Bag-1 NMHC (for various Tier-2 vehicles).

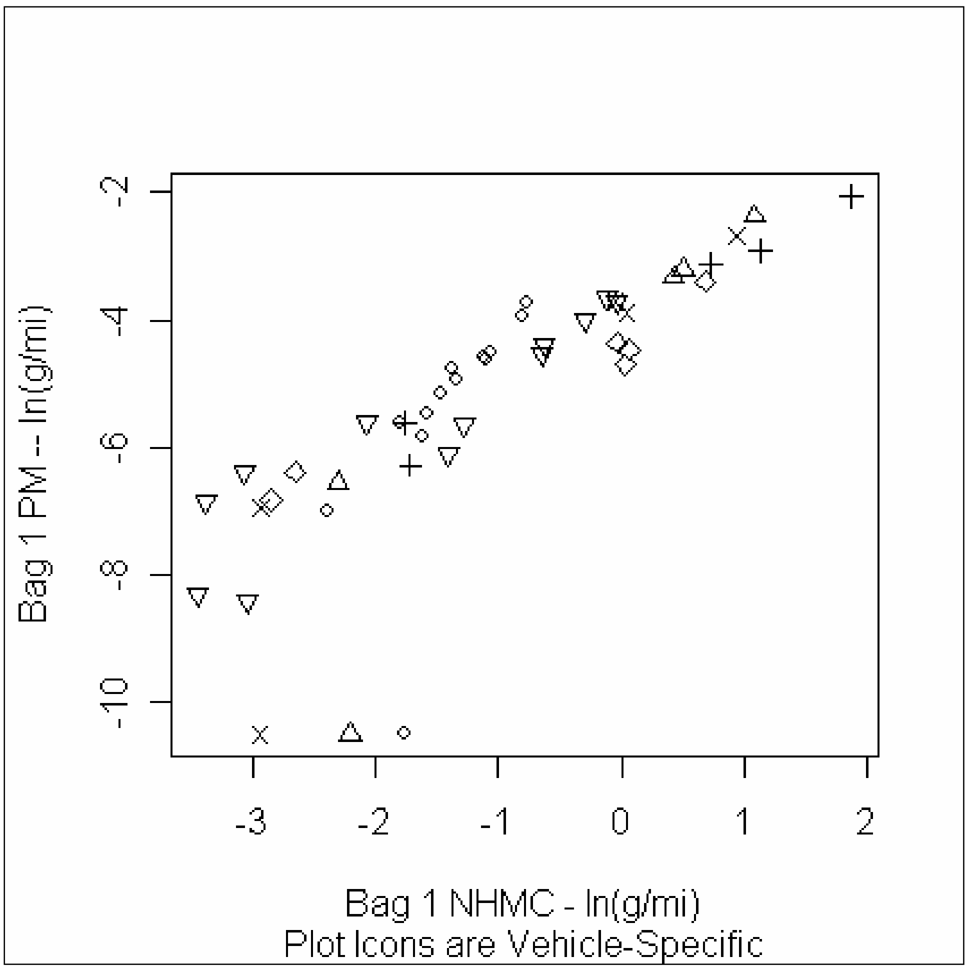


**Figure 2-6 FTP Bag 1 PM and FTP Bag 1 NMHC for Tier 2 Vehicles**

Therefore, the limitation on cold weather HC (or NMHC) emissions is expected to result in a proportional reduction in cold weather $PM_{2.5}$ emissions. In the MSAT-2 RIA (Table 2.1.-9), EPA estimated that this requirement would result in a 30 percent reduction of VOC emissions at 20º F. Applying the same analytical approach that was used in the RIA means that a 30 percent reduction in VOC emissions would correspond to a 30 percent reduction in PM emissions at 20º F (for Tier 2 cars and trucks).

Applying the 30 percent reduction for vehicles affected by the MSAT-2 requirements to the temperature effects calculated for the fully phased-in (2015+) MSAT-2 vehicles implies a PM increase as the temperature decreases from 72º to 20º F of:

$$\textit{Multiplicative Factor at } 20^{\circ}F \textit{ for MSAT-2 Vehicles} = 0.7 * e^{0.0463*(72-20)} = 7.8 \qquad \textbf{Equation 2-10}$$

Using Equation 2-10 with the MSAT-2 phase-in schedule from Table 2-6 leads to the following (multiplicative) increases as the temperature decreases from 72º to 20º F:

**Table 2-9 Multiplicative Increase in Cold Start $PM_{2.5}$ from 72º to 20° Fahrenheit for Gasoline Vehicles**

| Model Year | LDVs / LLDTs | LHDTs / MDPVs |
|---|---|---|
| 2008 | 11.1 | 11.1 |
| 2009 | 11.1 | 11.1 |
| 2010 | 10.3 | 11.1 |
| 2011 | 9.4 | 11.1 |
| 2012 | 8.6 | 10.3 |
| 2013 | 7.8 | 9.4 |
| 2014 | 7.8 | 8.6 |
| 2015 | 7.8 | 7.8 |

Solving for the corresponding log-linear terms gives us these "A" values:

**Table 2-10 Log-linear Temperature Effect for Start $PM_{2.5}$ Emissions (Coefficient A) for Gasoline Vehicles**

| Model Year | LDVs / LLDTs | LHDTs / MDPVs |
|---|---|---|
| 2008 | 0.0463 | 0.0463 |
| 2009 | 0.0463 | 0.0463 |
| 2010 | 0.0448 | 0.0463 |
| 2011 | 0.0432 | 0.0463 |
| 2012 | 0.0414 | 0.0448 |
| 2013 | 0.0394 | 0.0432 |
| 2014 | 0.0394 | 0.0414 |
| 2015 | 0.0394 | 0.0394 |

We confirmed this theoretically derived temperature effect for MSAT-2 compliant vehicles by comparing it to data from the OTAQ study, which was collected on actual MY2010 MSAT-2 compliant vehicles. The temperature effect developed for MOVES fits this data well, as shown in Figure 2-7.

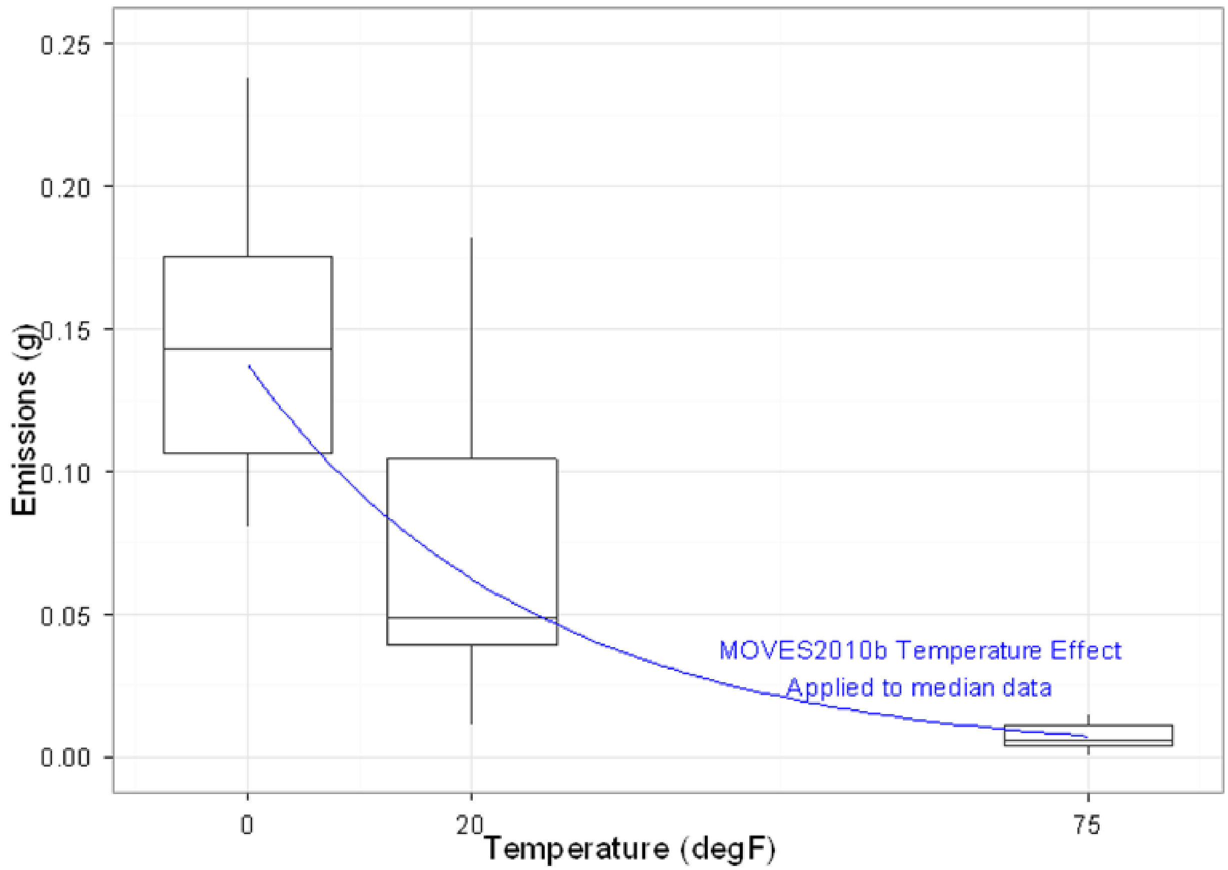


**Figure 2-7. FTP $PM_{2.5}$ Start Emissions, MSAT-2 Compliant Vehicles (7 PFI Vehicles, 40 Tests with Nonzero PM Measurements on E10 Fuel)**

Figure 2-8 presents the light-duty multiplicative temperature effects using the coefficient in Table 2-10, and the model form of Equation 2-9.

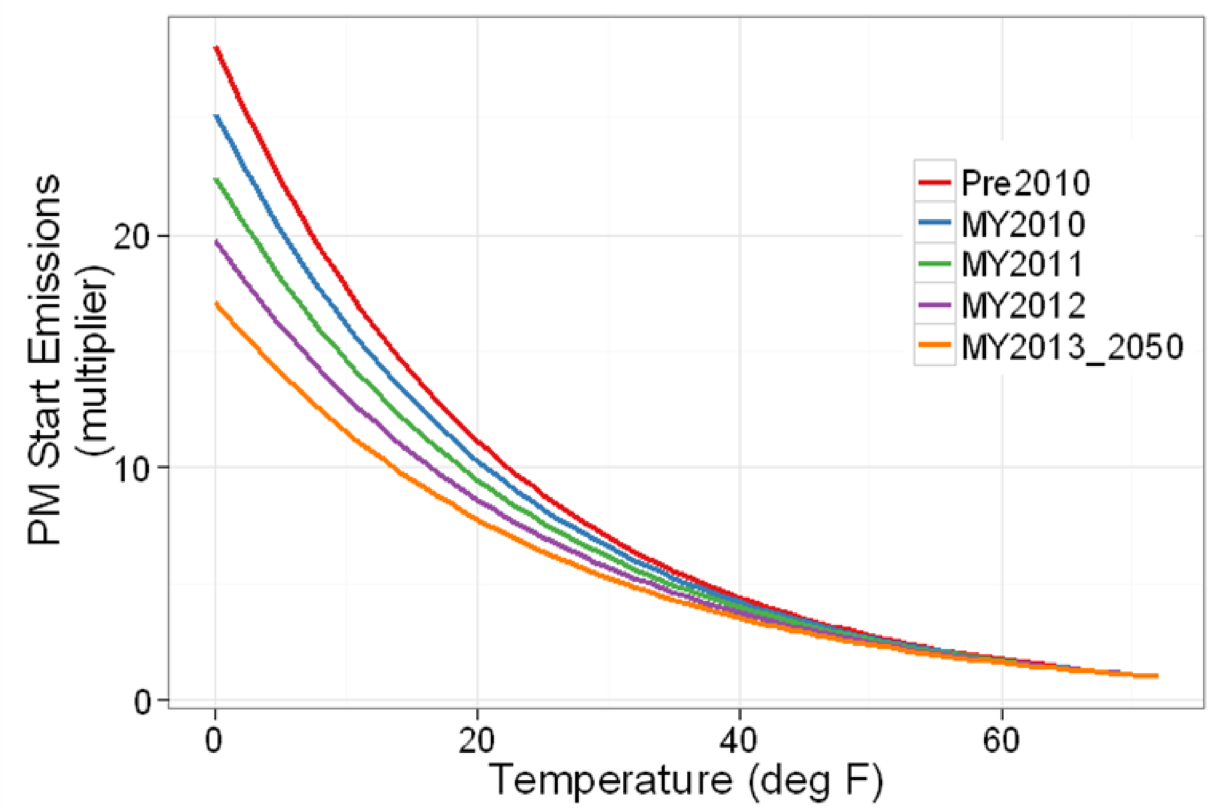


**Figure 2-8. PM Start Exhaust Emissions Effect for Gasoline Vehicles in MOVES**

Because the $PM_{2.5}$ speciation profile for gasoline vehicles did not change significantly between the winter and summer rounds of the KCVES,[13] we apply the same temperature adjustment to each component of the PM emissions, including elemental carbon, organic carbon, sulfate and other species.

## 2.3 Temperature Effects on Running Exhaust Emissions from Gasoline Vehicles

While MOVES is designed to model the impact of ambient temperature on running exhaust emissions, current data suggests that there is little effect of temperature on HC, CO, $NO_X$ or PM. The sections below discuss the relevant data and analysis for gaseous pollutants and for particulate matter.

### 2.3.1 HC, CO and $NO_X$ Running-Exhaust Temperature Effects

We examined the same data as the start temperature effects, to evaluate potential running temperature effects. These test data suggest that there is very little effect of temperature on running emissions of HC, CO, or $NO_X$. Regression analyses found that the coefficients (slopes) were not statistically significant (that is, the slopes were not distinguishable from zero). This finding is consistent with what we found in our analysis of the Kansas City Light-Duty Vehicle Emissions Study (KCVES).[11] The lack of correlation between running emissions and ambient temperature is illustrated (as an example) in our analysis[11] of data collected from the full-sample (496 vehicles) in KCVES:

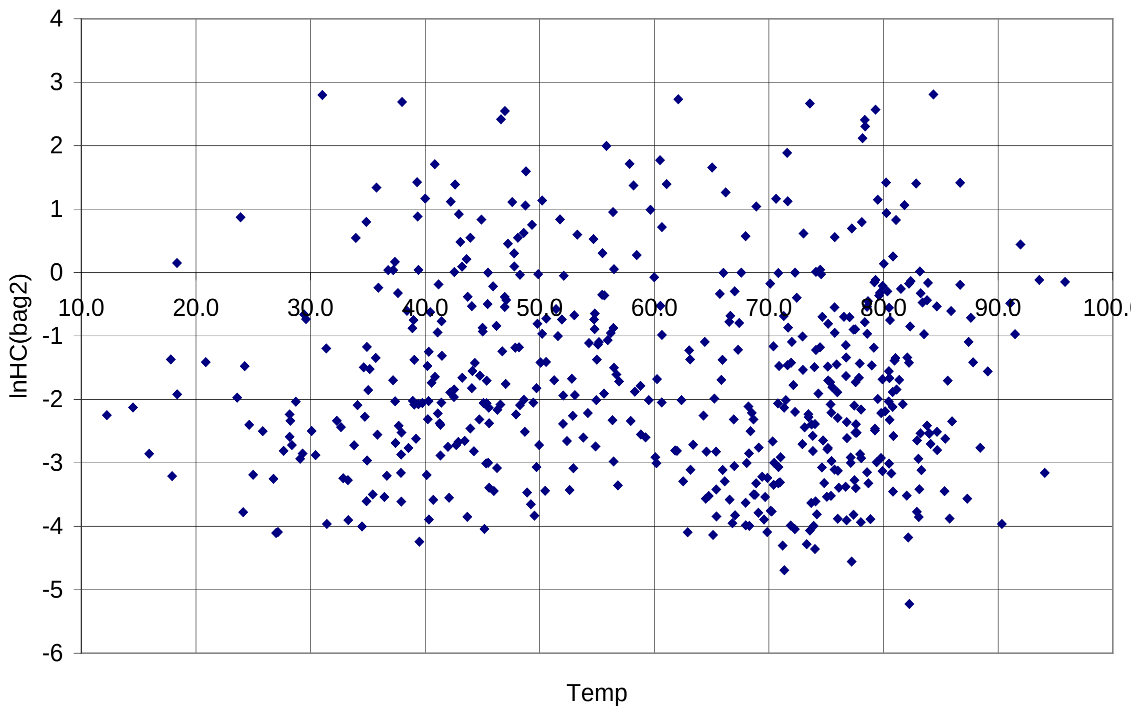


**Figure 2-9 Logarithm of Bag-2 HC Emission Rate Versus Temperature (deg F) from the Kansas City Light-Duty Vehicle Emissions Study**

In Figure 2-9, each point represents a single LA-92 Bag-2 test result from the Kansas City program. A visual inspection of this plot of the natural logarithm of the LA-92 Bag-2 HC emissions suggests no strong relationship between the hot-running HC emissions and the ambient temperature. Though not shown, the paired data showed similar relationships. The CO and $NO_X$ plots are similar in that they also do not indicate a significant trend.

As an additional test, we examined a set of continuous data collected on the IM240 cycle in the Chicago I/M program. To avoid potential confounding due to variable levels of conditioning vehicles experienced in the queues at the I/M stations, we only used the second IM240s when back-to-back IM240s were performed, and for single IM240s, we examined only the final 120 seconds of full duration IM240s. Based on this analysis, we found no evidence of a temperature effect for XX between 5 and 95°F.

The effect of temperature on hot running HC, CO, and $NO_X$ emissions is coded in MOVES using polynomial functions as multiplicative adjustments. Therefore, in MOVES, we set all of those adjustments equal to 1.0, that is, we estimate no change in running emissions with temperature for all model year gasoline vehicles.

### *2.3.2 PM Running-Exhaust Temperature Effects*

The initial analysis of the Kansas City Light-Duty Vehicle Emissions Study (KCVES) data[11,12] indicated that significant ambient temperature effects existed for both start (Bag1-Bag3) and running (Bag 2) PM emissions on the LA-92 cycle. Thus, MOVES2010 and MOVES2014 contained a temperature effect for running emissions for pre-2004 model year vehicles based on the Bag 2 measurements from paired vehicles tests conducted in the winter and summer of the KCVES.

For MOVES2014, we updated the PM temperature effect for running emissions for Tier 2 and later model year vehicles (2004+) based on data from the 2012 Cold Temperature Program (documented in Section 2.1.).Experimental data collected in the 2012 OTAQ program involved measurement of PM emissions on both the FTP (by phase) and the US06 cycles at temperatures of 0, 20, and 75°F of Tier 2 and MSAT-2-compliant vehicles. The results from these programs are plotted against temperature in Figure 2-10. We also fit log-linear models to the data, and found the effect of temperature was not statistically significant on either cycle. Based on these results, we removed the temperature effect for Tier 2 vehicles (model year 2004 and later) in MOVES2014.

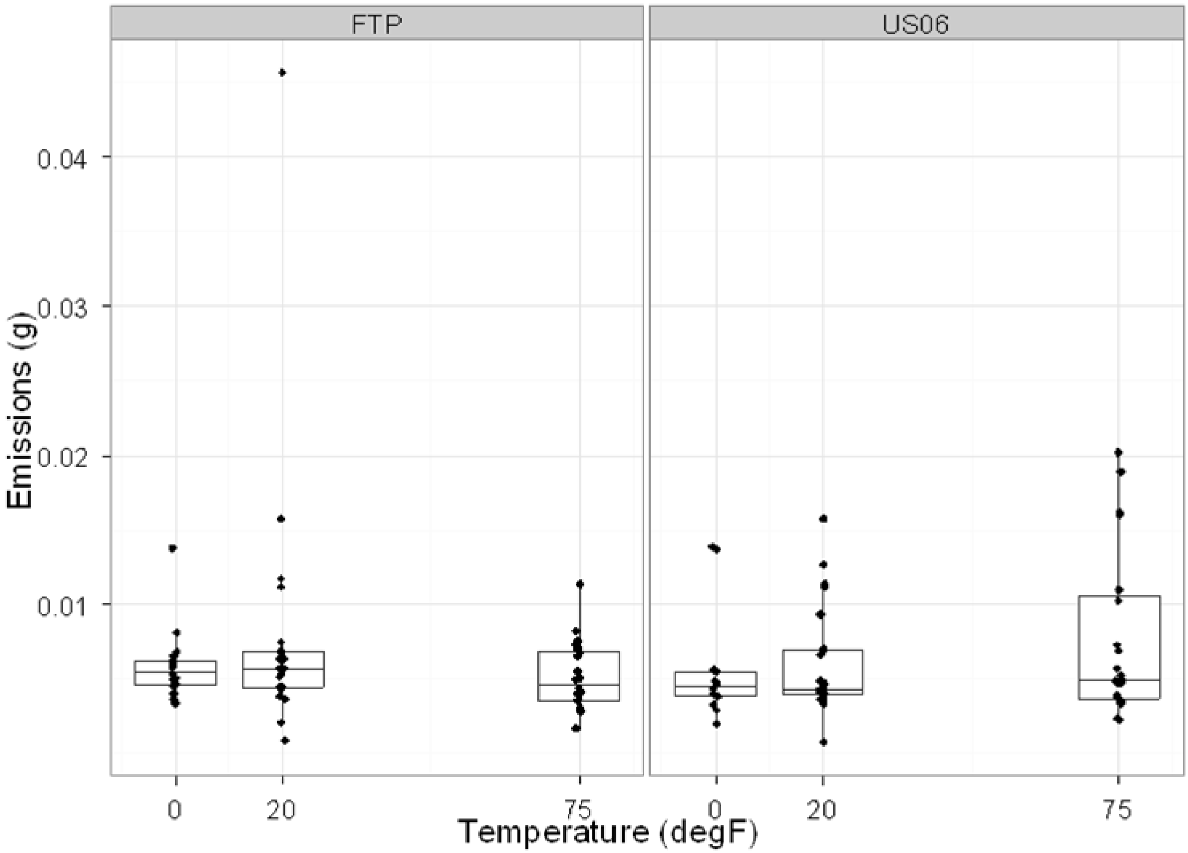


**Figure 2-10. Hot-running PM Emissions Measured on Two Cycles (FTP Bag 2, US06) on MSAT-2 Compliant MY 2010 Gasoline Vehicles, Reported as Grams/cycle**

These results contrast with the significant PM running temperature effect detected for Bag 2 emissions in the KCVES. Upon further analysis of the PM emissions from the KCVES study, we determined that much[a] of the temperature effect observed in the KCVES Bag 2 emissions is due to the short duration and relatively mild accelerations of the cold-start phase of the LA92 cycle, which is only 310 sec (1.18 mi) in length. We note that the PM temperature effect was much larger at the beginning of Bag 2 than at the end. In contrast, the cold-start phase of the FTP, used in the Cold Temperature Program is 505 seconds (3.59 miles) in length.

For MOVES201X, we conducted a literature review from other studies that have evaluated temperature effects on particulate matter emissions from gasoline vehicles including model years before 2004. The results are summarized in Table 2-11.

[a] We believe that the small, but statistically significant temperature effect that persists at the end of Bag 2, even after 1,025 seconds (17 minutes) of operation on the LA-92 in KCVES may be an artifact of this particular study, because this persistent temperature effect was not observed for hot-running emissions in other studies (Table 2-11).

**Table 2-11. Literature Review of Temperature Effects on Running PM2.5 emissions from Gasoline Vehicles**

| **Study** | **Vehicles and Test conditions** | **Findings on $PM_{2.5}$ emissions** |
|---|---|---|
| Measurements of Exhaust Particulate Matter Emissions from In-Use Light-Duty Motor Vehicles in the Denver, Colorado Area[14,15] | 71 light-duty gasoline vehicles from model year 1970 to 1996 tested in the summer of 1996 and winter of 1997 on a chassis dynamometer using bag 2 of the FTP driving schedule. | No significant ambient temperature. Linear mixed model fit by OTAQ staff. |
| Comprehensive particle characterization of modern gasoline and diesel passenger cars at low ambient temperature[16] | Two Euro-3 (apply to 2000 -2004 model year vehicles) port-injection gasoline vehicles (Renault Megane and Alfa 406 TS)<br>Tested +23, -7, and -20℃ on a chassis dynamometer on the common Artemis driving cycle (CADC), after warmed up on 50 minute IUFC15 driving cycle. | No temperature effect observed on running emissions. |
| Characterization of Metals Emitted from Motor Vehicles[17] | Emission rates derived from $PM_{2.5}$ concentrations measured at the entrance and exit concentration of the Howell tunnel in Milwaukee, WI. In the summer of 2000 and the winter of 2000-2001. Light-duty vehicles constituted between 90.6% to 93.9% of the vehicles, with 6.1% to 9.4% heavy-duty trucks. | Carbonaceous $PM_{2.5}$ (EC+OC) emission rates (mg/km) were significantly lower (49-51%) in the winter than the summer.<br>The winter tests had comparable or larger PM measurements of inorganic ions and metals (including Na and Cl) presumably due to road salt in the winter. |

The studies evaluated in the literature review (Table 2-11) did not observe temperature effects on PM exhaust emissions, even for model year vehicles similar to the years measured in the KCVES. Thus, we attribute the significant running PM temperature effect in KCVES to being an artifact of the measurement conditions of the study, including the short Bag 1 of the LA-92 cycle. Therefore, in MOVE201X, we have removed the running temperature effect for exhaust particulate matter emissions for all model year light-duty gasoline vehicles.

## 2.4 Temperature Effects on Diesel Vehicles

For diesel vehicles, MOVES applies a temperature adjustment only to HC start emissions; no other temperature adjustments are applied.

### 2.4.1 HC, CO and $NO_X$ Temperature Effects for Diesel Vehicles

We were able to identify only 12 diesel vehicles with FTP tests at multiple temperatures (9 passenger cars and 3 light-duty trucks). However, only two of those 12 vehicles were tested at temperatures within the normal FTP range (68º to 86º F). None of these diesel trucks were equipped with aftertreatment devices.

#### *2.4.1.1 Diesel Start Effects*

The average Bag-1 minus Bag-3 emissions for those tests are shown in Table 2-12. We stratified the test results into four temperature bands which yielded the following emission values (grams per start) and average temperature value:

**Table 2-12 Average Light-duty Diesel Vehicle Incremental Start Emissions (Bag 1- Bag3) by Temperature (grams per start)**

| Temperature, F | Count | HC | CO | $NO_X$ |
|---|---|---|---|---|
| 34.6 | 6 | 2.55 | 2.44 | 2.6 |
| 43.4 | 7 | 2.68 | 2.03 | 0.32 |
| 61.5 | 10 | 1.69 | 3 | 0.67 |
| 69.2 | 2 | 1.2 | 1.91 | 0.36 |

Figure 2-11 shows the plot of mean HC start emissions (above) versus temperature (where the vertical lines represent 90 percent confidence intervals and the "dashed" line represents a linear regression through the data).

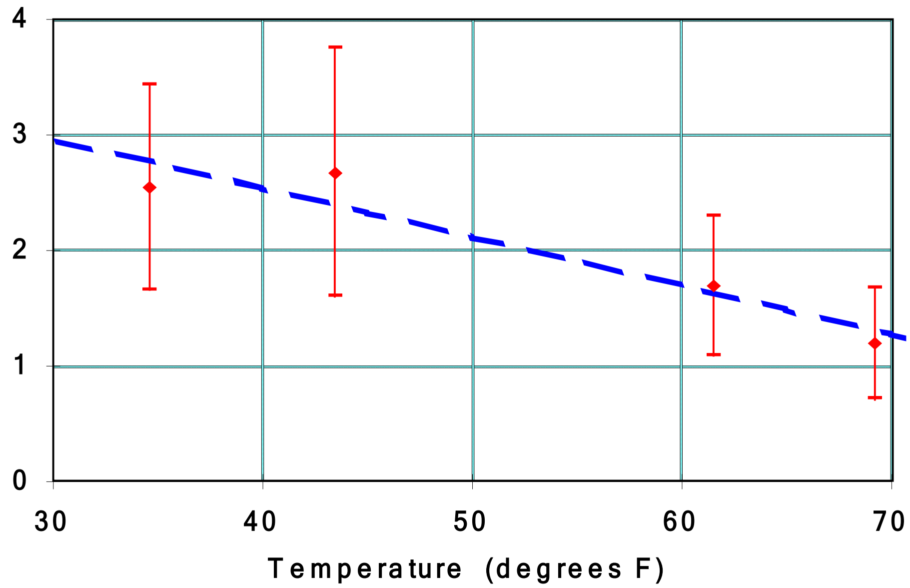


**Figure 2-11 Mean Light-duty Diesel Cold-start HC Emissions (in grams, shown on the y-axis) with 90% Confidence Intervals vs Temperature**

The dashed (blue) line in Figure 2-11 represents a linear regression line:

$$HC = (-0.0421 * Temperature) + 4.22 \qquad R^2 = 0.90$$ **Equation 2-11**

Transforming this equation into an equation that predicts the (additive) change/adjustment in the cold-start HC emissions from light-duty diesel vehicles (in the MOVES format), we obtain:

$$HC\ additive\ temperature\ adjustment = A * (Temp. - 75)$$
$$where:\ A = -0.0421$$ **Equation 2-12**

The coefficient associated with this temperature adjustment term is statistically significant although its coefficient of variation is relatively large (23.04 percent). We apply this adjustment to heavy-duty as well as light-duty vehicles due to limited data on heavy-duty diesel starts.

On the other hand, the cold-start CO and $NO_X$ emissions did not exhibit a clear trend relative to the ambient temperature. Plotting the mean CO and $NO_X$ cold-start emissions versus ambient temperature (with 90 percent confidence intervals) produced the following two graphs:

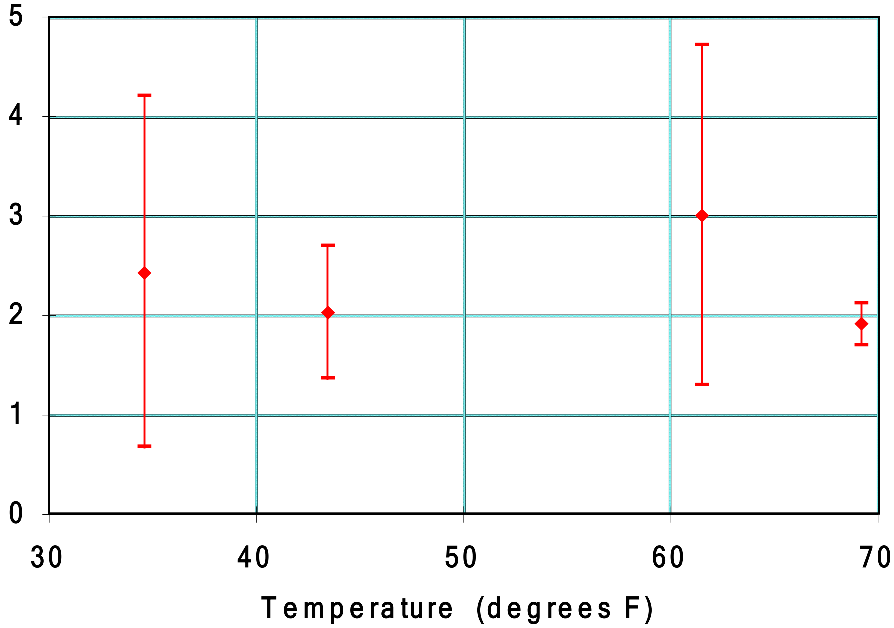


**Figure 2-12 Mean Light-duty Diesel Cold-start CO Emissions (in grams) with 90% Confidence Intervals vs Temperature**

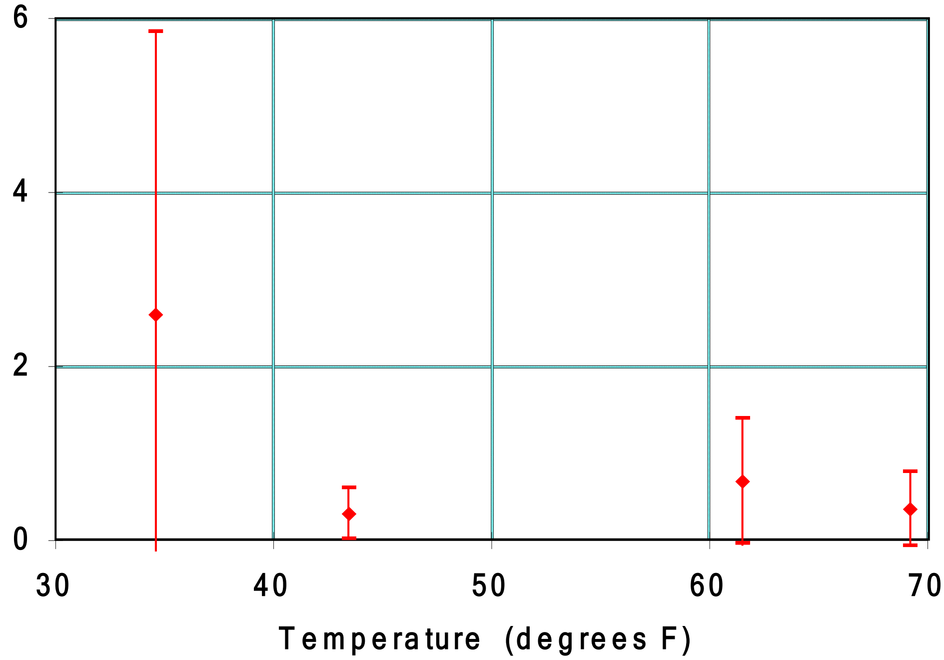


**Figure 2-13 Mean Light-duty Diesel Cold-start $NO_X$ Emissions (grams) with 90% Confidence Intervals vs Temperature**

Statistical analyses of both the diesel cold-start CO and $NO_X$ emissions failed to produce coefficients that were significantly different from zero. Therefore, for both cold-start CO and $NO_X$ adjustments for diesel vehicles, we set the temperature adjustment for start emissions to zero.

Given the small diesel start temperature effects, we did not evaluate the diesel running temperature effect for HC, CO, and $NO_X$. We set temperature effects for diesel running exhaust to zero, similar to the gasoline running exhaust adjustments.

The light-duty diesel HC start emissions were also applied to heavy-duty diesel vehicles in MOVES. All other temperature effects for diesels in MOVES are set to zero, including extended idle exhaust. Because of a lack of data no attempt has been made to calculate temperature effects for diesel vehicles with aftertreatment devices (such as diesel particulate filters or selective catalytic reduction systems) that are now required to meet current emission standards.

### 2.4.2 PM Temperature Effects for Diesel Vehicles

MOVES does not include any temperature effects for particulate matter emissions from diesel vehicles. As presented in the previous section, hydrocarbon emissions from conventional diesel engines have much lower temperature sensitivity than catalyst-controlled light-duty gasoline emissions. Limited data exists on the ambient temperature effects of particulate matter emissions from diesel engines.

The EPA does not have data on PM start emissions on US-certified diesel vehicles tested across different ambient temperatures. From a literature search, we were able to find two European test programs that measured PM diesel start emissions from European light-duty diesel engines and vehicles at cold and warm ambient temperatures.

Mathis et al. evaluated particle mass and number emissions from a conventional light-duty diesel vehicle, and a light-duty diesel equipped with a diesel particulate filter (DPF) at laboratory conditions measured at +32, -7, and -20℃.[16] Although the researchers observed an increasing trend in particle mass emissions (g/start) from the conventional diesel vehicle at colder temperatures, over the entire drive cycle, the particle number emission rates were not significantly impacted by the cold start contribution. The particle mass emissions from the DPF-equipped vehicle were two orders of magnitude smaller than the conventional diesel engines, but the start contributed the majority of the particle number emissions over the entire test cycle.

Sakunthalai et al. (2014[18]) also reported significant increase in PM start emissions from a light-duty diesel engine tested in a laboratory at +20 and -20℃. However, they only reported the PM mass concentrations of the exhaust, and not emission rates. Additionally, the engine was not equipped with an emission control system. Other researchers have reported that PM emissions are larger at cold start than hot start from diesel engines[19,20], but have not investigated the relationship of cold starts with ambient temperatures.

The reviewed studies suggest that temperature does influence cold start PM emissions from diesel vehicles. However, at this time, MOVES does not include temperature adjustments to diesel start emissions due to limited data on diesel engines and because diesel starts are a minor contributor to particulate mass emissions to the mobile-source emission inventory. The diesel particulate matter emission temperature effects can be revisited as additional data become available in future versions of MOVES.

## 2.5 Temperature Effects on Compressed Natural Gas Vehicles

MOVES201X models emissions from heavy-duty vehicles running on compressed natural gas. However, at the time the temperature corrections were developed, no data were available on temperature impacts of compressed natural gas emissions. As discussed in the heavy-duty report[7], the start emissions for CNG emissions for HC, CO, $NO_X$, and PM are set equal to diesel start emissions. We also applied the same temperature adjustments to CNG as diesel, that is, only the start temperature effects on HC emissions.

## *2.6 Temperature Effects on Start Energy Consumption*

The temperature effects on energy consumption in MOVES have not been updated since MOVES2004. As presented in heavy-duty report[7], the energy consumption from starts is a small fraction compared to the total energy use of both gasoline and diesel vehicles. As such, we have not prioritized updating the start energy rates or temperature adjustments in subsequent versions of MOVES.

In this section, we provide a summary of the start temperature effects used in MOVES. The analysis used to derive the temperature effects on start energy consumption in MOVES is documented in the MOVES2004 energy report.[21] No significant temperature effects for energy consumption were found for warmed-up vehicles in the analysis, thus MOVES does not contain temperature effect on running energy consumption.

MOVES applies temperature adjustments to the start energy consumption through a multiplicative adjustment. The form of the multiplicative adjustments used in MOVES is shown in Equation 2-13, which is applied to all ambient temperatures. Unlike the criteria emission rates temperature adjustments, MOVES does not limit the energy consumption adjustments to only cold temperatures, but also, adjusts the energy consumption for hot temperatures.

The multiplicative temperature adjustments are applied to all start operating modes of varying soak lengths. MOVES does have different baseline (75°F) start energy consumption rates for different soak times, which are documented with the baseline energy start rates.[7,23]

$$\begin{aligned} &\mathit{Multiplicative\ temperature\ adjustment} \\ &\quad = 1.0 + tempAdjustTermA \times (temperature - 75) \\ &\quad + tempAdjustTermB \times (temperature - 75)^2 \end{aligned}$$

**Equation 2-13**

Table 2-13 displays the coefficients used to adjust start energy consumption for gasoline, E85, diesel, and CNG-fueled vehicles. The temperature coefficients are stored in the MOVES temperatureAdjustment table by pollutant, emission process, fuel type, and model year range. E85-fueled vehicles use the same energy adjustments as gasoline vehicles, because they also use the same energy rates as comparable gasoline-fueled vehicles.[22] CNG vehicles use the same adjustments as diesel vehicles, because they use the same energy start rates as comparable diesel vehicles.[7]

**Table 2-13. Multiplicative Temperature Coefficients Used in MOVES**

| tempAdjustTermA | tempAdjustTermB | Fuel types | Model Years |
|---|---|---|---|
| -0.01971 | 0.000219 | Gasoline, E85 | 1960-2050 |
| -0.0086724 | 0.00009636 | Diesel, CNG | 1960-2050 |

Figure 2-14 displays the multiplicative temperature adjustments for starts as a function of temperature. At 75°F, the multiplicative adjustment is 1. Gasoline vehicles have a larger temperature effect than diesel vehicles, increasing to 4.8 at -20°F, while decreasing to 0.64 at

100°F. Whereas, the adjustment for diesel vehicles only increases to 2.7 at -20°F, and decreases to 0.85 at 100°F.

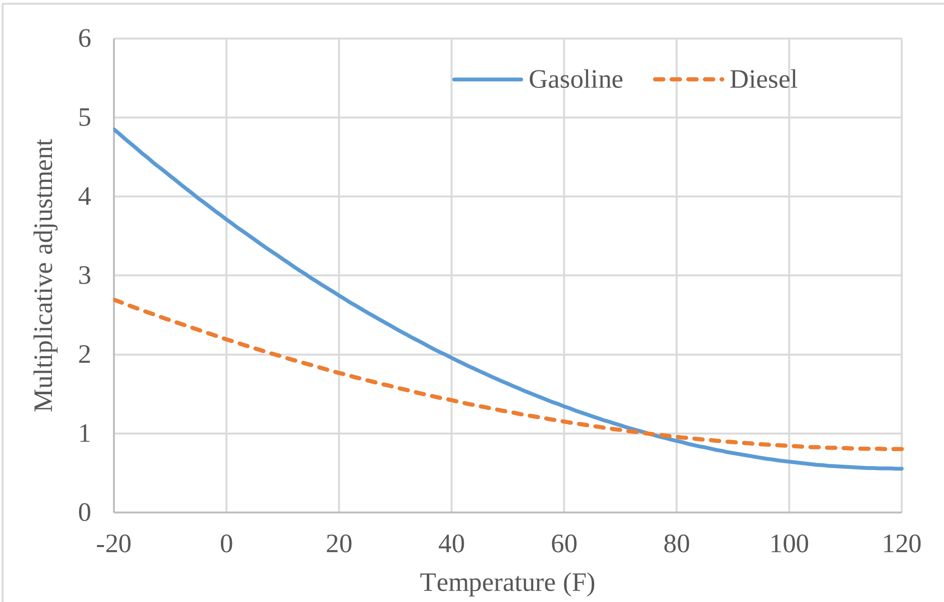


**Figure 2-14. Multiplicative Temperature Adjustments for Starts from Energy Consumption as a Function of Ambient Temperature**

## *2.7 Conclusions and Future Research*

With improved calibration and temperature management, ambient temperatures have less impact on emissions of newer vehicles than older ones, but MOVES201X continues to estimate a temperature effect for start HC, CO, $NO_X$ and PM emissions from gasoline vehicles, and HC start emissions from diesel and CNG vehicles.

We recognize that additional data and analysis could improve the MOVES temperature effects. Additional studies and analyses could include:

- Evaluating the benefits of applying log-linear or other mathematical models for pre-MSAT2 gasoline vehicle HC & CO temperature effects.

- Investigating ambient temperature effects on cold start emissions above certification levels, i.e. temperatures warmer than 75°F.

- Evaluating the interaction of ambient temperature effects and fuel effects.

- Evaluating the interaction of ambient temperature effects and deterioration.

- Conducting studies of ambient temperature effects in heavy-duty diesel vehicles, especially those equipped with emission control devices, including diesel particulate filters (DPF) and selective reduction catalysts (SCR).

- Conducting studies of temperature effects in vehicles using alternative fuels such as compressed natural gas and ethanol blends

- Incorporating data on the impact of temperature effects on new technology vehicles, including Tier 3 gasoline direct injection, stop-start technologies and hybrid technologies.

# 3 Humidity Adjustments

Water in the air cools the peak combustion temperature and lowers engine out $NO_X$ emissions. The $NO_X$ exhaust emissions rates in MOVES are adjusted from actual measurement conditions to a standard humidity. At run time, these $NO_X$ exhaust emissions base rates for gasoline, diesel, CNG, and E-85 are adjusted to the humidity conditions specified by the run spec.

## *3.1 Humidity Adjustment Equation*

In MOVES, the base exhaust emission rates for $NO_X$ in all modes and all processes are multiplied by a humidity adjustment factor, *K (unitless)*. In MOVES201X, as compared to MOVES2014, we:

1. Updated the coefficients for the gasoline equation (but kept the equation form as is). The same updated equation and coefficients are also used for CNG and E-85.
2. Added a new, and functionally different, set of equations and coefficients for diesel.
3. Updated the equation for calculating vapor pressure of water at saturation temperature. This updated equation is used in subsequent calculations for all fuels where the humidity adjustment is applied.
4. Created a new table 'humidityNoxAdjust', which associates each fuel type with a humidity adjustment equation for $NO_X$ and stores the coefficients for those equations. Simultaneously, we removed the humidity adjustment coefficients from the fuelType table.

MOVES2014 used the humidity adjustment equation given in 40 Code of Federal Regulations (CFR) 86.144-94(c)(7)(iv-viii) for both gasoline and diesel emissions with a coefficient specific to each fuel type. However, 40 CFR 1065.670 has more up-to-date equations for diesel emissions. The CFR Part 1065 equations have a different form and require two coefficients instead of one. CFR Part 1065 also has a gasoline equation, but we are choosing to retain the CFR Part 86 equations for gasoline since it is based on a larger gasoline vehicle dataset. Additionally, the CFR Part 86 equation is the equation used to adjust $NO_X$ data collected in Inspection & Maintenance programs which we use to develop the baseline gasoline rates in MOVES.

Thus, for all vehicles, MOVES201X uses Equation 3.1 and Equation 3.2 to calculate the absolute temperature and vapor pressure of water at saturation temperature:

$$T_K = \frac{5}{9} * (T_F - 32) + 273$$

**Equation 3.1**

$$P_{H2O} = 10^{\left[10.79574\cdot\left(1-\frac{273.16}{T_K}\right)-5.02800\cdot\log_{10}\left(\frac{T_K}{273.16}\right)+1.50475\cdot10^{-4}\left(1-10^{-8.2969\cdot\left(\frac{T_K}{273.16}-1\right)}\right)+0.42873\cdot10^{-3}\cdot\left(10^{\left[4.76955\cdot\left(1-\frac{273.16}{T_K}\right)\right]}-1\right)-0.2138602\right]}$$

**Equation 3.2**

The $P_{H2O}$ equation is from 40 CFR 1065.645.

The humidity adjustments for gasoline, CNG, and E-85 vehicles use Equation 3.3 and Equation 3.4 from 40 CFR 86.144-94(c)(7)(iv-viii).

$$H_{sp} = \frac{621.1 * \frac{H_{rel}}{100} * P_{H2O}}{(P_B * 3.38639) - \left(\frac{H_{rel}}{100} * P_{H2O}\right)}$$

**Equation 3.3**

$$K_{gas} = 1 - \left[\left(H_{sp} - 10.71\right) * C_A\right]$$

**Equation 3.4**

The humidity adjustment for diesel vehicles use Equation 3.5 and Equation 3.6 from 40 CFR 1065.670

$$X_{H2O} = \frac{\frac{H_{rel}}{100} * P_{H2O}}{P_B * 3.38639}$$

**Equation 3.5**

$$K_{diesel} = \frac{1}{(C_A * X_{H2O}) + C_B}$$

**Equation 3.6**

Where,
$C_{A\text{ or }B}$ = humidity adjustment coefficient. These are dependent on the fuel type, as shown in Table 3.1
$H_{sp}$ = specific humidity of ambient air (grams-water/kilograms-dryair). $H_{sp}$ values are limited by lower and upper bounds, as shown in Table 3.1.
$H_{rel}$ = relative humidity of ambient air (percent)
$K_{gas\text{ or }diesel}$ = humidity adjustment factor (unitless)
$P_B$ = barometric Pressure (inHg); 1 inHg = 3.38639 kPa
$P_{H2O}$ = vapor pressure of water at saturation temperature (kPa)
$T_F$ = Ambient temperature (deg F)
$T_K$ = Ambient temperature (K)
$X_{H2O}$ = mole fraction of water or specific humidity (moles-water/moles-dryair). $X_{H2O}$ values are limited by lower and upper bounds, as shown in Table 3.1.

**Table 3.1. $NO_X$ Humidity Adjustment Equations and Coefficients Used by MOVES.**

| Fuel Type | Equation Reference | $C_A$ | $C_B$ | $H_{sp}$ or $X_{H2O}$ Lower Bound[a] | $H_{sp}$ or $X_{H2O}$ Upper Bound[a] | $H_{sp}$ or $X_{H2O}$ Units |
|---|---|---|---|---|---|---|
| Gasoline | CFR 86 | 0.0329 | | 3.00 [b] | 17.71[b] | grams of water/kg of dry air |
| Diesel | CFR 1065 | 9.953 | 0.832 | 0.002 [c] | 0.035 [c] | moles of water/moles of dry air |
| CNG | CFR 86 | 0.0329 | | 3.00 | 17.71 | grams of water/kg of dry air |
| E-85 | CFR 86 | 0.0329 | | 3.00 | 17.71 | grams of water/kg of dry air |

Notes:
[a] If the computed $H_{sp}$ or $X_{H2O}$ is outside of corresponding [lower, upper] values, the bounding value is used.
[b] The lower and upper bounds for specific humidity in the CFR 86 method are changed from 21 and 124, in grains of water/pound of dry air in MOVES2014, to 3.00 and 17.71, in grams of water/kilogram of dry air in MOVES 201X based on 1 g/kg = 7 grain/lb.
[c] The lower and upper bounds for specific humidity in the CFR 1065 method are derived from the graph on page 98 of *Test Procedures for Highway and Nonroad Engines and Omnibus Technical Amendments – Technical Support Document and Summary and Analysis of Comments*, EPA420-R-05-008, June 2005, Office of Transportation and Air Quality, US Environmental Protection Agency.

## *3.2 Future Research*

Future research could investigate the emission impact of humidity on more recent gasoline, diesel, and alternatively-fueled engines and consider whether modern engine calibration and emission control technologies impact the humidity effect.

# 4 Air Conditioning Adjustments

The air conditioning (A/C) effects described below, and incorporated in MOVES201X were originally derived for MOVES2010. No changes to air conditioning calculations and parameters were made for MOVES201X, although there have been significant improvements to A/C energy efficiencies. As part of the analysis supporting the 2012-2016 Light Duty Greenhouse Gas standards, and the 2017-2025 Light Duty Greenhouse Gas Standards, we estimated improvements in air conditioning system efficiencies, starting in model year 2012 with full phase-in by 2019. In MOVES, we project the light-duty A/C improvements of these rules using the running energy rates as documented in the MOVES201X Greenhouse Gas and Energy Consumption Rates Report[23], rather than changing the A/C factors within MOVES. The MOVES A/C factors are multiplicative adjustments from the running energy rates, so a reduction in running energy rates also reduces energy consumption from light-duty vehicle air conditioning.

The air conditioning adjustment factors used in MOVES are based on a test procedure meant to simulate air conditioning emission response under extreme “real world” ambient conditions. These factors predict emissions which would occur during full loading of the air conditioning system, and are then scaled down in MOVES according to the ambient conditions specified in a modeling run. The second-by-second emission data were analyzed using the MOVES methodology of binning the data according to vehicle characteristics (source bins in MOVES) and vehicle specific power bins (operating modes in MOVES). The results of the analysis showed statistically significant and consistent air conditioning effects for three types of operation (deceleration, idle and cruise/acceleration) and the three primary exhaust pollutants (hydrocarbon, carbon monoxide and nitrous oxides). This report shows the results of the analysis for the air conditioning adjustments used in MOVES for HC, CO, $NO_X$ and energy consumption. The impact of A/C on particulate matter has not been evaluated for MOVES and therefore, MOVES currently has no air conditioning effect for PM emissions.

MOVES adjusts total energy consumption and exhaust running HC, CO and $NO_X$ emissions separately for each operating mode. The same adjustment value is used for all affected sourcetypes. MOVES applied the A/C effect for criteria pollutants (HC, CO and $NO_X$) only for passenger car, passenger truck and commercial light truck source types. The A/C effect on energy consumption is applied to all source types.

## *4.1 Air Conditioning Effects Data*

The data for the MOVES A/C Correction Factor (ACCF) was collected in 1997 and 1998 in specially designed test programs. In the programs, the same set of vehicles were tested at standard FTP test conditions (baseline) and at a nominal temperature of 95 F. Use of the same set of vehicles and test cycles was intended to eliminate most of the vehicle and test procedure variability and highlight the difference between a vehicle operating at extreme ambient conditions and at a baseline condition.

The data used to develop the MOVES ACCF consisted of emission results from 54 individual cars and light trucks tested over a variety of test schedules. Overall, the database consisted of a total of 625 test cycles, and 1,440,571 seconds of emission test and speed / acceleration data.

Because of the need to compute vehicle specific power on a modal basis, only test results which consisted of second-by-second data were used in the MOVES analysis. All second-by-second data were time aligned and checked for errors.

The distribution of test vehicles by model year is shown in Table 4-1. Model years 1990 through 1999 were included. The data set consists of 30 cars and 24 light trucks. No test data were available on other vehicle types (e.g. motorcycles or heavy-duty trucks). The individual test cycles on which the vehicles were run are shown with the test counts in Table 4-2. The data shows a balance between different test cycles, and cars and trucks. Unfortunately, the study did not contain any pre-1990 or post-1999 model years. The individual vehicles are listed in Appendix C.

Only vehicles which were coded as having an emission test with the A/C system on were selected for this analysis. The A/C On tests and the A/C Off (default for most EPA emission tests in general) were matched by VIN, test schedule and EPA work assignment. The matching ensured that the same vehicles and test schedules were contained in both the A/C On sample and the A/C Off sample.

**Table 4-1 Distribution of test vehicles by Model Year**

| Model Year | Count |
|---|---|
| 1990 | 5 |
| 1991 | 5 |
| 1992 | 6 |
| 1993 | 5 |
| 1994 | 7 |
| 1995 | 5 |
| 1996 | 13 |
| 1997 | 4 |
| 1998 | 3 |
| 1999 | 1 |
| TOTAL | 54 |

Table 4-2 summarizes the distribution of test-cycles analyzed. The test-cycles are defined in a MOBILE6 report.[24]

**Table 4-2 Distribution of tests by test cycle**

| Schedule Name | Count |
|---|---|
| ART-AB | 36 |
| ART-CD | 36 |
| ART-EF | 36 |
| F505 | 21 |
| FTP | 21 |
| FWY-AC | 57 |
| FWY-D | 36 |
| FWY-E | 36 |
| FWY-F | 36 |
| FWY-G | 36 |
| FWY-HI | 36 |
| LA4 | 23 |
| LA92 | 35 |
| LOCAL | 36 |
| NONFRW | 36 |
| NYCC | 36 |
| RAMP | 36 |
| ST01 | 36 |
| TOTAL | 625 |

## *4.2 Mapping Data to VSP Bins*

The overall dataset consisted of a sample of vehicle tests with the A/C system on and a sample of vehicle tests with the A/C system off. Both samples consisted on the same vehicles and all tests were modal with a data sampling of 1 hertz (second-by-second data collection). Prior to analysis, the data for each vehicle / test cycle combination was time-aligned to ensure that the instantaneous vehicle operating mode was in-sync with the emission collection system. Following time alignment, the vehicle specific power (VSP) was calculated for each vehicle test / second combination. This was done using Equation 4-1.

**Equation 4-1**

VSP = 985.5357 * Speed * Acoeff / Weight +
440.5729 * Speed^2 * Bcoeff / Weight +
196.9533 * Speed^3 * Ccoeff / Weight +
0.19984476 * Speed * Accel + GradeTerm

*Where*

VSP is the vehicle specific power for a given second of operation in units of KW / tonne.
Speed is the instantaneous vehicle speed for a given second in units miles / hour.
Accel is the instantaneous vehicle acceleration for a given second in unit of miles/hr-sec
Weight is the test vehicle weight in pounds.

Acoeff = 0.7457*(0.35/(50*0.447)) * ROAD_HP
Bcoeff = 0.7457*(0.10/(50*50*0.447*0.447)) * ROAD_HP
Ccoeff = 0.7457*(0.55/(50*50*50*0.447*0.447*0.447)) * ROAD_HP

*Where*

ROAD_HP = 4.360117215 + 0.002775927 * WEIGHT (for cars)
ROAD_HP = 5.978016174 + 0.003165941 * WEIGHT (for light trucks)

GradeTerm (KW/tonne) = 4.3809811 * Speed * Sin(Radians(GradeDeg))

*Where*

GradeDeg is the road grade in units of degrees. This term is zero for dynamometer tests.

4.3809811 (m^2 * hr / (s^3 * miles) =
9.80665(m/s^2) * 1609.34(m/mile) / 3600(secs/hr)
KW / tonne = m^2 / s^3
9.80665(m/s^2) is the gravitation constant.

After computing the VSP for each vehicle test / second combination, we assigned the individual seconds to the MOVES VSP bins. These VSP bins are defined in Table 4-3. VSP bins 26 and 36 were not defined because bins 27-30 and bins 37-40 overlap them.

**Table 4-3 VSP bin definitions**

| VSP Label | Definition |
|---|---|
| 0 | Braking |
| 1 | Idling |
| 11 | Low Speed Coasting; VSP< 0; 1<=Speed<25 |
| 12 | Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25 |
| 13 | Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25 |
| 14 | Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25 |
| 15 | Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25 |
| 16 | Cruise/Acceleration; 12<=VSP; 1<=Speed<25 |
| 21 | Moderate Speed Coasting; VSP< 0; 25<=Speed<50 |
| 22 | Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50 |
| 23 | Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50 |
| 24 | Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50 |
| 25 | Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50 |
| 26 | Cruise/Acceleration; 12<=VSP; 25<=Speed<50 |
| 27 | Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50 |
| 28 | Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50 |
| 29 | Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50 |
| 30 | Cruise/Acceleration; 30<=VSP; 25<=Speed<50 |
| 33 | Cruise/Acceleration; VSP< 6; 50<=Speed |
| 35 | Cruise/Acceleration; 6<=VSP<12; 50<=Speed |
| 36 | Cruise/Acceleration; 12 <= VSP; 50<=Speed |
| 37 | Cruise/Acceleration; 12<=VSP<18; 50<=Speed |
| 38 | Cruise/Acceleration; 18<=VSP<24; 50<=Speed |
| 39 | Cruise/Acceleration; 24<=VSP<30; 50<=Speed |
| 40 | Cruise/Acceleration; 30<=VSP; 50<=Speed |

An average emission result for each pollutant (HC, CO and $NO_X$) with and without A/C operation was computed for each VSP Bin. This resulted in 69 (23 VSP bins x 3 pollutants) pairs of emission averages. However, preliminary analysis of the data grouped into the 23 bins (defined in Table 4-3) showed unsatisfactory statistical results. In the general, no trends were evident across VSP bins or within similar subsets of VSP bins. The trends were highly erratic and the results were generally not statistically significant. In addition, most of the bins labeled 30 or higher had very few data members. An analysis of cars versus trucks was also performed, and showed no statistical difference between the two.

To produce more consistent results, the individual VSP bins were collapsed down to three principal bins. These are the Braking / Deceleration bin, the Idle bin and the Cruise / Acceleration bin. These large bins are quite different in terms of engine operation and emissions performance. The Braking bin consisted of VSP Bin 0 in Table 4-3, the Idle bin was VSP Bin 1 and the Cruise / Acceleration bin contained the remaining 21 bins.

## *4.3 Air Conditioning Effects on Emissions*

### *4.3.1 Full A/C Adjustments for HC, CO and $NO_X$ Emissions*

Full A/C adjustments were generated for each of the nine VSP Bin and pollutant combinations. This was done by dividing the mean “With A/C” emission factor by the mean “Without A/C” emission factor for each of the VSP Bin / pollutant combinations. The Full A/C adjustments are shown in Table 4-4. Measures of statistical uncertainty (coefficient of variation of the mean) were also computed using the standard error of the mean. They are shown in Table 4-4 as “Mean CV of CF.”

**Table 4-4 Full air conditioning adjustments for HC, CO and $NO_X$**

| Pollutant | Operating Mode | opModeID | Full A/C CF | Mean CV of CF |
|---|---|---|---|---|
| HC | Braking / Decel | 0 | 1.0000 | 0.48582 |
| HC | Idle | 1 | 1.0796 | 0.74105 |
| HC | Cruise / Accel | 11 - 40 | 1.2316 | 0.33376 |
| CO | Braking / Decel | 0 | 1.0000 | 0.31198 |
| CO | Idle | 1 | 1.1337 | 0.77090 |
| CO | Cruise / Accel | 11 - 40 | 2.1123 | 0.18849 |
| $NO_X$ | Braking / Decel | 0 | 1.0000 | 0.19366 |
| $NO_X$ | Idle | 1 | 6.2601 | 0.09108 |
| $NO_X$ | Cruise / Accel | 11 - 40 | 1.3808 | 0.10065 |

Note the higher air conditioning effect for $NO_X$ at idle. These results are consistent with those obtained from Nam et al. (2000)[25] who showed that at low load conditions, A/C greatly increased $NO_X$ emissions due to reduced residual gas fractions in-cylinder.

### *4.3.2 Full A/C Adjustments for Energy Consumption*

The use of a vehicle's A/C system will often have a sizeable impact on the vehicle's energy consumption. This was found statistically by analyzing the available second-by-second data on CO2 and other gaseous emissions, and converting them to an energy basis using standard EPA vehicle fuel economy certification equations. The vehicle emission data were binned by VSP bin (see above). Mean values were computed and separate analysis was done as a function of sourceBinID (combination of vehicle type, fuel type and model year), and the results were not statistically different across sourceBinID given the relatively small sample sizes. As a result, the A/C adjustments for energy are a function of only VSP bin. The resulting A/C adjustments are shown in Table 4-5.

**Table 4-5 Full air conditioning adjustments for energy**

| VSPBin | A/C Factor | VSPBin | A/C Factor | VSPBin | A/C Factor |
|---|---|---|---|---|---|
| 0 | 1.342 | 21 | 1.294 | 30 | 1.294 |
| 1 | 1.365 | 22 | 1.223 | 33 | 1.205 |
| 11 | 1.314 | 23 | 1.187 | 35 | 1.156 |
| 12 | 1.254 | 24 | 1.167 | 37 | 1.137 |
| 13 | 1.187 | 25 | 1.157 | 38 | 1.137 |
| 14 | 1.166 | 26 | 1.127 | 39 | 1.137 |
| 15 | 1.154 | 27 | 1.127 | 40 | 1.137 |
| 16 | 1.128 | 28 | 1.127 | | |
| | | 29 | 1.127 | | |

Only very small amounts of data were available for VSP bins 26 through 29 and VSP bins 37 through 40. As a result, the data from these bins was averaged together and binned into two groups. The resulting group averages were used to fill the individual VSP bins. This averaging process has the effect of leveling off the effect of A/C at higher power levels for an engine. This is an environmentally conservative assumption since it is likely that the engine power devoted to an A/C compressor probably continues to decline, sometimes to zero, as the overall power demand of the engine is increased.

To summarize, for HC, CO and $NO_X$, detailed VSP was not found to be an important variable in regards to A/C adjustment and A/C usage. However, full A/C adjustments greater than one were found for all pollutants for both Idle and Cruise / Acceleration modes. For $NO_X$ Idle mode, a fairly large multiplicative adjustment of 6.2601 was obtained. This large factor reflects the relatively low levels of $NO_X$ emissions during idle operation. A moderately high multiplicative A/C adjustment of 2.1123 for CO Cruise / Accel was also obtained. These adjustments will double CO emissions under extreme conditions of A/C usage. A/C adjustments of less than or equal to one were found for the Braking / Deceleration mode for all three pollutants. These were set to one for use in the MOVES model.

## 4.4 Adjustments to Air Conditioning Effects

In MOVES, the adjustments for each operating mode are weighted together by the operating mode distribution calculated from the driving schedules used to represent the driving behavior of vehicles. Average speed, road type and vehicle type will affect the operating mode distribution.

meanBaseRateACAdj = SUM(meanBaseRate*(fullACAdjustment-1.0)*opModeFraction)

Since not all vehicles are equipped with air conditioning, and air conditioning is normally not on all of the time, the full air conditioning effect on emissions is adjusted before it is applied to the emission rate. The adjustment account for (a) the fraction of vehicles in each model year that are equipped with air conditioning, (b) the fraction of vehicles equipped with air conditioning of each age that have an operational air conditioning system and (c) the fraction of those vehicle owners who have air conditioning available to them that will turn on the air conditioning based on the ambient temperature and humidity (heat index[26]) of the air outside their vehicles. These MOVES defaults are documented in the Population and Activity report.[27] The fraction of vehicles equipped with air conditioning, the fraction of operational air conditioning and the fraction of air conditioning use are used to adjust the amount of "full" air conditioning that occurs in each hour of the day.

EmissionRate = (meanBaseRateACAdj * ACPenetration*functioningACFraction*ACOnFraction) + meanBaseRate

The air conditioning adjustment is a multiplicative adjustment applied to the emission rate after it has been adjusted for fuel effects.

Air conditioners are employed for defogging at all temperatures, particularly, at lower temperatures. This secondary use of the A/C along with associated emission effects is not addressed in MOVES.

## 4.5 Conclusions and Future Research

MOVES applies air conditioning effects to emissions from all vehicles except motorcycles. The impact depends on pollutant, operating mode, ambient temperature and humidity, and the anticipated availability of air conditioning in the vehicle type, model year and age being modeled.

There are a number of areas where our understanding of air conditioning impacts could be improved. These include:

- Evaluation of the impact of air conditioning use on particulate matter emissions.
- Studies of air conditioning effects in a broader range of model years, particularly those with the most recent emission control technologies.
- Studies of air conditioning effects in a broader range of vehicles, particularly in heavy-duty diesel vehicles.
- Evaluation of air conditioning effects in the highest VSP/STP bins.

- Evaluation of the emissions impact of air conditioners in their role as defoggers.
- Updates to information on the fraction of vehicles equipped with air conditioning and their malfunction rates.

# 5 Inspection and Maintenance Programs

Inspection and Maintenance (I/M) programs are generically any state or locally mandated inspection of highway motor vehicles intended to identify those vehicles most in need of emissions-related repair and requiring repairs of those vehicles. There is great variation in how vehicles are selected for inclusion in the programs, how and when vehicles are tested, and what happens when vehicles fail. MOVES is designed to take these variations into the account when estimating the emission benefits of these programs.

## *5.1 Inspection & Maintenance in MOBILE6*

Because MOVES draws heavily on the approaches developed for MOBILE6.2 to represent the design features of specific I/M programs, it is useful to briefly review these methods. Readers interested in a more thorough treatment of the topic are encouraged to review the relevant MOBILE6 documentation.[28]

The MOBILE6.2 model used a methodology that categorized vehicles according to emitter status (High emitters and Normal emitters), and applied a linear growth model to project the fraction of the fleet that progresses from the Normal emitter to the High emitter status as a function of age. Average emission rates of High and Normal emitters were weighted using the High emitter fraction to produce an overall average emission rate as a function of age, model year group and vehicle type. The emissions generated represented the emissions of the fleet in the absence of I/M (the No I/M emission rate).

A similar approach was used to generate I/M emission rates. In this case the initial starting point for the function (where age=0) was the same as the No I/M case. However, the effects of I/M programs and associated repairs were represented by reductions in the fraction of high emitters, which consequently affected the average emission level of the fleet. Balancing these emissions reductions due to I/M repairs were the re-introduction of high emitters in the fleet due to deterioration of vehicle emission control systems after repairs. The underlying I/M and non-I/M deterioration rates were assumed to be the same.

MOBILE6 modeled the non-I/M and I/M emission cases diverging from each other over time, with the I/M rates being lower. The percentage difference between these two rates is often referred to as the overall I/M reduction or I/M benefit.

## *5.2 Inspection & Maintenance in MOVES*

The MOVES emission rates contain estimates of emission levels as a function of age, model year group and vehicle type for areas where no I/M program exists (the mean base rate, or the non-I/M reference rates) and for an area representing the "reference I/M program" (the I/M reference rates). As detailed in the MOVES light-duty emission rate report, the I/M reference rates for light-duty gasoline vehicles (the principal target of I/M programs) were derived using data from the enhanced I/M program in Phoenix, Arizona (as operated from calendar year 1995 through 2002) and represent the design features of that program.  The difference between the non-I/M and I/M reference rates are assumed to represent the I/M benefit of the Phoenix program design assuming perfect compliance. Equation 5-1 shows this relationship in a mathematical form.

$$Standard\ IM\ Difference = E_{nonIM} - E_{IM} \qquad \textbf{Equation 5-1}$$

where $E_{non\text{-}IM}$ and $E_{IM}$ are the non-I/M and I/M reference rates, respectively.

The Phoenix program design was selected as the reference program because most of the underlying data for MOVES light-duty emission rates came from this source. The selection does not imply any judgment on the strengths or weaknesses of this specific program.

The object of this process is to generate a general model which can be used to represent all I/M programs in the United States. The MOVES approach is to compare individual program designs against the reference program for purposes of developing adjustment to the "standard I/M difference" representing design features differing from those in the reference program. This concept is shown mathematically in Equation 5-2,

$$E_p = RE_{IM} + (1 - R)E_{nonIM} \qquad \textbf{Equation 5-2}$$

where $E_p$ is the adjusted emission rate for a "target" I/M program, $E_{IM}$ is the reference rate, $E_{nonIM}$ is the non-I/M reference rate, and $R$ is an aggregate adjustment representing the difference in average emission rates between the target program and the reference program.

Depending on the value of $R$, $E_p$ may be greater than $E_{nonIM}$, fall between $E_{nonIM}$ and $E_{IM}$, or be less than $E_{IM}$. Thus this framework can represent target programs as more effective or less effective than the reference program. In MOVES, $R$ is referred to as the "IMFactor."

Re-arranging Equation 5-2 and solving for $R$ gives leads to Equation 5-3. This equation shows the I/M adjustment as the ratio of the emission difference between a proposed I/M program design and the Standard I/M Difference

$$R = \frac{E_p - E_{nonIM}}{E_{IM} - E_{nonIM}} \qquad \textbf{Equation 5-3}$$

## *5.3 Development of MOVES I/M Factors*

Early in the MOVES development process, it was decided that developing the I/M adjustment factors based on a completely new analysis was infeasible. A major obstacle was a lack of suitable emissions and I/M program data representing the full range of program designs. Data sets for certain I/M programs (i.e., transient test based programs) were generally quite complete and robust. However, mass emission results and random vehicles samples were quite scarce for other test types such as the Acceleration Simulation Mode (ASM), steady-state, idle tests and OBD-II scans. This situation was particularly true for data on old model years at young ages (i.e., a 1985 model year at age five).

As a result, EPA developed I/M adjustment factors based on the information incorporated in MOBILE6.2. Mechanically, this step was achieved by running the MOBILE6.2 model about 10,000 times over a complete range of pollutant–process combinations, inspection frequencies, calendar years, vehicle types, test types, test standards, and model year group / age combinations. The mean emission results for each combination were extracted from the output and used to compute estimated values for IMFactor. The IMFactor table includes the following fields:

- Pollutant / Process
- Test Frequency
- Test Type
- Test Standard
- Regulatory Class
- Fuel Type (Only gasoline/ethanol fuels have IMFactors)
- Model Year Group
- Age Group
- IMFactor

The IMFactor value was computed for all reasonable combinations of the parameters listed in the IMFactor table. A separate MOBILE6.2 run was done for each parameter combination (Target design, $E_p$), and a second set of runs were done for the reference program (Reference design, $E_{IM}$). The IMFactor ($R$) was then calculated from the mean emission results from these two runs and the non-I/M case using Equation 5-3. The reference program has inputs matching the Phoenix, Arizona I/M program during the time in which the data used in the MOVES emission rate development were collected (CY 1995-2005). The reference design represents a biennial frequency with an exemption period for the four most recent model years. It uses three different I/M test types (basic idle test for MY 1960-1980, transient tailpipe tests for MY 1981-1995 (IM240, IM147), and OBD-II scans for MY 1996-and-later). Each of these test types became the reference for the respective model year groups.

The specific combinations of MOBILE6.2 runs performed are shown in Table 5-1 below. Each of these runs represents a particular test type and test standard design which was expressed as a ratio to the standard reference tests. A set of these runs were done for each calendar year 1990 through 2030, for cars, light trucks and heavy-duty gasoline vehicles and for pollutants HC, CO and $NO_X$.

The first four runs represent the Non-I/M reference and the three Arizona I/M references.

**Table 5-1 MOBILE6.2 runs used to populate the MOVES I/M adjustment factor**

| RUN # | Description | Type |
|---|---|---|
| 1 | Non I/M Base | Non I/M Reference |
| 2 | IM240 Base (Biennial IM240/147) | I/M Reference |
| 3 | OBD Base (Biennial OBD Test) | I/M Reference |
| 4 | Basic Base (Loaded – Idle Test) | I/M Reference |
| 5 | Biennial - IM240 - Phase-in Cutpoints | Target I/M Design |
| 6 | Annual - IM240 - Phase-in Cutpoints | Target I/M Design |
| 7 | Biennial - IM240 - Final Cutpoints | Target I/M Design |
| 8 | Annual - IM240 - Final Cutpoints | Target I/M Design |
| 9 | Biennial - ASM 2525/5015 - Phase-in Cutpoints | Target I/M Design |
| 10 | Annual - ASM 2525/5015 - Phase-in Cutpoints | Target I/M Design |
| 11 | Biennial - ASM 2525/5015 - Final Cutpoints | Target I/M Design |
| 12 | Annual - ASM 2525/5015 - Final Cutpoints | Target I/M Design |
| 13 | Biennial - ASM 2525 - Phase-in Cutpoints | Target I/M Design |
| 14 | Annual - ASM 2525 - Phase-in Cutpoints | Target I/M Design |
| 15 | Biennial - ASM 2525 - Final Cutpoints | Target I/M Design |
| 16 | Annual - ASM 2525 - Final Cutpoints | Target I/M Design |
| 17 | Biennial - ASM 5015 - Phase-in Cutpoints | Target I/M Design |
| 18 | Annual - ASM 5015 - Phase-in Cutpoints | Target I/M Design |
| 19 | Biennial - ASM 5015 - Final Cutpoints | Target I/M Design |
| 20 | Annual - ASM 5015 - Final Cutpoints | Target I/M Design |
| 21 | Annual - OBD - | Target I/M Design |
| 22 | Annual - LOADED/IDLE | Target I/M Design |
| 23 | Biennial - IDLE | Target I/M Design |
| 24 | Annual - IDLE | Target I/M Design |
| 25 | Biennial - 2500/IDLE | Target I/M Design |
| 26 | Annual - 2500/IDLE | Target I/M Design |

The MOBILE6.2 database output option was chosen for all runs. This step produced large sets of results which were further stratified by facility-cycle / start process and age. This output format necessitated additional processing of the facility rates into composite running and start factors (in MOVES the IMFactor is a function of running and start processes).

MOVES2014a had an error in the calculation of the IMFactor values which affected the 1981 through 1995 model years for vehicles 10 years and older. This problem was noted by the Coordinating Research Council in their E-101 report[29] on the MOVES2014 version of the model. This problem was rectified in MOVES201X by recalculating the IMFactor values for all source types in this model year and age range. The new IMFactor values increase HC, CO and $NO_X$ emissions compared to MOVES2014a in I/M areas with programs that cover these model years by less than 1% in calendar year 1999 increasing to nearly 3% in calendar year 2010. The impact of this problem diminish after calendar year 2010 as these model years are retired from the fleet. The impact of this change for specific areas will vary depending on the age distribution and other factors.

## *5.4 I/M Compliance Factors*

In addition to the IMFactor, MOVES adjusts rates for particular programs by applying an additional multiplicative "Compliance Factor" (IMCompliance). While the IMFactor (*R*) represents the theoretical effectiveness of a specific I/M program design relative to the reference design, as described above, the values of the IMComplianceFactor ($C$ ) are specific to individual programs and represent their overall operational effectiveness and efficiency. Program characteristics which impact the I/M compliance factor include waiver rates, compliance rates and overall operational efficiency. The compliance factor may vary from 0 to 100 where zero would represent a totally failed program and 100 a perfectly successful program. Factors which tend to reduce the complianceFactor are the systematic waiver of failed vehicles from program requirements, the existence of large numbers of motorists who completely evade the program requirements, technical losses from improperly functioning equipment or inadequately trained technicians.

The MOBILE6 compliance rate, waiver rate and effectiveness rate were used to determine the MOVES Compliance Rate. The new MOVES Compliance Rate is a broader concept that incorporates three separate MOBILE6.2 inputs.  shows the relationship.

$$C = M6ComplianceRate * M6EffectivenessRate * (1 - M6WaiverRate \qquad \textbf{Equation 5-4}$$

MOVES does not have separate inputs for the effect of waivers on I/M benefits. Section 3.10.6.2 of the guidance document for MOVES201X[30] describes how to calculate the MOVES compliance rate to include the effect of waivers.

In MOVES, it is assumed that any repairs attempted on vehicles receiving waivers are not effective and do not result in any reduced emissions.

## *5.5 Calculation of I/M Emission Rates*

Calculation of the emission rate for vehicles subject to an I/M program begins with the calculation of the IMAdjustFract. The IMAdjustFract combines the IM Factor for the program design and the Compliance Factor for the program characteristics to create a single factor. The Compliance Factor is in units of percent and is converted to a fraction.

$$IMAdjustFract = (IMFactor * ComplianceFactor * 0.01) \qquad \textbf{Equation 5-5}$$

The next step is estimate a program-specific “with I/M” emission rate by weighing together the emission rate for the I/M reference program and the non-I/M emission rate, using the IMAdjustFract.

$$TargetRate = IMRate * IMAdjustFract + NonIMRate * (1.0 - IMAdjustFract) \qquad \textbf{Equation 5-6}$$

## 5.6 Development of Default MOVES I/M Program Inputs

Information about which pollutant-processes are covered by I/M programs in various counties and calendar years is contained in the MOVES database table IMCoverage. This coverage information is allowed to vary by pollutant (process, county, year, regulatory class, and fuel type). The table also lists the I/M compliance factors described above

The IMCoverage table includes the use of I/M program identifiers called IMProgramIDs. A particular county will likely have several IMProgramIDs that reflect different test types, test standards or inspection frequencies being applied to different regulatory classes, model year groups or pollutant-process combinations. For example, a county in calendar year 2007 may have an IMProgramID=1 that annually inspects pre-1981 model year cars using an Idle test, and an IMProgramID=2 that biennially inspects 1996-and-later model year light-trucks using an OBD-II test.

The IMCoverage table also shows other important I/M parameters for each IMProgramID. These include the relevant model year range (beginning and ending model year), the frequency of inspection (annual, biennial, continuous/monthly), test type (Idle, IM240, ASM, OBD-II) and the test standard.

The structure of the IMCoverage table in the MOVES database is:

- Pollutant / Process
- State / County
- Year
- Source Use Type
- Fuel Type (only gasoline and ethanol fuels)
- Beginning Model Year of Coverage
- Ending Model Year of Coverage
- InspectFreq
- IMProgramID
- I/M Test Type
- I/M Test Standards
- UseIMyn
- Compliance Factor

For official state submissions, it is expected that the state will enter their own set of program descriptive parameters and compliance factors which reflect current and expected future program operation. However, MOVES contains a set of I/M program descriptions for all calendar years intended to reflect our best assessment of the programs in each state.

The underlying data used to construct the default inputs for I/M programs before calendar year 2011 were taken from MOBILE6.2 input files used in the NMIM model to compute the National Emission Inventory of 2011. The MOBILE6 data fields listed in Table 5-2 were extracted and processed into the various fields in the MOVES IMCoverage table for each state and county.

**Table 5-2 I/M Coverage table data sources**

| MOBILE6 Data | MOVES I/M Coverage Parameter |
|---|---|
| Compliance Rate | Used in the MOVES Compliance Rate Calculation |
| I/M Cutpoints | Used to determine MOVES I/M Test Standards |
| Effectiveness Rate | Used in the MOVES Compliance Rate Calculation |
| Grace Period | Used in MOVES to Determine Beginning Model Year of Coverage |
| Model Year Range | Used in MOVES to Determine Ending Model Year of Coverage |
| Test Type | Used to determine MOVES I/M Test Type |
| Vehicle Type | Used to determine MOVES Regulatory Class input |
| Waiver Rate | Used in the MOVES Compliance Rate Calculation |

As seen in Table 5-2, MOBILE6.2 and MOVES do not have exactly compatible parameter definitions.

In addition to the Compliance Rate described above, other fields in the IMCoverage table complete the description of each I/M program in effect in each county. The MOBILE6.2 I/M Cutpoints data were used only to determine level of stringency of a state's IM240 program (if any). The MOBILE6.2 Test Type inputs provided a description of the specific I/M tests performed by the state and test standards for the ASM and Basic I/M tests. The MOBILE6.2 inputs of Grace Period and Model Year Range were used to determine the MOVES Beginning and Ending model year data values for each I/M program. The MOBILE6.2 vehicle type input was mapped to the MOVES regulatory class.

The UseIMyn toggle is a user feature that allows the user to completely disable the modeling of I/M for one or more of the parameter combinations.

For MOVES201X, the IMCoverage table default parameters for calendar year 2011 through 2013 were derived using the IMCoverage tables from the county databases (CDBs) provided to EPA for the 2011 National Emission Inventory (NEI) project[31] (Version1). These tables were available for review by states and updated as needed. The I/M program descriptions from these CDBs were extracted from the CDBs and compiled in the default IMCoverage table for calendar year 2011. The I/M descriptions for 2012 and 2013 calendar years were derived from the 2011 I/M descriptions, assuming no changes in the basic I/M program design, but updating the model year coverage values to properly account for the existing grace periods in the future calendar years.

The 2014 I/M program descriptions were derived from the 2014 NEI (Version 1) CDBs following review by the states, and the 2015 and later calendar year assume no changes in the basic 2014 I/M program design, but update the model year coverage values to properly account for the existing grace periods in the future calendar years.

All of the I/M program descriptions were checked using a script to look for cases where a model year coverage either conflicted with other rows in the I/M description or where gaps without coverage were left between model years. This check also looked for cases where the coverage beginning model year occured later than the ending model year coverage. Each problem identified was compared to the I/M program descriptions found in the 2013 EPA I/M Program Data, Cost and Design Information report[32] to resolve conflicts. The county coverages in some states was also updated for some calendar years.

In addition to the updates in the I/M program descriptions, the table was updated to make sure each I/M program covered E85-fueled vehicles in the same way as for gasoline in all calendar years. Any program elements claiming benefits for inspections to reduce liquid fuel leaks (pollutant process ID 113) were dropped from the default I/M program descriptions. MOVES does not offer any benefits from inspection programs to detect liquid fuel leaks.

Table 5-3 shows the states with I/M program descriptions in the default I/M coverage table and shows the number of counties covered by the programs by calendar year.

**Table 5-3 Default States Having I/M Programs**

| | | Calendar Years | | |
|---|---|---|---|---|
| **State** | **StateID** | **Minimum** | **Maximum** | **Counties** |
| Alaska | 2 | 1990 | 2009 | 2 |
| | | 2010 | 2050 | 1 |
| Arizona | 4 | 1990 | 2050 | 2 |
| California | 6 | 1990 | 1990 | 7 |
| | | 1999 | 2050 | 40 |
| Colorado | 8 | 1990 | 2014 | 7 |
| | | 2015 | 2050 | 9 |
| Connecticut | 9 | 1999 | 2050 | 8 |
| Delaware | 10 | 1990 | 2050 | 3 |
| District of Columbia | 11 | 1990 | 2050 | 1 |
| Georgia | 13 | 1999 | 2050 | 13 |
| Idaho | 16 | 1990 | 2010 | 1 |
| | | 2011 | 2050 | 2 |
| Illinois | 17 | 1990 | 2050 | 11 |
| | | 2002 | 2002 | 9 |
| Indiana | 18 | 1990 | 2000 | 4 |
| | | 2001 | 2050 | 5 |
| Kentucky | 21 | 1990 | 2005 | 4 |
| Louisiana | 22 | 2000 | 2050 | 2 |
| Maine | 23 | 1990 | 2050 | 1 |
| Maryland | 24 | 1990 | 2050 | 14 |
| Massachusetts | 25 | 1990 | 2050 | 14 |
| Minnesota | 27 | 1990 | 2050 | 7 |
| Missouri | 29 | 1990 | 2050 | 5 |
| Nevada | 32 | 1990 | 2050 | 2 |
| New Hampshire | 33 | 2002 | 2010 | 3 |
| | | 2011 | 2050 | 10 |
| New Jersey | 34 | 1990 | 2050 | 21 |
| New Mexico | 35 | 1990 | 2050 | 1 |
| New York | 36 | 1990 | 2000 | 9 |
| | | 2001 | 2050 | 62 |
| North Carolina | 37 | 1990 | 2002 | 9 |
| | | 2003 | 2005 | 12 |
| | | 2006 | 2050 | 48 |
| Ohio | 39 | 1990 | 2050 | 14 |
| Oregon | 41 | 1990 | 2000 | 4 |
| | | 2001 | 2050 | 6 |
| Pennsylvania | 42 | 1990 | 2000 | 11 |
| | 42 | 2001 | 2050 | 25 |
| Rhode Island | 44 | 2000 | 2050 | 5 |
| Tennessee | 47 | 1990 | 2050 | 6 |
| Texas | 48 | 1990 | 1999 | 4 |
| | | 2000 | 2010 | 10 |
| | | 2011 | 2050 | 17 |
| Utah | 49 | 1990 | 2050 | 4 |
| Vermont | 50 | 1990 | 2050 | 14 |
| Virginia | 51 | 1990 | 2050 | 10 |
| Washington | 53 | 1990 | 2050 | 5 |
| Wisconsin | 55 | 1999 | 2050 | 7 |

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# Appendix A Derivation of Default Temperature and Humidity Values

For default temperature and humidity values to use in the temperature and humidity adjustment calculations described in the main body of the report, MOVES uses the 10-year average temperature and relative humidity values from calendar years 2001 through 2011 by month and by hour (standard time) for each county in the United States for all calendar years. Due to the limited number of hourly observation stations (about 200 sites), interpolation of the available data is required. In areas where climate can vary significantly over distance, such as in mountainous terrain and near coastlines or deserts, this interpolation will not always produce representative results. Moreover, it is important that the diurnal range of the average hourly temperatures match those of the average monthly minimum and maximum values. This aspect arises due to the averaging process and to the fact that daily maximum and minimum temperatures do not always occur at the same hourly observation time.

To correct the diurnal range problem, EPA has developed a method to adjust the average hourly temperatures so that the corresponding hourly-based maximum and minimum temperatures match those of the true monthly maximum and minimum values. To correct the spatial problem, all of the daily and monthly maximum and minimum temperature observations made by the National Weather Service (NWS) and its Cooperative Observation branch (over 6000 sites) and the Federal Aviation Administration (FAA) are used.

## Appendix A-1 Data Sets and Quality Control

The National Climatic Data Center (NCDC) is the national and international depository for weather observations. As part of its many duties, the NCDC publishes and maintains many climatic data sets. “Quality Controlled (QCLCD) Local Climatological Data” files were obtained for all locations across the United States, Puerto Rico, and the Virgin Islands from the NCDC for this analysis.

There can be significant problems with this information. Primary among these problems is that many stations with daily data do not have corresponding monthly averages, and vice-versa. Further, some stations may have the same identification numbers while others may have missing or incorrect latitude and longitude coordinates. During the processing of the 2009 data, nearly 10% of the 1654 stations were found to have identification and/or location problems.

Missing monthly temperatures can be calculated from the daily maximum and minimum observations for these stations for the years of interest. To resolve the mislabeled station IDs and location data, it was necessary to contact NCDC to obtain updated tables with corrected IDs before processing the data.

In addition to the hourly temperature and dew point data, the identification number and geographic location (latitude and longitude) for all available weather stations across the United States, Puerto Rico, and the Virgin Islands were obtained from the NCDC files. Using

Geographical Information System (GIS) software, the locations of the hourly weather observation stations were validated. To resolve duplicate IDs and latitude/longitude issues, careful analysis of the station history files and conversations with state climatologists and National Weather Service offices were made. Our contractor, Air Improvement Resource Inc. (AIR), hand-edited the IDs and latitude/longitude data and supplied updates to our data and to the NCDC.

For temperature disputes, such as maximum temperature less than minimum temperature (caused by mistyped data entry), hourly and/or daily data from other nearby sites were consulted and the data corrected accordingly.

For each station, an inventory was made as to the number of hours with joint temperature and dew point data. In order to be included in the analysis, each station had to have at least 50% data recovery for each hour of each month.

The daily absolute maximum and minimum temperature data for all available stations were processed into monthly averages. These stations covered all classifications, including First-Order (National Weather Service), Second-Order (both Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS)), and cooperative (local). Following NCDC guidelines, a month's averages were considered valid when no more than 5 days had missing data during that month. For each station, the hourly temperature and dew point data was scanned for missing values. For each missing data period lasting only 1 hour, the missing values was replaced with an interpolated value from the two adjacent valid readings

After these filters were applied, the average monthly maximum and minimum temperature data were adjusted to the common midnight-to-midnight observational period. This adjustment is necessary since many of the cooperative stations take their observations either early in the morning or late in the afternoon rather than at midnight. These observation times induce a bias into the monthly temperature averages. Correction values were obtained from the NCDC and applied to the monthly averages.

## Appendix A-2 County Temperature Assignment

An octal search with inverse distance weighting was used to assign the monthly maximum and minimum temperatures to each U.S. county. Population centroids (latitude and longitude) for each county were obtained from the 2010 United States Census. Population, rather than geographic, centroids were used to provide a reasonable estimate of where the county's vehicle miles traveled and nonroad activity would be concentrated. From each county's centroid, the distance and direction to each weather station was calculated. The shortest distance was computed using the standard great circle navigation method and the constant course direction was computed using the standard rhumb line method. A rhumb line is a line on a sphere that cuts all meridians at the same angle; for example, the path taken by a ship or plane that maintains a constant compass direction. Based on the computed directions, the stations were assigned to an octant, as follows:

- Octant 1: $0° < Dir \leq 45°$
- Octant 2: $45° < Dir \leq 90°$
- Octant 3: $90° < Dir \leq 135°$
- Octant 4: $135° < Dir \leq 180°$
- Octant 5: $180° < Dir \leq 225°$
- Octant 6: $225° < Dir \leq 270°$
- Octant 7: $270° < Dir \leq 315°$
- Octant 8: $315° < Dir \leq 360°$

For each octant, the stations were sorted by distance. The station closest to the centroid for each octant was chosen for further processing. If the closest station was more than 200 miles away, that octant was ignored. Such situations occurred near the oceans and the along the Canadian and Mexican borders. The temperatures from these 8 (or less) stations were then weighted together using inverse-distance weighting

Sometimes the county centroid and the octant weather stations are in different time zones. To remove the effects of differing time zones between county centroids and the weather stations, the temperature and dew point data from each octant weather station was synchronized to the same local hour (that is, the standard time at the county centroid was used).

## Appendix A-3 Temperature Recalculation

Each county has daily maximum and minimum temperatures based on the spatial averaging describe above. The daily maximum and minimum temperature are averaged over all the days in each month to generate the monthly average maximum (AMax) and monthly average minimum (AMin) temperature.

The temperatures in each of the 24 hours are separately averaged over all the days in each month. This produces a set of 24 temperatures for each month for each county. This set is a time profile for the average daily temperatures in the month.

This temperature profile is stretched so that the maximum and minimum values match the average maximum and minimum temperatures for the month. The equation used for each hour is given below:

$$AdjTemp_h = AMin + (Temp_h - PMin) * ((AMax - AMin)/(PMax - PMin))$$

Where:

h is hour of the day,
$AdjTemp_h$ is the adjusted hourly temperature,
$Temp_h$ is the hourly temperature in the profile,
AMin is the average monthly minimum temperature,

AMax is the average monthly maximum temperature,
PMin is the minimum temperature based on the averaged 24 hourly temperatures in the profile,
PMax is the maximum temperature based on the averaged 24 hourly temperatures in the profile.

After this adjustment is applied, the maximum and minimum of the adjusted hourly temperatures will exactly match the average monthly maximum and minimum temperatures.

## Appendix A-4 Relative Humidity Recalculation

Relative humidity depends on both temperature and dew point. Unfortunately, unlike daily maximum and minimum temperatures, supplemental dew point data is not available. Consequently, an investigation and literature search was made to determine a suitable estimation method. Surprisingly, few were found. The scheme outlined below was suggested by the NCDC and was used in this analysis:

At any given time, the difference between the temperature and dew point is known as the dew point depression (DPD). Since the dew point can never exceed the temperature, the minimum DPD is zero (100% relative humidity) while the maximum can be several tens of degrees, depending on how dry the air is. From the original data, the DPD was computed at each hour.

After the hourly temperatures were adjusted to be consistent with the county minimum and maximum temperatures as described above, the DPDs were subtracted from the hourly temperatures to estimate the corresponding dew point. The corresponding relative humidity was then computed from these two values. In keeping with standard meteorological practices, the relative humidity is always computed with respect to water, even if the temperature is below freezing. Comparative tests showed that the new calculated relative humidity results were very close to the original values, which is the desired outcome.

## Appendix A-5 Calculation of 10 Year Averages

The monthly average hourly temperatures for each county from each calendar year from 2001 through 2011 were averaged to determine the default 10-year average temperatures stored in the MOVES ZoneMonthHour table for each county. The relative humidity values were converted to specific humidity (humidity ratio) for each hour before averaging and then converted back to relative humidity.

## Appendix B **OTAQ Light-duty gasoline 2012 Cold Temperature Program**

| Vehicle Name | Model Year | Injection | Emissions Std | MSAT? | Odometer | Displ (L) | Cyl. |
|---|---|---|---|---|---|---|---|
| Buick Lucerne | 2010 | PFI | Tier 2/Bin 4 | MSAT-2 | 22000 | 3.9 | V-6 |
| Honda Accord | 2010 | PFI | Tier 2/Bin 5 | MSAT-2 | 24000 | 2.4 | I-4 |
| Hyundai Sante Fe | 2010 | PFI | Tier 2/Bin 5 | MSAT-2 | 18000 | 2.4 | I-4 |
| Jeep Patriot | 2010 | PFI | Tier 2/Bin 5 | MSAT-2 | 22000 | 2 | I-4 |
| Kia Forte EX | 2010 | PFI | Tier 2/Bin 5 | MSAT-2 | 25000 | 2 | I-4 |
| Mazda 6 | 2010 | PFI | Tier 2/Bin 5 | MSAT-2 | 24000 | 2.5 | I-4 |
| Mitsubishi Gallant | 2010 | PFI | Tier 2/Bin 5 | MSAT-2 | 38000 | 2.4 | I-4 |
| Cadillac STS | 2010 | GDI | Tier 2/Bin 5 | MSAT-2 | 21000 | 3.6 | V-6 |
| VW Passat | 2006 | GDI | Tier 2/Bin 5 | pre-MSAT | 103000 | 2 | I-4 |

Tested at $0^{o}$F

# Appendix C Air Conditioning Analysis Vehicle Sample

**Table C-1 Vehicle Sample for the Air Conditioning Analysis**

| Model Year | Make | Model | Vehicle Class | Weight |
|---|---|---|---|---|
| 1990 | DODGE | DYNA | CAR | 3625 |
| 1990 | NISSAN | MAXI 0 | CAR | 3375 |
| 1991 | CHEVROLET | CAVA 0 | CAR | 2750 |
| 1991 | FORD | ESCO GT | CAR | 2625 |
| 1992 | CHEVROLET | CAVA | CAR | 3000 |
| 1992 | CHEVROLET | LUMI | CAR | 3375 |
| 1992 | MAZDA | PROT | CAR | 2750 |
| 1992 | SATURN | SL | CAR | 2625 |
| 1992 | TOYOTA | CORO | CAR | 2500 |
| 1993 | CHEVROLET | CORS | CAR | 3000 |
| 1993 | EAGLE | SUMM 0 | CAR | 2500 |
| 1993 | HONDA | ACCO 0 | CAR | 3250 |
| 1993 | TOYOTA | CAMR 0 | CAR | 3250 |
| 1994 | CHRYSLER | LHS | CAR | 3750 |
| 1994 | FORD | ESCO | CAR | 2875 |
| 1994 | HYUNDAI | ELAN | CAR | 3000 |
| 1994 | SATURN | SL | CAR | 2750 |
| 1995 | BUICK | CENT | CAR | 3995 |
| 1995 | BUICK | REGA LIMI | CAR | 3658 |
| 1995 | FORD | ESCO | CAR | 2849 |
| 1995 | SATURN | SL | CAR | 2610 |
| 1995 | SATURN | SL | CAR | 2581 |
| 1996 | CHEVROLET | LUMI 0 | CAR | 3625 |
| 1996 | HONDA | ACCO | CAR | 3500 |
| 1996 | HONDA | CIVI | CAR | 2750 |
| 1996 | PONTIAC | GRAN PRIX | CAR | 3625 |
| 1996 | TOYOTA | CAMR | CAR | 3625 |
| 1997 | FORD | TAUR | CAR | 3650 |
| 1998 | MERCURY | GRAN MARQ | CAR | 4250 |
| 1998 | TOYOTA | CAMR LE | CAR | 3628 |
| 1990 | JEEP | CHER | LDT1 | 3750 |
| 1990 | PLYMOUTH | VOYA | LDT1 | 3375 |
| 1991 | CHEVROLET | ASTR 0 | LDT1 | 4250 |
| 1991 | PLYMOUTH | VOYA | LDT1 | 3750 |
| 1992 | CHEVROLET | LUMI | LDT1 | 3875 |
| 1993 | CHEVROLET | S10 | LDT1 | 2875 |
| 1994 | CHEVROLET | ASTR | LDT1 | 4750 |
| 1994 | PONTIAC | TRAN | LDT1 | 4250 |
| 1996 | FORD | EXPL | LDT1 | 4500 |
| 1996 | FORD | RANG | LDT1 | 3750 |

| Model Year | Make | Model | Vehicle Class | Weight |
|---|---|---|---|---|
| 1990 | CHEVROLET | SURB | LDT2 | 5250 |
| 1991 | FORD | E150 0 | LDT2 | 4000 |
| 1994 | FORD | F150 | LDT2 | 4500 |
| 1996 | FORD | F150 | LDT2 | 4500 |
| 1996 | DODGE | DAKO PICK | TRUCK | 4339 |
| 1996 | DODGE | D250 RAM | TRUCK | 4715 |
| 1996 | DODGE | GRAN CARA | TRUCK | 4199 |
| 1996 | DODGE | CARA | TRUCK | 4102 |
| 1996 | FORD | F150 PICK | TRUCK | 4473 |
| 1997 | DODGE | GRAN CARA | TRUCK | 4318 |
| 1997 | DODGE | DAKOT | TRUCK | 4382 |
| 1997 | PONTIAC | TRANSSPOR | TRUCK | 4175 |
| 1998 | DODGE | CARA GRAN | TRUCK | 4303 |
| 1999 | FORD | WIND | TRUCK | 4500 |