Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES2014

United States
Environmental Protection
Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

United States Environmental Protection Agency

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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
HLDT	Heavy Light 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 Data
SFTP	Supplemental Federal Test Procedure
THC	Total Hydrocarbons (FID detection)
VIN	Vehicle Identification Number
VOC	Volatile Organic Compounds

1 Introduction

The highway vehicle emission rates in the MOVES model database 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 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 is an update to the previously posted MOVES2014 report (EPA-420-R-14-012, December 2014[3]). These changes include Section 2.6, which documents the temperature adjustments for energy consumption. We have also revised the description of the development of the inspection and maintenance benefits for MOVES in Section 5.3, along with Equation 18 in that section, and have documented MOVES2014a updates to the default MOVES I/M Program inputs in Section 5.6.

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 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 NOx emissions

For the analysis of 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 NOx). The data used in these analyses are from the following sources:

Table 2-1 Summary of Data Sources

Data Source	Test	Temperatures Tested (degF)	# 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:
  http://www.epa.gov/otaq/models.htm

- **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 Effects of Temperature 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 NOx 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:

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

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

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 for the adjustment equations are stored in the MOVES database table *StartTempAdjustment*. This table contains temperature effect coefficients for each model year group and pollutant. In MOVES2010, the temperature effects for all model years used polynomial functions (Equation 2-1) and these are retained in MOVES2014 for older model year groups. Reanalyzing data from our previous test programs was outside the scope of the update for MOVES2014. For MOVES2014, we used the log-linear form for more recent model year vehicles for which we had new data, as detailed in Section 2.2.1.2. The data processing and the model fitting process differed for the polynomial and log-linear fits, and each is described separately below.

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-fueled vehicles.

2.2.1.1 *Polynomial Fits*

MOVES2014 retained the MOVES2010 coefficients for HC emissions for all pre-2006 gasoline vehicles, and for CO emissions for pre-2001 gasoline vehicles.

These coefficients 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
- 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.

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

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°, but in MOVES these coefficients are applied to all ambient temperatures < 75° F.

In MOVES2014, the CO temperature effect that MOVES2010 used for the 1994-2000 model years was applied to all model years from 1986-2000. The MOVES2010 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. (The base CO emission rates, however, are unchanged from MOVES2010, and still vary across this model year range.)

2.2.1.2 Log-linear Fits

In updating the start temperature effects for MOVES2014, we focused on the most recent model year groups and implemented an improved methodology. For the updated cold temperature effects in MOVES2014, we fit regression models to data from the ORD, MSAT and OTAQ cold temperature programs[a]. These datasets were analyzed to determine an HC temperature effect for model years 2006+ and a CO temperature effect for model years 2001+. The CO temperature effects were applied to the 2001-2005 model years 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.

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 nonintuitive behavior when fitted to the data (negative values, non-monotonically increasing

[a] 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.

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:

$$\log(\mathrm{y}) = \propto + \beta_1 \cdot Temp + Veh$$ **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:

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

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

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

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

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

Where A = β_1, and B= $e^{\alpha + 75 \cdot \beta_1}$. B is essentially the 'Base Cold Start' at 75F, with units of (g/start). The $e^{A(Temp-75)}$ term is a multiplier which increases the cold start at lower temperatures.

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:

$$Additive\ Grams = Be^{A*(T-75)} + C$$ **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 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 (α_2). No statistical 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 (α_1)	3.5502	0.1433	80	24.8	2.8E-39
Temperature (β_1)	-0.0380	0.0022	80	-17.5	4.3E-29
pre-MSAT (α_2)	0.7378	0.2066	11	3.6	0.0044
Temperature (β_1) × pre-MSAT (α_2)	-0.0003	0.0032	80	-0.1	0.9225

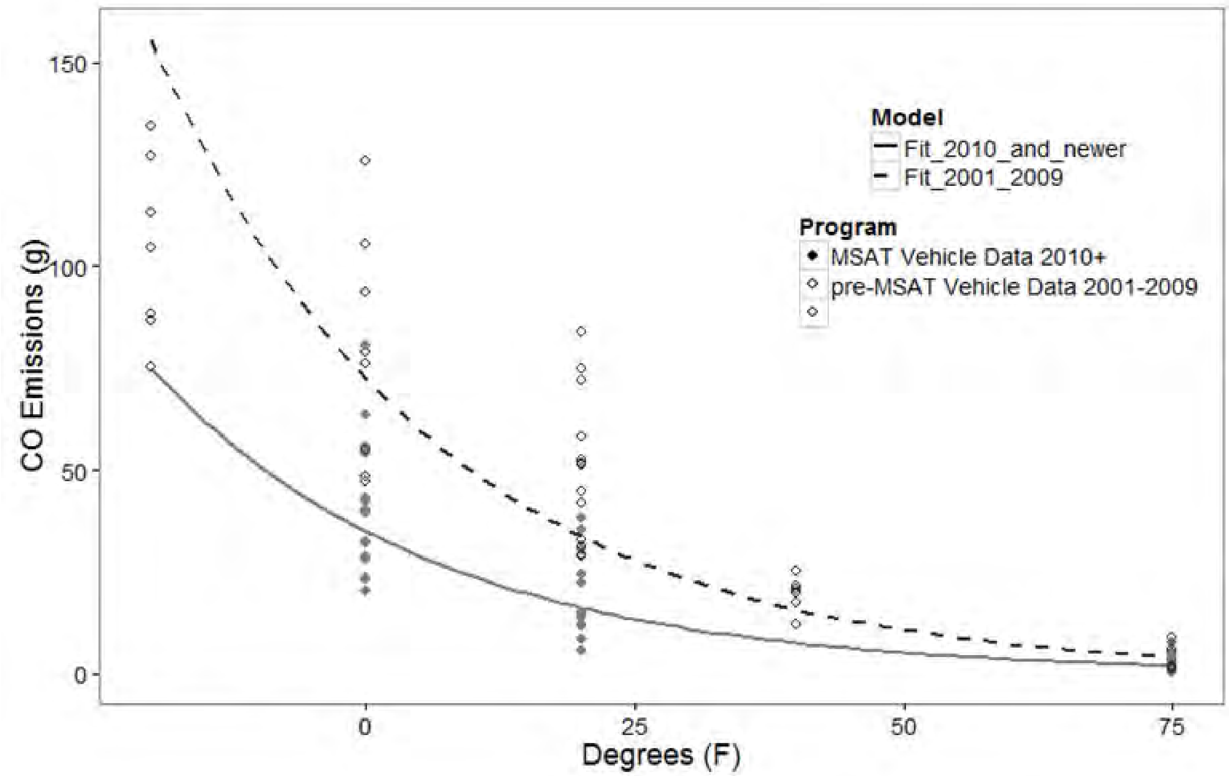
Because there was not a significant temperature effect between the pre-and post-MSAT-2 vehicles, we estimated the temperature effect (β_1) from a model fit where the pre-MSAT-2 and post MSAT-2 vehicles are pooled together as shown in Table 2-4.

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 (α_1)	0.6914	0.1400	81	4.94	4.1E-06
Temperature (β_1)	-0.038	0.0016	81	-24.08	1.1E-38
pre-MSAT (α_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



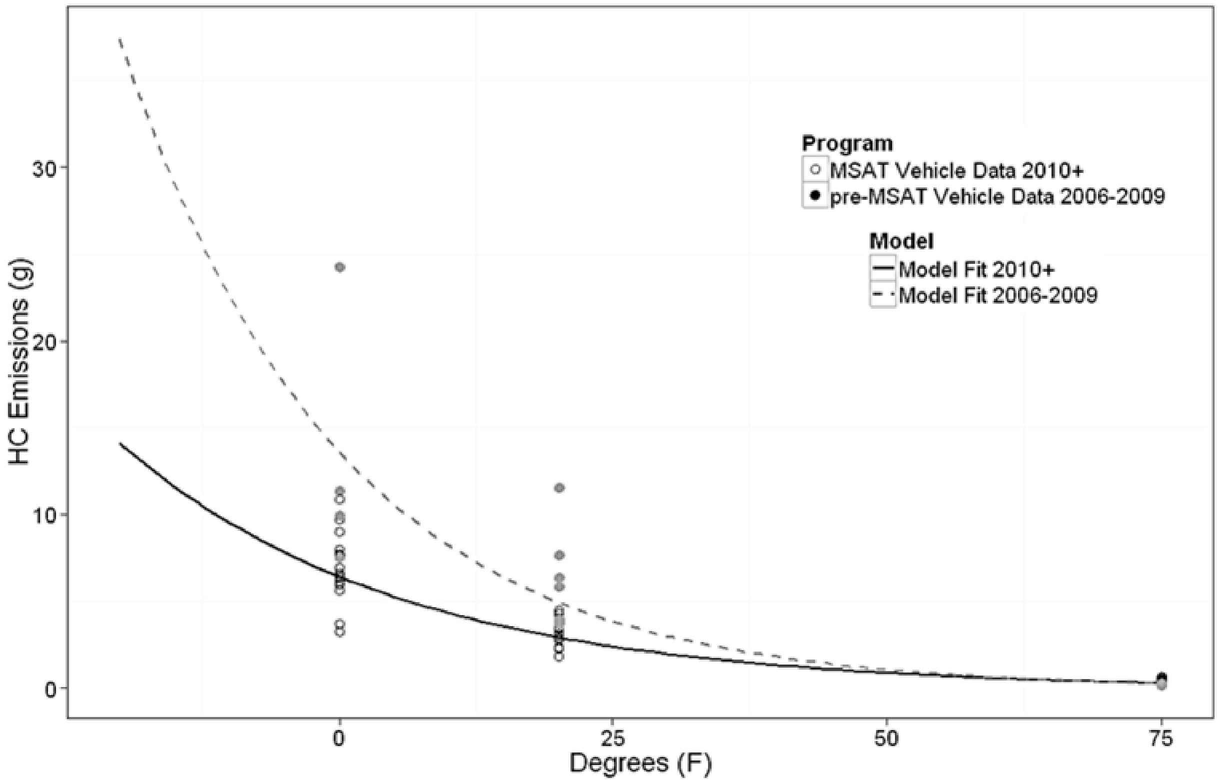
For HC emissions, a significant difference was detected in the log-linear temperature effect (β_1) between the pre-MSAT-2 and MSAT-2 compliant vehicles as shown in Table 2-5 (p-value of the Temperature × pre-MSAT term is much smaller than 0.05).

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 (α_1)	1.8613	0.1321	56	14.1	4.6E-20
Temperature (β_1)	-0.0394	0.0011	56	-34.6	1.7E-39
pre-MSAT (α_2)	0.7503	0.2254	9	3.3	0.0088
Temperature (β_1) × pre-MSAT (α_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 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 heavy light-duty trucks (HLDTs) (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, specifically:

Table 2-6 Phase-in of vehicles meeting cold weather HC standard

Model Year	LDVs / LLDTs	HLDTs / 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 MOVES database *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. HLDTS/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 HLDTs/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 MOVES2014. 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

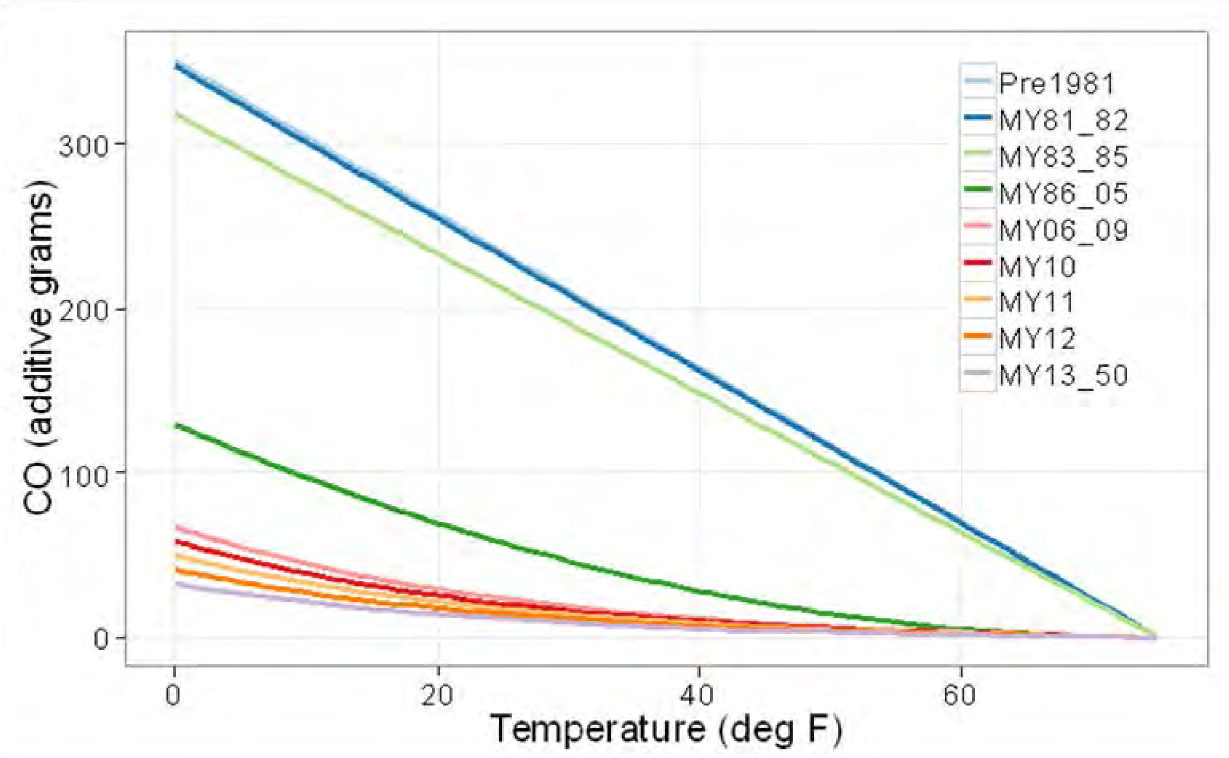
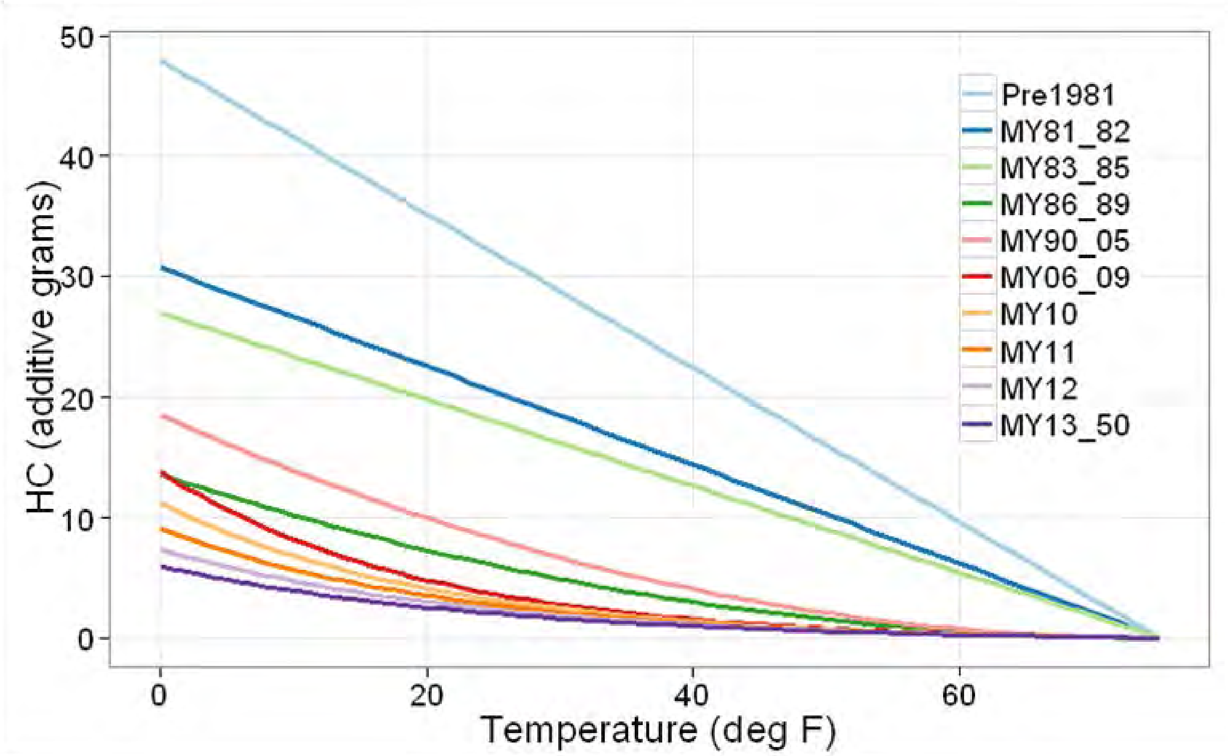


Figure 2-4 HC additive cold start temperature effects for gasoline vehicles by model year groups



2.2.2 Temperature Effects on Gasoline NOx Start Emissions

Cold-start NOx 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; NOx is favored under the lean burn, high temperature engine operation more typical of running emissions. However, NOx emissions are impacted by the inefficiencies of the three-way catalyst at low temperatures, and a small cold start temperature sensitivity is expected.

MOVES2014 applies the same NOx temperature effect as was used in MOVES2010. Due to the small temperature effects and the variability of the data, for MOVES2010, this effect was calculated by averaging all the available NOx 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 NOx emissions from the MSOD, ORD, and MSAT programs.

Table 2-8. Average incremental cold start NOx emissions by temperature for gasoline vehicles calculated from the MSOD, ORD, and MSAT programs

Temp F	Delta NOx (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:

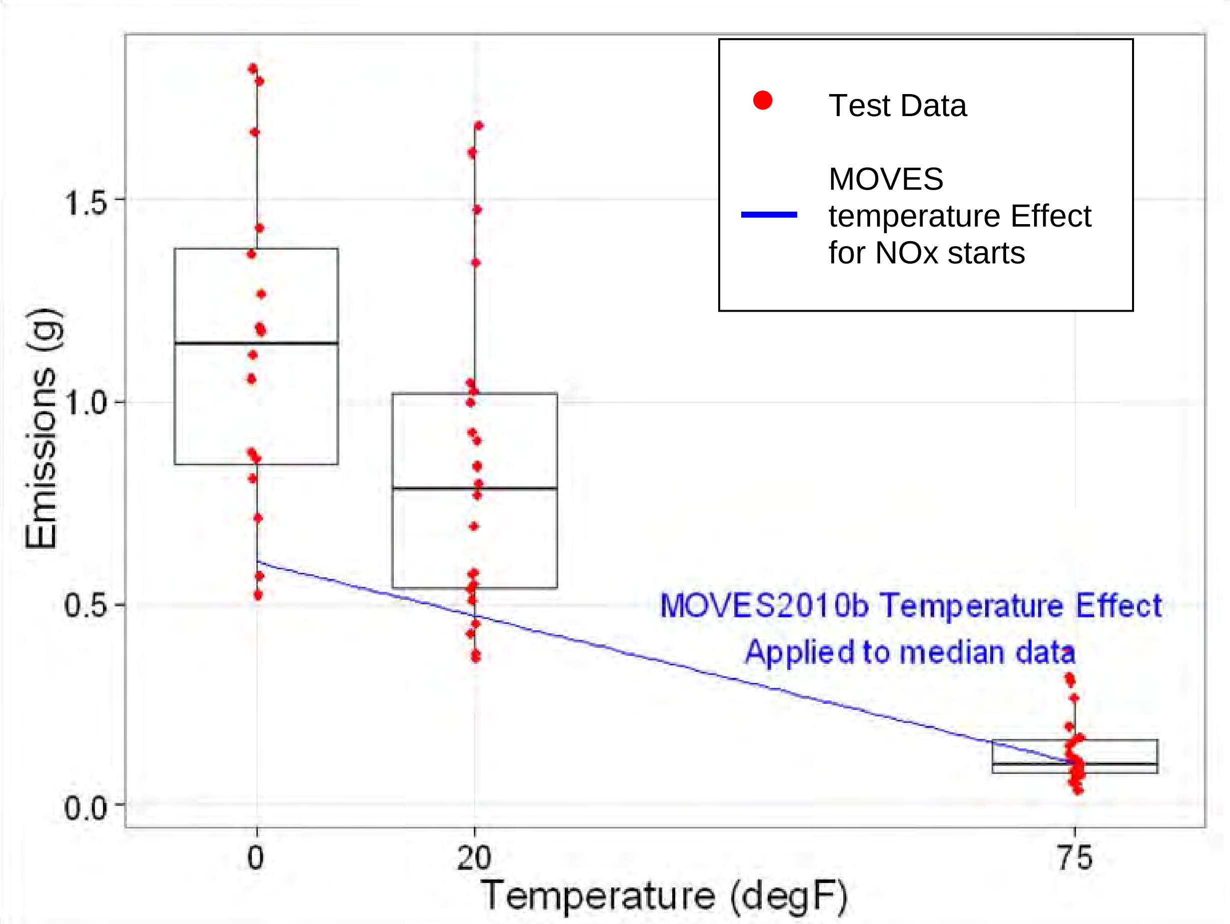
*NOx temperature additive adjustment = A * (Temp. – 75)*
where: A = -0.009 **Equation 2-8**
$R^2 = 0.61$

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 NOx emissions for temperatures greater than 75° F, while the data in Table 2-4 indicates an increase in cold-start NOx 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, for MOVES2014, we have set the NOx additive adjustment to zero for temperatures higher than 75° F.

For MOVES2014, we investigated whether the NOx temperature correction needed to be updated for vehicles subject to the MSAT-2 rule. Figure 2-5 shows a comparison between NOx start emissions data from OTAQ Cold Temperature Program (all vehicles, PFI and GDI, 2006-2010 model year vehicles) and the emissions predicted using MOVES2010 temperature effects. Because start emissions compose such a small percentage of total NOx emissions, the differences between the MOVES2010 effects and the NOx data from the OTAQ Cold Temperature Program were considered negligible. Thus we have maintained the MOVES2010 NOx temperature adjustment estimated in Equation 2-8 for all model years in MOVES2014.

Figure 2-5 FTP start NOx emissions, Bag 1 – Bag 3, model years 2006+



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 small temperature differences between the phases) as derived in the EPA report (2008[11]) and Nam et al. (2010[12]).

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

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

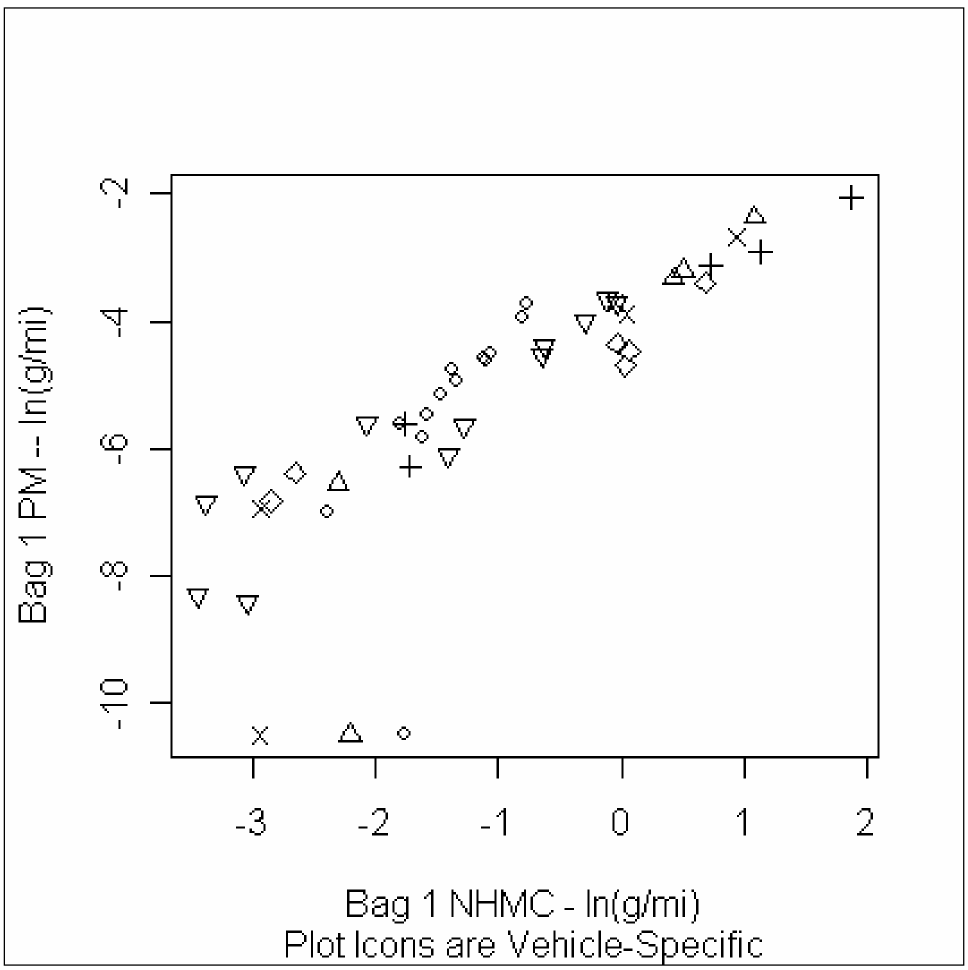
Where T= Temperature

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 that 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+) pre-MSAT-2 vehicles implies a PM increase as the temperature decreases from 72º to 20º F of:

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

Using Equation 2-10 with the information 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	HLDTs / 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	HLDTs / 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

For MOVES2014, 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 previously developed for MOVES2010 fits this data well, as shown in Figure 2-7Figure 2-7. FTP $PM_{2.5}$ start emissions, MSAT-2 compliant vehicles. Thus we have retained the PM start temperature effects estimated for the MSAT-2 rule in MOVES2014.

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)

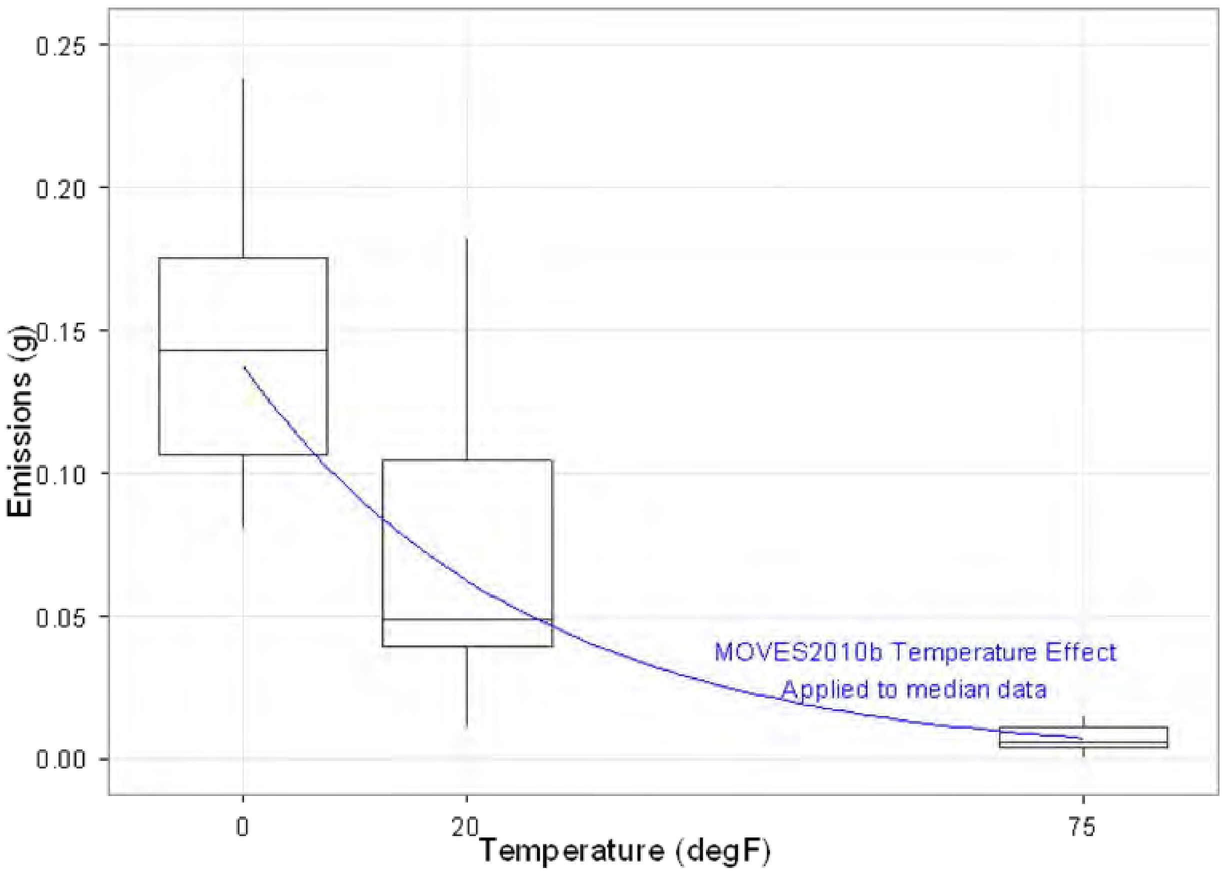
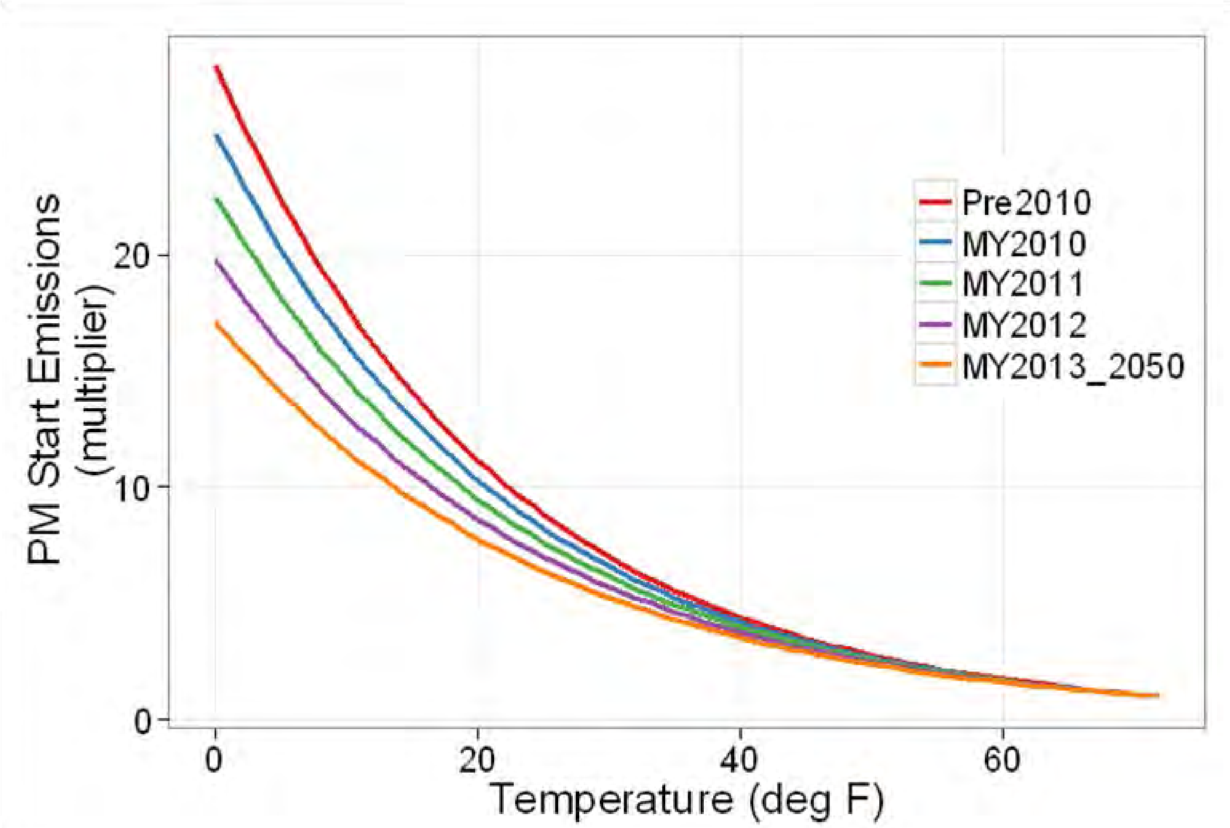


Figure 2-8 graphs the light-duty multiplicative temperature effects using the coefficient in Table 2-10, and the model form of Equation 2-9.

Figure 2-8. PM start exhaust emissions effect for gasoline vehicles in MOVES2014



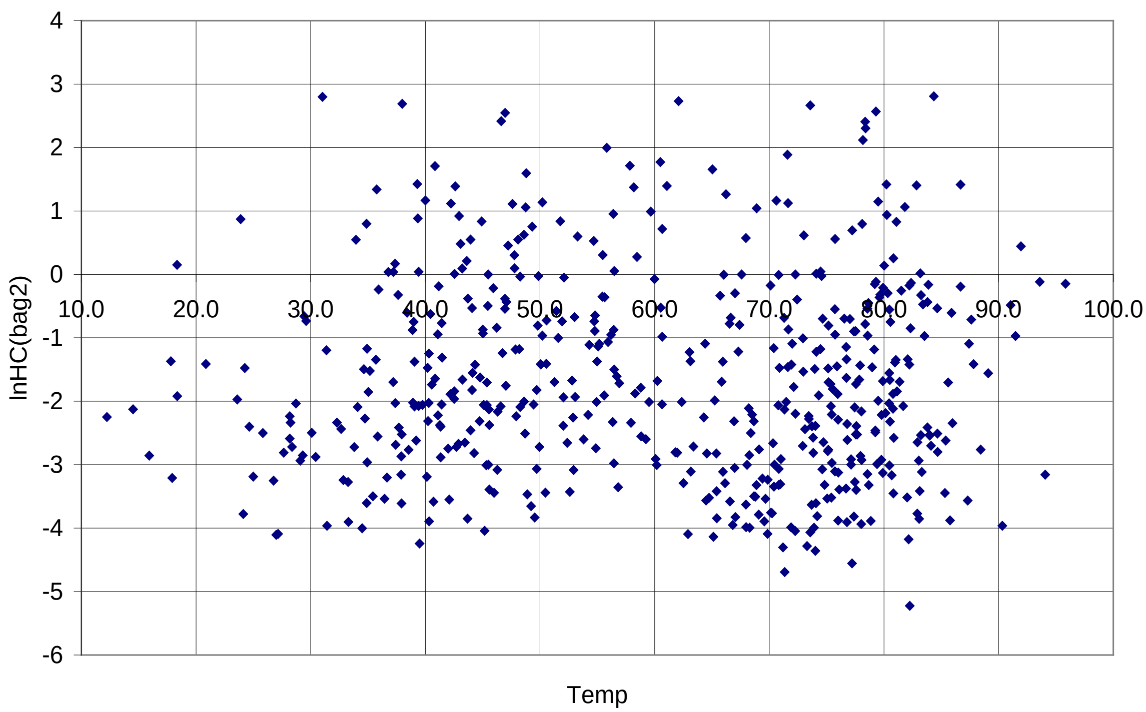
Because the $PM_{2.5}$ speciation profile for gasoline vehicles did not change significantly between the winter and summer rounds of the Kansas City Light-duty vehicle emissions study,[13] we apply the same temperature adjustment to each component of the PM emissions, including elemental carbon, organic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

2.3 Temperature Effects on Running-Exhaust Emissions from Gasoline Vehicles

2.3.1 HC, CO and NOx Running-Exhaust Temperature Effects

MOVES is designed to model temperature effects for running-exhaust for HC, CO, and NOx. However, the available data does not support a running temperature effect for any model year groups. In MOVES2010, 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 NOx. 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 EPA (2008)[11]for the data 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 this plot, 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 NOx 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 used only 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 between 5 and 95°F.

The effect of temperature on hot running HC, CO, and NOx emissions is coded in MOVES using polynomial functions as multiplicative adjustments. In MOVES2014, we continue to 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 analysis of the Kansas City data[11,12] indicated that significant ambient temperature effects exist for both start and running PM emissions. The temperature effect for hot-running conditions was estimated using the same equation as starts, but a different cold start effect, as shown in Equation 2-11:

$$\textit{Multiplicative factor} = e^{\boldsymbol{A}*(72-T)} \qquad \textbf{Equation 2-11}$$

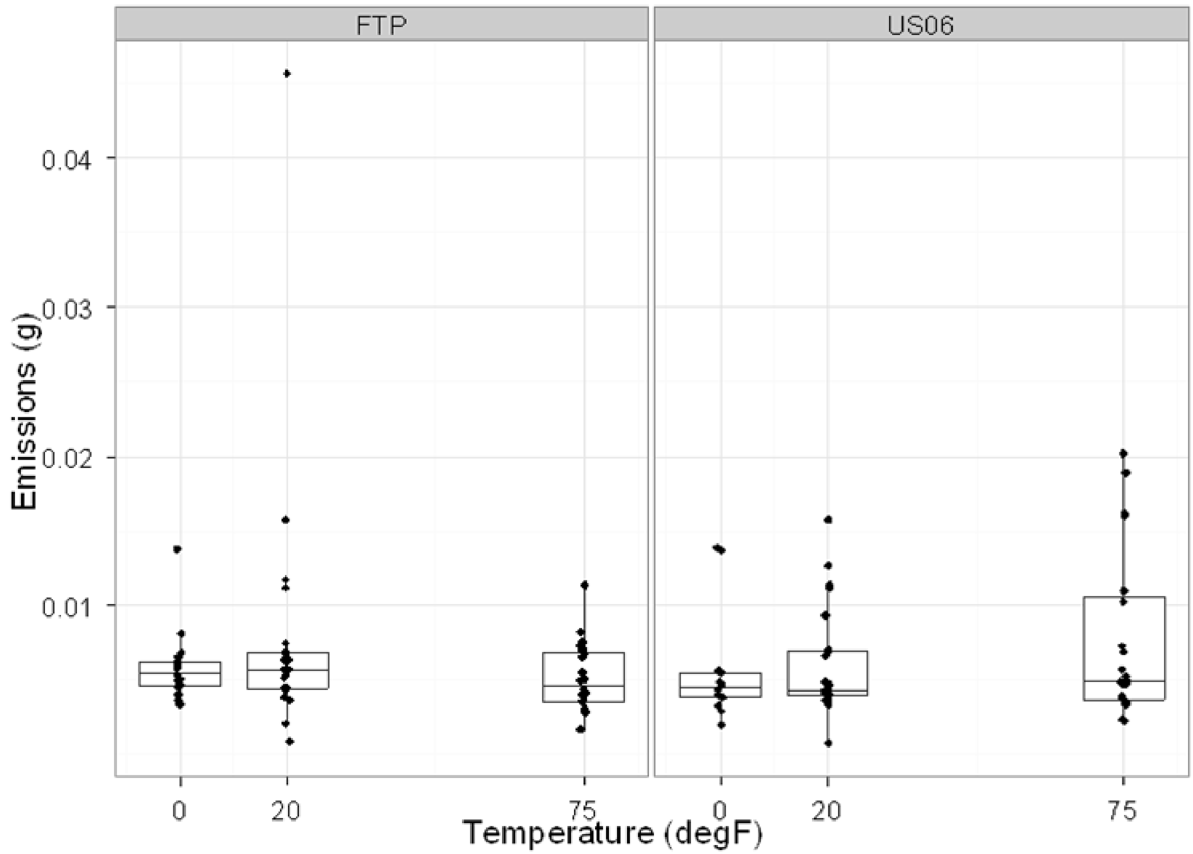
Where T = Temperature

A = temperature effect, A = 0.0318 for bag-2 from the KCVES

In MOVES2010, we applied the 0.0318 temperature effect for PM running-exhaust emissions for all model year gasoline vehicles.

For MOVES2014, we re-evaluated the PM temperature effect for running emissions for Tier 2 and MSAT-2-compliant vehicles, because our data tested on these vehicles suggested there was little impact of temperature on running PM emissions. 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. 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. This evidence suggested that for Tier 2 vehicles, PM emissions are not influenced by ambient temperature when the engines are fully warmed up.

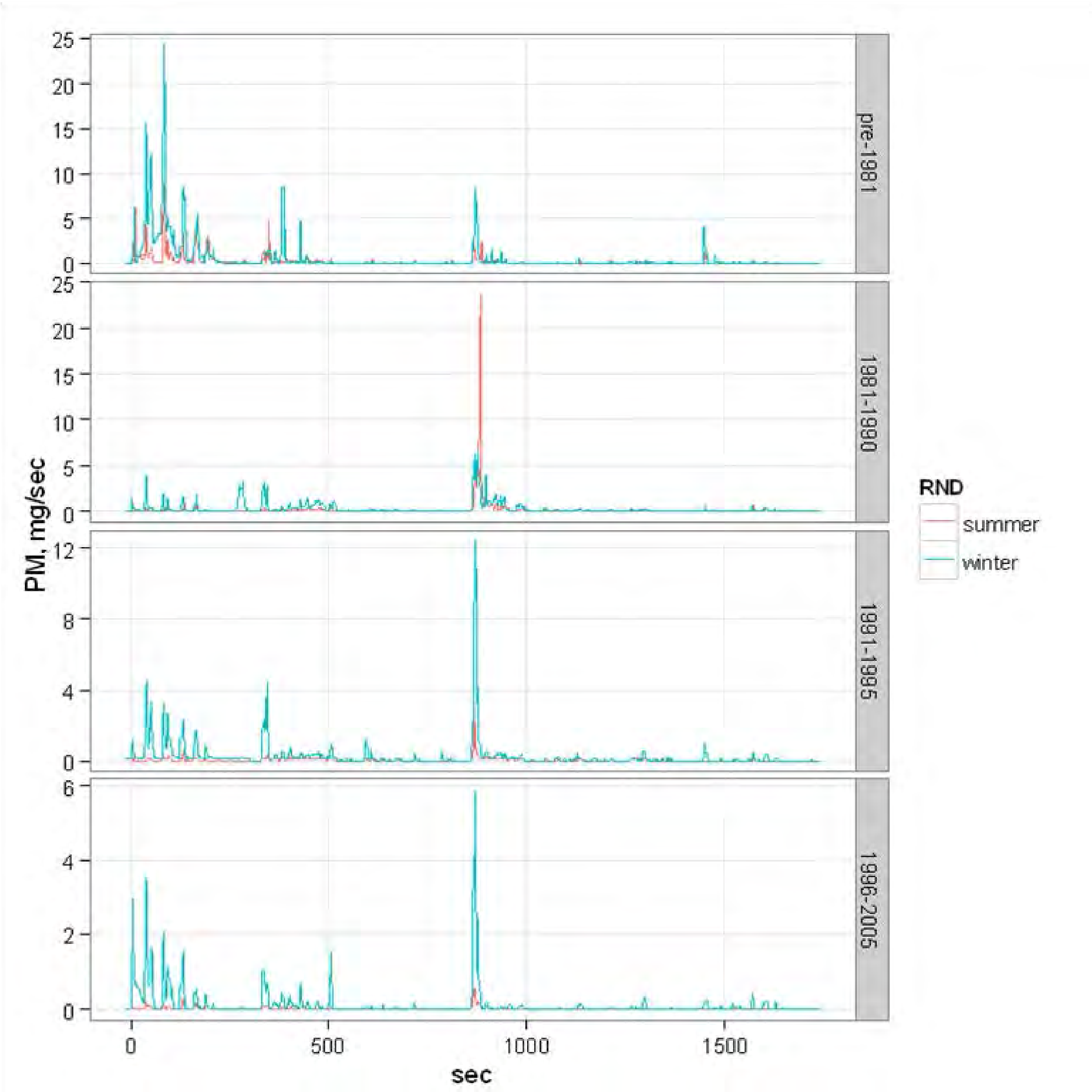
Figure 2-10. Hot-running PM Emissions measured on two Cycles (FTP Bag 2, US06) on MSAT-2 compliant MY 2010 gasoline vehicles, reported as grams/cycle.



These results contrast with the significant PM running temperature effect detected for bag 2 emissions in the Kansas City Study. We hypothesized that the temperature effect observed in the KCVES bag 2 emissions may have been due in part to the short duration of the cold-start phase of the LA92 cycle, which is only 310 sec (1.18 mi) in length. In contrast, the cold-start phase of the FTP, used in the more recent studies, is 505 seconds (3.59 miles) in length. Bag 1 of the LA92 is also a considerably "milder" drive schedule in terms of accelerations, than bag 1 of the FTP, thus giving less opportunity for the engine and catalyst to obtain more optimum temperature regimes to avoid PM formation. One interpretation of the trend observed in the Kansas City results is that vehicles were not fully conditioned at the end of the first phase of the LA92. The implication is that emissions observed in the early portion of the hot-running phase could have reflected "start" rather than "running" emissions, which could have explained the apparent presence of a temperature effect for hot-running emissions. Similarly, Mathis et al. (2004) did not observe a temperature effect on PM emissions from running emissions for two modern three-way catalyst equipped port-fuel injected (PFI) vehicles tested in a laboratory at +23, -7, and -20°C[14].

To evaluate this hypothesis, we re-analyzed the continuous (second-by-second) data from the Kansas City program. Three sets of time series were considered, including second-by-second measurements of PM (DustTrak measurements normalized to the Teflon filter measurements), black carbon (photoacoustic analyzer) and hydrocarbon emissions (flame ionization detector). The second-by-second measurements were analyzed to evaluate whether an effect of ambient temperature could be observed only during the first portion of hot-running phase in the LA92. An aggregate time series for PM emissions, averaged for the set of paired measurements (20 vehicles measured in both the summer and winter) are graphed in Figure 2-11. Except for model-year group 1981-1990, the winter time measurements are noticeably higher than the summer measurements even beyond 1,000 seconds.

Figure 2-11 Second-by-second average $PM_{2.5}$ emissions for paired vehicle tests in the KCVES.



We fit log-linear models (of the form of Equation 2-3) to test the statistical significance of temperature on the log of PM emissions for bag 1, bag 1 + bag 2, and varying segments of each of the bags. The estimated temperature effect (β_1) are shown in Table 2-11 for both a pooled sample (419 vehicles), and the paired sample (20 vehicles). The pooled data includes all the vehicles measured in Kansas City that had valid second-by-second measurements. All the temperature effects were statistically significant (p-value <0.05), except for the tests noted with asterisks. The statistical models confirm the observations made in Figure 2-11. The temperature effect is largest for the segment of emissions closest to the cold start (bag 1), and decreases as the engine warms up with time. However, the PM emissions in bag 2 were influenced by temperature even after removing the first 570 seconds (bag 2 >570 s) and first 1,025 seconds (bag 2 >1,025 s)..

Table 2-11 Log-linear temperature effect (β_1) measured in the KCVES

	PM		BC		HC	
Model	**pooled**	**paired**	**pooled**	**paired**	**pooled**	**paired**
bag 1	-0.047	-0.051	-0.047	-0.050	-0.018	-0.020
bag 1 + bag 2 < 570 s	-0.039	-0.048	-0.045	-0.049	-0.017	-0.019
bag 1+bag 2	-0.029	-0.041	-0.036	-0.044	-0.014	-0.017
bag 2	-0.020	-0.035	-0.015	-0.033	-0.003 **	-0.006
bag 2 > 570 s	-0.017	-0.032	-0.012	-0.030	-0.001**	-0.004**
bag 2 >1,025 s	-0.008	-0.020	-0.004**	-0.022	-0.003**	-0.005*

*p-value > 0.05 ,** p-value >0.10

The re-analysis of Kansas City study suggested that, as suspected, much of the running temperature effect apparent in bag 2 is due to the short warm-up in bag 1 of the LA-92. However, it also showed that a temperature effect on bag 2 emissions persists even after 1,025 seconds (17 minutes) of operation on the LA-92 cycle. One of the difficulties in reconciling the results from the cold temperature PM test programs is that both the driving cycles and the vehicle technologies differ between test programs (i.e. driving cycle and vehicle technologies are confounding variables). This makes it difficult to determine if the differing temperature effects observed for running conditions are due to technology differences, driving cycle, or both.

Based on the available data, in MOVES2014, we have retained the PM running temperature effect estimated from Kansas City for all 2004-and-earlier model year vehicles. This step was taken for several reasons:

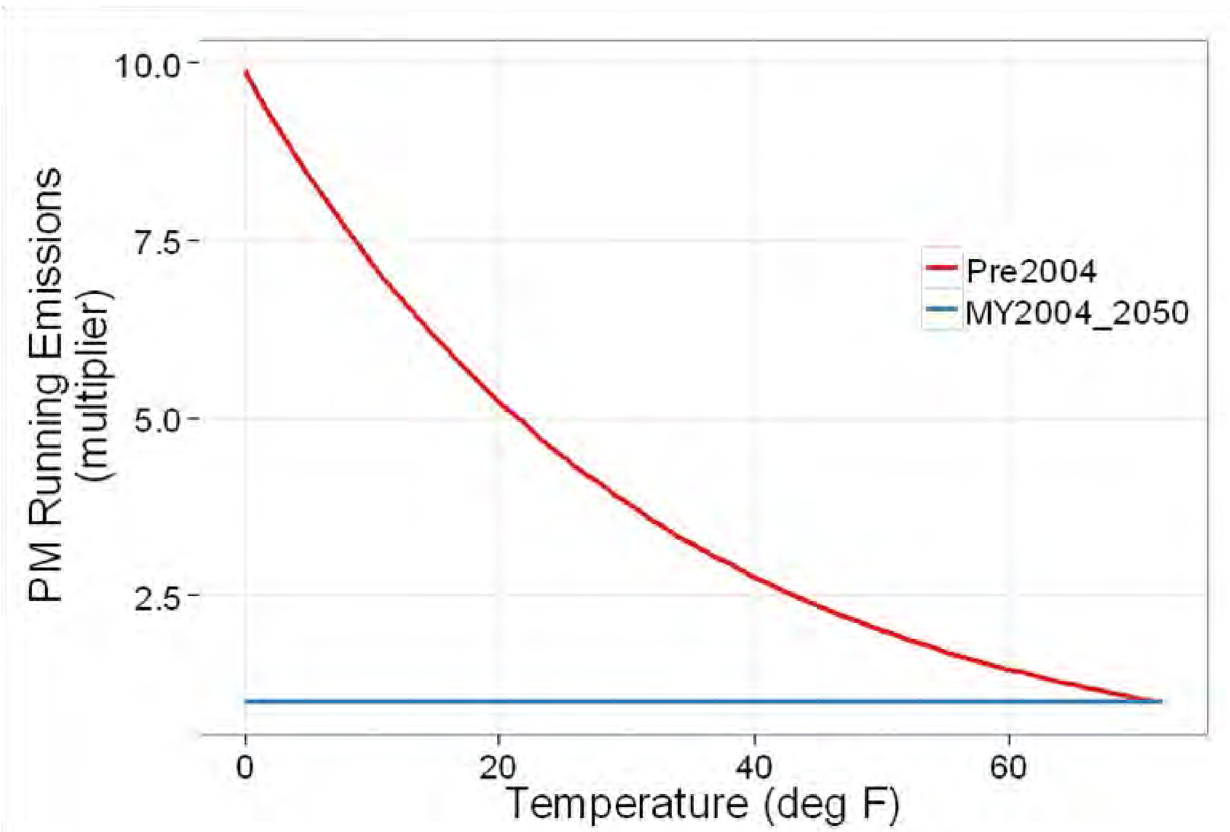
1. Kansas City was conducted in 2004/2005 and includes measurements from 1960's era vehicles to 2005 model year vehicles. The temperature effect estimated in MOVES is applicable to the vehicle technologies tested in Kansas City. Kansas City only tested a few 2005 vehicles, none of which were compliant with the Tier 2 standards.
2. A large portion of the PM running temperature estimated in Kansas City appears to be due to the short length of bag 1 in the LA-92 cycle. However, the temperature effect was found to still be significant at the end of bag 2. The trip length for light-duty gasoline vehicles used in MOVES ranges from 2 to 9 miles. This length is less than the combined length of bag 1 and bag 2 of the LA-92 (9.81 miles). Therefore, we believe that retaining the running temperature effect in MOVES will not lead to an overestimation of PM emissions for typical emission inventories.

For 2005-and-later model year vehicles, we removed the running temperature effect. This step was taken for the following reasons:

1. The available data on Tier 2 light-duty gasoline vehicles did not show a temperature effect on bag 2 of the FTP cycle or the US06. Because the light-duty gasoline phase-in of Tier 2 standards began with model year 2005, we have removed the running temperature effect for 2005 and later model year vehicles.
2. MOVES PM start effects used to model the Tier 2 MSAT-2 vehicles provides a relatively good fit to the start emission data as shown in Figure 2-7. We appear to be capturing the magnitude of PM emissions from the cold start and associated warm-up period from these vehicles with the cold start temperature effects alone.

Figure 2-12 displays the temperature adjustments for running exhaust particulate matter emissions from gasoline vehicles in MOVES.

Figure 2-12. PM running exhaust emissions effect for gasoline vehicles in MOVES2014



2.4 *Effects of Temperature on Diesel Fueled Vehicles*

2.4.1 HC, CO and NOx Temperature Effects for Diesel Vehicles

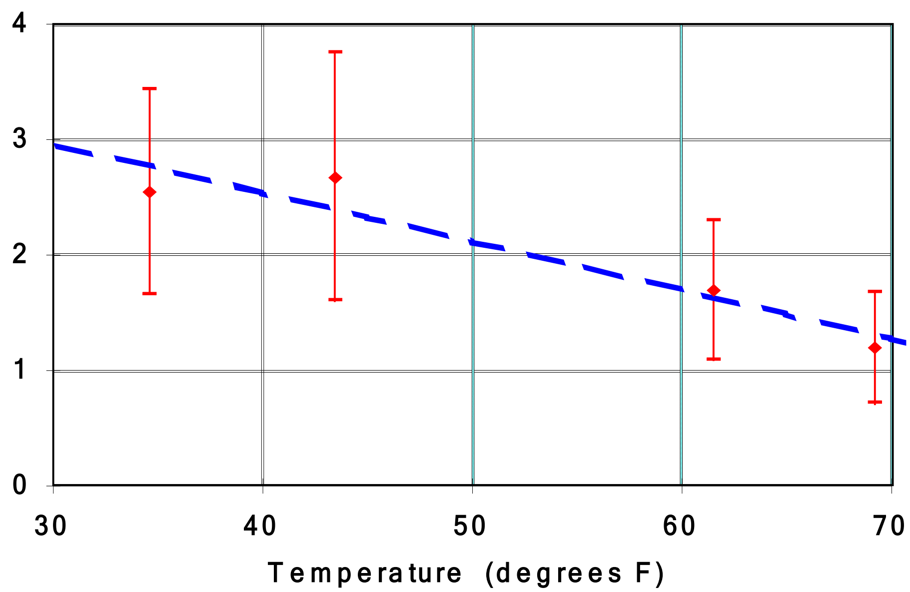
We were able to identify only 12 diesel-fueled vehicles with FTP tests at multiple temperatures (nine passenger cars and 3 light-duty trucks). However, only two of those 12 vehicles were tested at temperatures within the normal FTP range (68º to 86º F). None of these diesel trucks were equipped with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

When we plotted the mean HC start emissions (above) versus temperature, we obtained the following graph (where the vertical lines represent 90 percent confidence intervals and the "dashed" line represents a linear regression through the data).

Figure 2-13 Mean light-duty diesel cold-start HC emissions (in grams) with 90% confidence intervals vs temperature.



The dashed (blue) line in Figure 2-13 is a linear regression line having as its equation:

$$HC = (-0.0421 * Temperature) + 4.22 \qquad R^2 = 0.90$$ **Equation 2-12**

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

$$\text{HC additive temperature adjustment} = A * (\text{Temp.} - 75)$$
$$\text{where: } A = -0.0421$$ **Equation 2-13**

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.

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

Figure 2-14 Mean light-duty diesel cold-start CO emissions (in grams) with 90% confidence intervals vs temperature

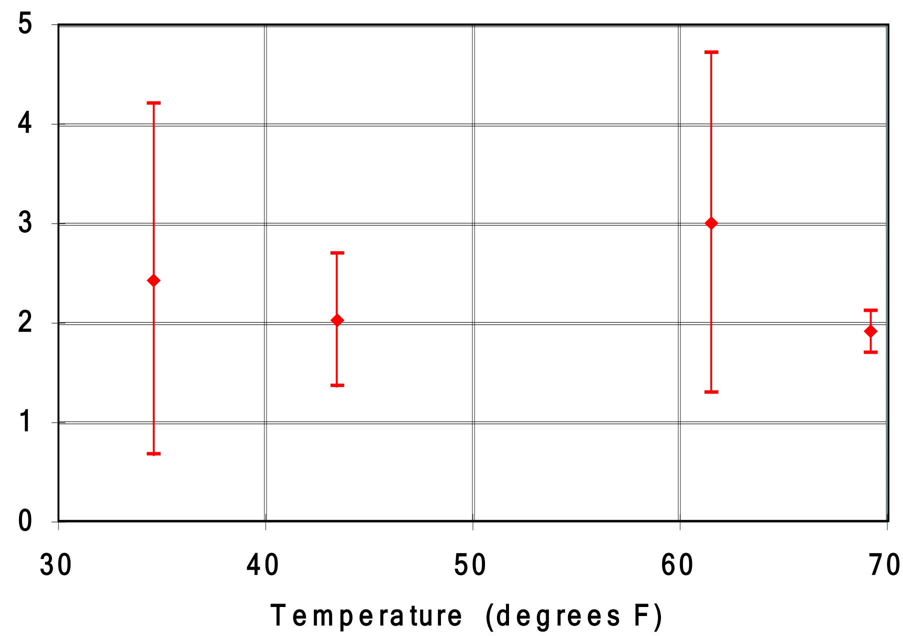
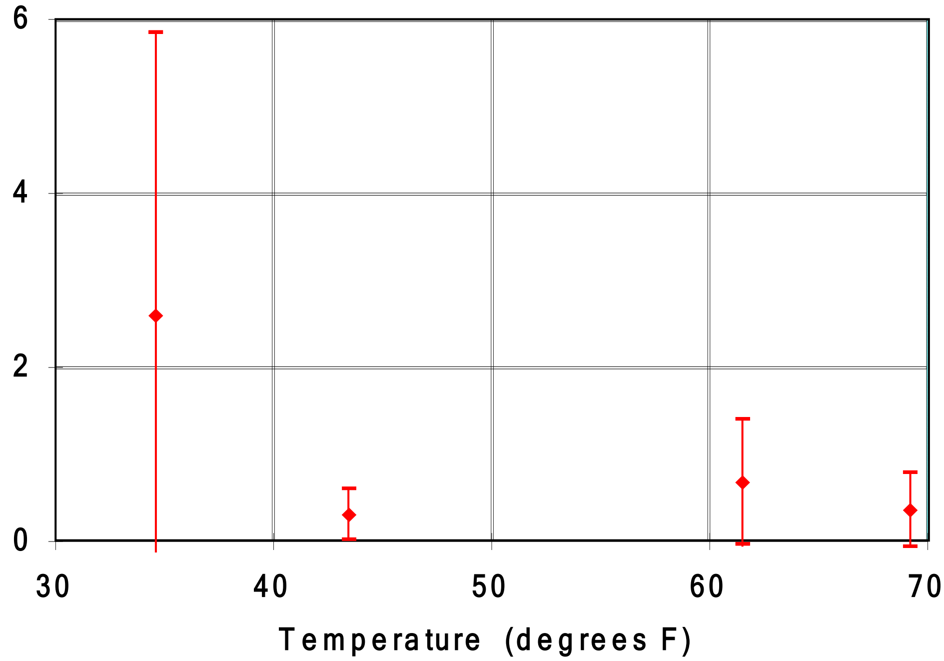


Figure 2-15 Mean light-duty diesel cold-start NOx emissions (grams) with 90% confidence intervals vs temperature



Statistical analyses of both the diesel cold-start CO and NOx emissions failed to produce coefficients that were significantly different from zero. Therefore, for both cold-start CO and NOx adjustments from diesel-fueled vehicles, we propose to 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 NOx. 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. Similar to light-duty vehicles, all other temperature effects 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 after-treatment devices (such as diesel particulate filters or oxidation catalysts) that are now required to meet current emission standards.

2.4.2 PM Temperature Effects for Diesel Vehicles

MOVES2014 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. (2004[14]) 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˚C. The researchers measured an increasing trend in particle mass emissions (g/start) from the conventional diesel vehicle at colder temperatures, but 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[15]) also reported significant increase in PM start emissions from a light-duty diesel engine tested in a laboratory at +20 and -20C. 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[16,17], 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.

2.5 Compressed Natural Gas Temperature Effects

MOVES2014 currently models emissions from compressed natural gas used to fuel transit buses. However, no data were available on temperature impacts of compressed natural gas emissions. As discussed in the heavy-duty report, the start emissions for CNG emissions for HC, CO, NOx, and PM are set equal to diesel start emissions. We also applied the same temperature adjustments to CNG as diesel, which only includes 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.[18] 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 2-14, 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.[7,21]

$$\begin{aligned} &\mathit{Multiplicative\ temperature\ adjustment} \\ &\qquad = 1.0 + \mathit{tempAdjustTermA} \times (\mathit{temperature} - 75) \\ &\qquad + \mathit{tempAdjustTermB} \times (\mathit{temperature} - 75)^2 \end{aligned} \tag{Equation 2-14}$$

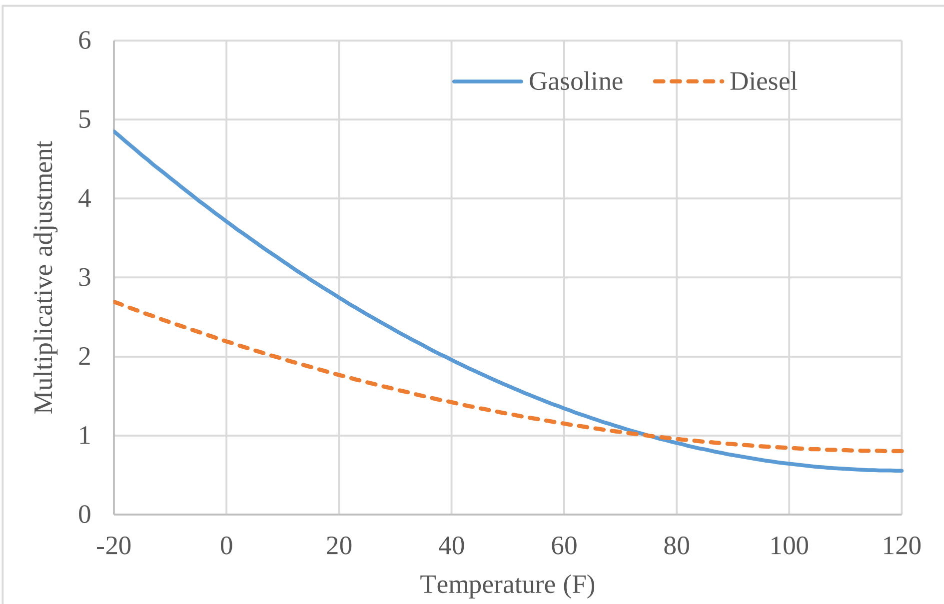
Table 2-13 displays the coefficients used to adjust start energy consumption for gasoline, E85, diesel, and CNG fueled-vehicles. The temperature coefficients are stored in the MOVES temperatureadjustment table by pollutant, emission process, fuel type, and model year range. E85 fueled vehicles use the same energy adjustments as gasoline vehicles, because they also use the same energy rates as comparable gasoline-fueled vehicles.[19] CNG vehicles (CNG transit buses) use the same adjustments as diesel vehicles, because they use the same energy start rates as comparable diesel transit buses.[7]

Table 2-13. Multiplicative temperature eoefficients 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 2-16 displays the multiplicative temperature adjustments for starts as a function of temperature used in MOVES2014. At 75°F, the multiplicative adjustment is 1. Gasoline fueled-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 2-16. Multiplicative temperature adjustments for starts from energy consumption as a function of ambient temperature.



2.7 Conclusions and Future Research

The temperature adjustments within MOVES have a significant impact on the emissions estimated for gasoline vehicles. The OTAQ Cold Temperature program was an important study to evaluate, validate, and update the temperature sensitivities in MOVES for modern vehicles. Based on our evaluation of the study, we updated the temperature emission effects for HC and CO starts, and removed the PM running-exhaust temperature effect for Tier 2 compliant vehicles.

We recognize that the current temperature effects in MOVES have limitations. Additional studies/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 gasoline direct injection, stop-start technologies and hybrid technologies

3 Humidity Adjustments

Water in the air cools the peak combustion temperature and lowers NOx emissions. MOVES adjusts both gasoline and diesel vehicle exhaust NOx emissions to account for humidity.

3.1 Humidity Adjustment Equation

In MOVES, the base exhaust emission rates for NOx in all modes and all processes are multiplied by a humidity adjustment. This factor is calculated using the following formula:

$$K = 1.0 - ((\text{Bounded Specific Humidity} - 75.0) * \text{Humidity Correction Coefficient})$$

Equation 3-1

The bounded specific humidity is in units of grains of water per pound of dry air. The specific humidity is not allowed to be lower than 21 grains and is not allowed to be larger than 124 grains. If the specific humidity input exceeds these limits, the value of the limit is used to calculate the humidity adjustment. Appendix B shows how the hourly relative humidity values are converted to specific humidity used in this equation using temperature and barometric pressure.

Table 3-1. Humidity correction coefficients used by MOVES

Fuel Type	Humidity Correction Coefficient
Gasoline	0.0038
Diesel Fuel	0.0026

The diesel humidity correction coefficient is derived from the Code of Federal Regulations[20]. The gasoline humidity correction coefficient is carried over from the coefficient used in the MOBILE6 model.

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 emission control technologies impact the humidity effect.

4 Air Conditioning Adjustments

The air conditioning (A/C) effects described below, and incorporated in MOVES2014 were originally derived for MOVES2010. No changes to air conditioning calculations and parameters were made for MOVES2014, 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 significant 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 MOVES2014 Greenhouse Gas and Energy Consumption Rates Report[21], 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 ambient conditions 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 results 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, NOx and energy consumption. The impact of A/C on particulate matter has not been evaluated for MOVES. MOVES currently has no air conditioning effect for PM emissions.

MOVES adjusts total energy consumption and exhaust running HC, CO and NOx emissions separately for each operating mode. MOVES models A/C effects for criteria pollutants (HC, CO and NOx) only for passenger car, passenger truck and commercial light truck source types. Energy consumption is affected for all source types. The same adjustment values are used for all source use types affected within a pollutant type.

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 should 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 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 quality controlled checked.

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, heavy 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 nice balance between different test cycles, and cars and trucks. Unfortunately, the study does not contain any pre-1990 or post-1999 model years. A complete list of the individual vehicles and a basic description is shown in Appendix C.

Only vehicles which were coded as having an emission test with the A/C system on were selected. 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 contains the distribution of test-cycles analyzed. A definition of the test-cycles is included in a MOBILE6 report.[22]

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 NOx) 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 NOx 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 NOx

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
NOx	Braking / Decel	0	1.0000	0.19366
NOx	Idle	1	6.2601	0.09108
NOx	Cruise / Accel	11 - 40	1.3808	0.10065

Note the higher air conditioning effect for NOx at idle. These results are consistent with those obtained from Nam et al. (2000)[23] who showed that at low load conditions, A/C greatly increased NOx 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 VSPBin (see above). A mean value was computed for each combination of VSPBin. 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 VSPBin. 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 VSPBins 26 through 29 and VSPBins 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 VSPBins. 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 as the overall power demand of the engine is increased. In fact, in some vehicle designs the A/C unit will be shut off by an engine controller if the driver demands a very high level of power from the vehicle. In the future, EPA hopes to re-evaluate the assumption of a constant A/C factor for the high VSPBins.

For HC, CO and NOx, 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 NOx Idle mode, a fairly large multiplicative adjustment of 6.2601 was obtained. This large factor reflects the relatively low levels of NOx 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

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[24]) of the air outside their vehicles. These

MOVES defaults are documented in the Population and Activity report.[25]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.

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. Since these programs are location specific, there is great variability 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.[26]

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). 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.

$$Standard\ IM\ Difference = E_{nonIM} - E_{IM}$$ **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 virtually all of the underlying data for MOVES 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,

$$E_p = RE_{IM} + (1 - R)E_{nonIM}$$ **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

$$R = \frac{E_p - E_{nonIM}}{E_{IM} - E_{nonIM}}$$ **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 decided to develop 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 utilized. 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 is then calculated from the mean emission results from these two runs and the non-I/M case. Equation 5-4 illustrates the formula, which was derived in the previous section as Equation 5-3.

$$R = \frac{(E_p - E_{nonIM})}{(E_{IM} - E_{nonIM})} \qquad \textbf{Equation 5-4}$$

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 NOx.

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).

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. It may vary from 0 to 1.0 where zero would represent a totally failed program and 1.0 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. Most default IMCompliance factors are greater than 90 percent.

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.

$$IMAdjustFract = (IMFactor * ComplainceFactor * 0.01)$$ **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.

$$TargetRate = IMRate * IMAdjustFract + NonIMRate * (1.0 - IMAdjustFract)$$ **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 each the I/M compliance factor 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 model year information as a model year range (beginning and ending model year), the frequency of inspection (annual, biennial and continuous/monthly), test type (Idle, IM240, ASM, OBD-II) and 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
- Ignore I/M toggle (user control variable)
- Compliance Factor

A full update to the IMCoverage table was beyond the scope of MOVES0214. Much of the data in the default IMCoverage table is out of date. 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.

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.

Table 5-2 I/M Coverage table data sources

NMIM Data Source	MOVES I/M Coverage Parameter
MOBILE6 Compliance Rate	Used in the MOVES Compliance Rate Calculation
I/M Cutpoints	Used to determine MOVES I/M Test Standards
MOBILE6 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
MOBILE6 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. Extraction and processing of the MOBILE6.2 inputs for all of the individual states was required. 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. Equation 5-7 shows the relationship.

$$C = M6ComplianceRate * M6EffectivenessRate * (1 - M6WaiverRate$$ **Equation 5-7**

MOVES does not have separate inputs for the effect of waivers on I/M benefits. Section 3.10.6.2 of the technical document for MOVES2010[27] describes how to calculate the MOVES compliance rate to include the effect of waivers. An updated version of this report will be published for MOVES2014.

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

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

The IMCoverage table default parameters for calendar year 2011 and later were updated for MOVES2014 using the IMCoverage tables from the county databases (CDBs) provided to EPA for the 2011 National Emission Inventory (NEI) project[28] (Version1). A CDB was created for every county in the nation containing an IMCoverage table. 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 later 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 State of Georgia provided a complete set of I/M program descriptions for their 13 counties with I/M programs for all calendar years 1999 through 2050 after the NEI. These changes were also included in the update.

For MOVES2014a, all of the I/M program descriptions were further 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 were left between model years without coverage. This check also looked for cases where the coverage beginning model year occurs 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[29] to resolve conflicts. The county coverages in some states was also changed for some calendar years.

The counties with coverage changes are:

- Six Florida counties (12011, 12031, 12057, 12086, 12099 and 12103) were removed for all calendar years.
- Three Louisiana counties (22005, 22047, and 22063) were removed for all calendar years.
- Three Texas counties (48071, 48291 and 48473) were removed for all calendar years.
- One Minnesota county (27171) was removed for all calendar years.
- One Pennsylvania county (42073) was removed for all calendar years.
- Two Colorado counties (8041 and 8097) were removed from all calendar years.
- Four Kentucky counties (21015, 21037, 21111 and 21117) were removed for 2006 and later calendar years.
- One Alaska county (2090) was removed for 2010 and later calendar years.
- Seven Colorado counties (8001, 8005, 8013, 8014, 8031, 8035, 8059) were populated with new I/M data for 2011 and later calendar years.
- Two Colorado counties (8069 and 8123) were replaced with a copy of the (new) 2015 and later calendar year coverage from county 8001. All previous calendar year I/M was removed for these counties.
- Thirteen Georgia counties (13057, 13063, 13067, 13077, 13089, 13097, 13113, 13117, 13121, 13135, 13151, 13223 and 13247) were populated with new I/M data for 1999 and later calendar years from the GA_2002.imcoverage table provided by Georgia.
- 40 California counties were populated with new I/M data for 2011 and later calendar years.
  (6001, 6007, 6011, 6013, 6017, 6019, 6021, 6029, 6031, 6037,
  6039, 6041, 6047, 6053, 6055, 6057, 6059, 6061, 6065, 6067,
  6069, 6071, 6073, 6075, 6077, 6079, 6081, 6083, 6085, 6087,

6089, 6095, 6097, 6099, 6101, 6103, 6107, 6111, 6113, 6115)In addition to the updates in the I/M program descriptions, all of the counties were altered 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. MOVES2014a does not offer any benefits from inspection programs to detect liquid fuel leaks.

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Appendix A 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°F

Appendix B   Calculation of Specific Humidity

Equations to convert relative humidity in percent to specific humidity (or humidity ratio) in units of grains of water per pound of dry air (ref. CFR section 86.344-79, humidity calculations).

Inputs:

T_F is the temperature in degrees F.

P_b is the barometric pressure.

H_{rel} is the relative humidity

$$T_K = \left(5/9\right)\left[T_F - 32\right] + 273$$

$$T_0 = 647.27 - T_K$$

$$H_{ratio\ or\ specific\, humidity} = 4347.8 * P_V / (P_b - P_V)$$

$$P_V = \left(H_{rel}/100\right) P_{db}$$

$$P_{db} = 29.92 * 218.167 * 10^{\left(-T_0/T_K\right)\left[\frac{\left(3.2437 + 0.00588 T_0 + 0.0000000117 T_0^3\right)}{1 + 0.00219 T_0}\right]}$$

$$= 6527.557 * 10^{\left(-T_0/T_K\right)\left[\frac{\left(3.2437 + 0.00588 T_0 + 0.0000000117 T_0^3\right)}{1 + 0.00219 T_0}\right]}$$

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

Model Year	Make	Model	Vehicle Class	Weight
1994	PONTIAC	TRAN	LDT1	4250
1996	FORD	EXPL	LDT1	4500
1996	FORD	RANG	LDT1	3750
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

Appendix D Response to Peer Review Comments on Chapter 2: Temperature Adjustments

This section provides a verbatim list of peer reviewer comments submitted in response to the charge questions for Chapter 2 (Temperature Adjustments), and includes EPA responses to the peer-review. The other chapters of the report (Humidity adjustments, Air Conditioning Adjustments, and Inspection and Maintenance Adjustments) document areas that did not have major changes for MOVES2014 and thus were not subject to another round of peer-. To view the peer-review for those sections, please see the MOVES2010 Report.[30]

D.1 Adequacy of Selected Data Sources

Does the presentation give a description of selected data sources sufficient to allow the reader to form a general view of the quantity, quality and representativeness of data used in the development of emission rates? Are you able to recommend alternate data sources might better allow the model to estimate national or regional default values?

D.1.1 Dr. Chris Frey

The report appears to deal with the best available data sources as of the time that it was drafted. The main difficulty with the current draft is the lack of sufficient specification/description of the selected data and adequate or sufficient explanation in some cases of how it was used or interpreted. See detailed comments for specifics.

> *RESPONSE: A tabular summary of data sources has been added (Table 2-1) to assist the reader in understanding the details of particular test programs. We have also improved the explanation of how the data was used.*

D.1.2 Dr. Joe Zietsman

The description of the data sources is adequate and I am not aware of others that may be more suitable. The limitations of the data, specifically with regard to the age of the datasets, have been acknowledged in the report. There is clearly a need for more extensive and current data.

Specifically with regard to Section 2.1, it would help to better describe what data was used for the analysis of start emissions versus the validation. Also it wasn’t clear if the data used was based on testing conducted in controlled test chambers, or just based on measured ambient/intake air temperatures, or is a mix of both types of data.

> *RESPONSE: A tabular summary of data sources has been added (Table 2-1) to address any shortcomings in the descriptions of test procedures. We have also clarified whether the temperature was controlled or ambient.*

D.2 Clarity of Analytical Methods and Procedures

Is the description of analytic methods and procedures clear and detailed enough to allow the reader to develop an adequate understanding of the steps taken and assumptions made by EPA to develop the model inputs? Are examples selected for tables and figures well chosen and designed to assist the reader in understanding approaches and methods?

D.2.1 Dr. Chris Frey

In general, the answer to this question is a qualified yes. The general concepts are mentioned, but could be better organized. There should be more emphasis on not just describing what was done but also giving some rationale as to why (see specific comments). The examples are generally well-chosen but not communicated with sufficient specificity. Lack of specificity will lead to reader misinterpretation.

D.2.2 Dr. Joe Zietsman

Overall, the methods and procedures were clearly documented. However, there are numerous examples where more clarity is desirable:

Under Section 2.2, it would help to clarify earlier what the applicable model year groups are for the application of the polynomial versus the exponential functions. Also suggest labeling the equations.

> *RESPONSE: We added text to clarify that we only implemented log-linear functions in cases where we had additional data. We also labeled the equations. In order to keep the text short, we did not specify the model years where the log-linear equations begin, because it differs for CO, HC, and NOx, but this made clear in the following tables.*

Table 2-1 [now Table 2-2] and related text – why is the terminology of polynomial function (with c=0 for all groups) retained though the best fit model has been established as a quadratic?

> *RESPONSE: We removed C from Equation 2-1 and Table 2-2.*

The description of the polynomial model fit (page 10, paragraph 1) is unclear. Seems as though last two sentences if interchanged could help with clarity.

> *RESPONSE: We removed the first sentence, to keep the focus on MOVES2014.*

Figures 2-1, 2-2 – the legend indicates four fit lines, whereas only 2 are shown. Looks as though in both cases two datasets were combined. Description and clarification is required.

> *RESPONSE: The legends were changed to distinguish the model fits from the data points.*

Page 13, first paragraph, "the temperatures to be lower across all temperatures" – revise/clarify.

> *RESPONSE: The text has been changed to the intended meaning "emissions to be lower across all temperatures."*

D.3 Appropriateness of Technical Approach

Are the methods and procedures employed technically appropriate and reasonable, with respect to the relevant disciplines, including physics, chemistry, engineering, mathematics and statistics? Are you able to suggest or recommend alternate approaches that might better achieve the goal of developing accurate and representative model inputs? In making recommendations please distinguish between cases involving reasonable disagreement in adoption of methods as opposed to cases where you conclude that current methods involve specific technical errors.

D.3.1 Dr. Chris Frey

In general, analysis should be reported with sufficient detail as to the input data and methods so that an independent investigator can reproduce the analysis and get the same answer. Thus, disclosure of the data used for modeling fitting (e.g., in an appendix) would be helpful.

The issue of developing accurate and representative model inputs is not a purely quantitative one. Judgments have to be made regarding what data can reasonably represent fleet average emission rates for a given vehicle type, fuel, and range of model years (and other factors). These judgments are inherently qualitative. The report is making use of available data in a reasonable manner. The report should include a section on key limitations and future needs to help prioritize (if resources can be applied to do it) what data should be collected to better inform the development of these adjustment factors. Stated another way, what lessons are learned from this analysis that could inform future data collection that in turn would provide a better basis for future correction factors?

> *RESPONSE: We added a Conclusions and Future Research Section where we address limitations due to the scope of the MOVES2014 update, and areas that could be prioritized for future updates.*

D.3.2 Dr. Joe Zietsman

As mentioned previously, I believe the methods are reasonable and most appropriate keeping in mind the data limitations and context.

D.4 Appropriateness of Assumptions

In areas where EPA has concluded that applicable data is meager or unavailable, and consequently has made assumptions to frame approaches and arrive at solutions, do you agree that the assumptions made are appropriate and reasonable? If not, and you are so able, please suggest alternative sets of assumptions that might lead to more reasonable or accurate model inputs while allowing a reasonable margin of environmental protection.

D.4.1 Dr. Chris Frey

In general, the approach and assumptions are reasonable. See specific comments for some details of where some additional explanation is needed.

D.4.2 Dr. Joe Zietsman

One area that is clearly lacking is with regards to temperature effects on diesel vehicles. As noted, the set of 12 vehicles for which FTP data at multiple temperatures are available comprise passenger cars and light duty trucks – the extrapolation of these to heavy duty trucks (including for extended idling) is a concern. I believe some data might exist that can be looked at to better support or modify the current approach. This data is likely to be outside of FTP cycle data and would include cold starts at different temperature ranges – I can think of ORNL and TTI work as examples. While the data may not be directly usable for MOVES 2014 it can be used as a cross-check.

> *RESPONSE: Updating the diesel temperature effects was not within the scope of the MOVES2014 update, but could be revisited in future MOVES models. We mention this in the Conclusions and Future Research section.*

D.5 Consistency with Existing Body of Data and Literature

Are the resulting model inputs appropriate, and to the best of your knowledge and experience, reasonably consistent with physical and chemical processes involved in exhaust emissions formation and control? Are the resulting model inputs empirically consistent with the body of data and literature that has come to your attention?

D.5.1 Dr. Chris Frey

The report would benefit from a literature review of what is known about whether or how temperature affects cold start emissions and hot stabilized emissions for gasoline and diesel vehicles, with a focus on the most important factors and on issues that would help in explaining and interpreting trends observed in the data used here. For example, statements are made several times that cold start temperature adjustments are not made for temperatures over 75 F. Is there some theoretical reason as to why such adjustments are not needed? In the absence of technical context, this choice comes across as arbitrary and perhaps unjustified. Perhaps the explanation is that cold start temperature adjustments exist at higher temperatures than 75 F, but that they would tend to decrease the cold start by small amounts that are difficult to estimate. Therefore, a choice was made not to estimate them, which is supported by some analysis based on empirical data (explain). To the extent that this leads to bias in the emissions estimates from MOVES at high temperatures, it will tend to slightly overestimate the emissions, which may be desirable direction of bias for a regulatory model.

> *RESPONSE: We added text in Section 2.2 stating that 75F is considered normal operation temperature per the FTP test. Because the FTP cycles served as the baseline for the certification and the cold start emissions data, we did not investigate the impacts of temperature beyond 75 F. This is a research area that could be worth investigating in the future.*

D.5.2 Dr. Joe Zietsman

Yes, considering the limited data I feel the resulting model inputs are appropriate. As more data and analyses become available, they can be adjusted.

D.6 Updates to Temperature Adjustment Data

For the MOVES2014 update of Chapter 2: Temperature Adjustments, certain temperature adjustments were updated with new data (e.g. HC and CO cold starts from later model year *gasoline vehicles, PM running effect for 2005+ my vehicles), while other adjustments were deemed sufficient from MOVES2010 and were left unchanged (e.g. HC and CO cold starts for pre-2000 MY vehicles, PM and NOx cold starts, PM running effect on pre-2005 vehicles). Did the EPA give sufficient description for its rationale for making or not making these changes in MOVES2014?*

D.6.1 Dr. Chris Frey

The impression that the report gives is that the previous adjustments were generally left unchanged, but not that they were evaluated and found to be adequate. Hence, the text could be more clear as to the decision making process here and whether it was based on evaluation with independent data not originally used to develop the existing MOVES 2010 adjustments.

> *RESPONSE: We added text in Section 2.2 stating that "We did not consider reanalyzing data from our previous test programs with the log-linear fit (Equation 2-2), because it was considered outside the scope of the update for MOVES2014."*

For adjustments for new model year groups, it is not really entirely clear as to why a log-linear model is any better than a polynomial model in that the reader is not shown quantitative results (with supporting data and graphs, and statistical summaries of goodness of fit and statistical significance) to support such a choice. There is some qualitative discussion to justify the decision on the bottom of page 10, but the description is vague. It would help if there was a quantitative comparison of both types of models fit to the same data set to illustrate why the log linear mixed model is better, and if some fundamental reason could be given for the preference. The reader/user may wonder if a loglinear model would give a better fit to data for the earlier model year groups and, thus, if the earlier model year groups should be reanalyzed with the newer model form. EPA should report on whether they considered doing this or whether they made a comparison upon which it was decided not to reanalyze the MOVES 2010 adjustments. If so, then why would the loglinear model be better for newer data but not for older data? Is it because newer data tend to be smaller in magnitude?

> *RESPONSE: We added text in Section 2.2.1.2, to further the rationale for using log-linear models, focusing on the intuitive benefits of the log-linear approach (yields a monotonically increasing, positive values). In our analysis, we did evaluate goodness of fit statistics between different approaches (Mean Absolute Error, and Root Mean Square Error), but they were of secondary importance because the other approaches yielded spurious relationships, unless additional structure was imposed on the model (e.g. forcing terms to be zero). As such, we decided that it was not necessary to compare goodness of fits statistics to support our decision to use log-linear models.*

D.6.2 Dr. Joe Zietsman

When I looked specifically for the information/rationale in the text, I find it is adequately described. However, it would have been useful to provide a summary table containing a list of updates vs what was left unchanged and listing the rationale(s).

> *RESPONSE: This may be appropriate for technical reviewers to focus on the updates for MOVES2014. However, the intent of the technical documentation is to be comprehensive regarding all the temperature effects in MOVES2014, whether they are newly*

incorporated or the same as MOVES2010. We decided not to address this comment, because it would distract from the primary purpose of documenting all the temperature effects currently used in MOVES2014.

D.7 General/Catch-All Review

D.7.1 Dr. Chris Frey

This is a significant report that documents an important part of the MOVES emission factor model, which is used nationally for a wide variety of regulatory and other analyses. As such, it is critically important that the report be well written and very clear. While the current draft of the report is good in many respects, it comes across as a draft and is not in final form in terms of the critical thinking needed to make sure that it clearly communicates information to the reader.

For each of the major sections, it will help the reader to have clearly labeled sections that deal with light duty vehicles and with all other vehicle source categories. It will also help to clearly define and consistently use terms and concepts.

The communication of what was done, and why, should be more clear and complete. Ideally, sufficient information should be communicated regarding the underlying data and inference approaches such that an independent investigator can reproduce the results and obtain the same answer. Many of the detailed comments given below under "specific comments" are aimed at this objective.

Figure and table captions need to be more specific.

In general, be careful about significant figures. It is pretty rare in this type of work that data are known with more than 3 significant figures. However, in various places, numbers are reported with 5 or more significant figures. Even if the original data might be known with many significant figures, its adoption for use in representing a national fleet introduces uncertainty, since the original data may not represent the U.S. national fleet as it exists today.

Many specific comments are given below that elaborate on responses given above in response to the charge questions.

RESPONSE: We addressed Dr. Chris Frey's comments regarding vehicle source categories, figure and table captions, and significant figures in his specific comments below.

Specific Comments: Numbers refer to page/paragraph/line in the paragraph

Section 2 – please give the reader some overview of this section. Is this about LDVs only? This text starts out with LDVs but no objective or context is given. Define the scope. Give a lcear statement of the objectives of this section.

RESPONSE: We added an overview to Section 2 to state that the temperature effects are applicable to light-duty and heavy-duty vehicles. We revised Section 2.1, including the heading, to be specific to gasoline vehicles. We specified in Table 2-4 that the temperature effects apply to all gasoline vehicles in MOVES.

7/5: a study design would help the reader, before diving into details of individual studies. This section 2.1 needs a summary table to help guide the reader through all of these studies. The table should include the following columns: Data Source (name of study, with references), Type of Test (e.g., FTP, LA92, IM240, etc.), a column indicating if cold start is addressed (yes/no), a column indicating if hot stabilized tailpipe emissions are addressed (yes/no), the temperature range of the measurements, the number of vehicle measurements (reported separately for cold start and hot stabilized), the range of model years, and the range of vehicle size (or other factor).

RESPONSE: A table summarizing the programs analyzed for modeling has been added to aid the reader (Table 2-1).

7/5/2 "FTP tests" not "FTPs"

RESPONSE: Addressed.

8, section 2.2, statements are made here as to what was done without context or explanation. State a purpose/objective followed by an overview, and save details for later. However, when mentioned, explain WHY no adjustments are given for temperatures over 75 oF, and why there are no "additive" adjustments for temperatures below 75 oF. to a reader who is reading this for the first time, these out-of-context statements are very confusing, and this material is not organized. Also, for all of the discussion of the first equation (number the equations), later it turns out that in application this equation is reduced to just one term in each case. The text is confusing also in that it states that HC, CO, and NOx cold start emissions "were modeled" but it does not become clear until later as to the distinction between what is already in MOVES 2010 versus what is new for MOVES2014. Thus, in just 7 lines of material, the text offers far more confusion than illumination.

RESPONSE: An overview has been added to this section as well as some explanation for the guiding principles used in this analysis, including the decision to only model temperature effects below 75 F temperature. We numbered the equations to be able to reference them in the text. We also added text discussing our rationale for maintaining temperature effects from MOVES2010, and incorporating new temperature effects in MOVES2014 based on newer data.

It would help if there is a clear summary of what is in MOVES 2010 before discussing what is new for MOVES 2014. The latter should be accompanied by an explanation of why.

RESPONSE: Clarification has been added as to what was in MOVES 2010 and what has been changed for MOVES2014 in Section 2.2.

Section 2.2.1 is very difficult to follow. It would help to have an introduction paragraph that gives an overview of this section. Otherwise, it feels like getting pulled along a path without knowing to where it is leading.

RESPONSE: An overview has been added to describe the process of analyzing this dataset before discussing the polynomial and log-linear model fitting procedures.

In Section 2.2.1, it is important to show, either here or in an appendix, the original data and the fitted regression models, along with disclosure of the coefficient of determination of each model, and the t-ratio and p-value of each coefficient. Just showing model predictions is not enough – information should be given so that it is clear how the model parameters were estimated and regarding the goodness-of-fit of these models. It is also important to be clear as to what results are statistically significant.

RESPONSE: We added tables with the model parameter estimates, and the t-ratio and p-values of the estimated model parameters in Table 2-3, Table 2-4, Table 2-5. We also added discussion about our model fitting procedures, and the rationale behind selecting the final model.

The terms "significant difference" and "statistical difference" are used to indicate a p-value of < 0.05. Also, the data can be viewed graphically in Figure 2-1 and Figure 2-2.

The text here tends to say "here's what we did" without explaining why. E.g., the next to last paragraph declares what was done, but does not provide insight as to why a polynomial function was used, or why additive adjustments are set to zero above 75 oF. After reading the entire chapter, it is still not clear as to why no adjustments are made above 75 oF, except that maybe they are small in value. Is there some theoretically reason as to why higher temperatures might not shorten cold start duration or lower total cold start emissions?

RESPONSE: Clarification has been added to the beginning of the chapter on this issue. 75 is considered the ambient temperature at which standard certification FTP test cycle is conducted. Theoretically, temperatures above 75 could have some impact on shortening cold start duration but that analysis has not been performed.

Table 2-1 caption is unclear. Polynomial model coefficients for what model, for what vehicle, for what variable? Captions should ALWAYS be specific and clearly communicate what the content is about. Furthermore, information should be communicated regarding the R2 of each of these models, and confirmation should be given that values not shown were statistically not significantly different from zero and therefore were set to zero or, if there is some other reason, then explain. To avoid confusion, for the CO results for the 2000-2005 (not 1990-2005) model year range, indicate either n/a or use grey to 'grey out' so that it is clear that the missing values here are intentional.

RESPONSE: The table [now Table 2-2] has been edited to help avoid confusing the reader with overlapping model year groups. We added heading text stating the ranges of model years that the effects apply to. We also added 'grey-out' boxes to indicate that missing values are intentional.

While I don't have a significant concern in particular about the model forms used here, the text could be more clear and organized. i.e. after reading this, my impression is that the linear form of the first equation on page 8 is a legacy from the previous version of MOVES, and that the log-linear form is now preferred… for the latter, a rationale should be given earlier for this preference, supported by details later.

RESPONSE: A sentence has been added to this section overview (2.2) to address the scope of the MOVES2014 update, and why the polynomial form is retained in MOVES.

10/1: the explanation would be more clear if the data were shown graphically along with trend lines representing the preferred model and the alternative model that was originally considered. Some of the text is unclear… e.g., "unbalanced nature of the analysis" … in particular, the word "nature" is vague. If the issue here is that there was a smaller sample size for -20 oF than at other temperature, then say so more specifically. Also, "This" in the last sentence has the wrong antecedent and thus the sentence does not make sense.

RESPONSE: The paragraph has been edited to explicitly state the smaller sample size of vehicles tested at -20F. We removed the last sentence to the paragraph that did not value to the paragraph, and was unclear to the reviewers.

10/2: [now page 11] a temperature effect is inferred, not developed. Here again, 'anomalies' are best illustrated by visualizing the data either here or in an appendix.

RESPONSE: We changed the test to state that the temperature effects are inferred. We also added Figures 2-3 and 2-4 to visualize all the temperature effects used in MOVES (using both the polynomial and log-linear models).

10/2, [page 11] next to last line… table indicates 1990 and later but text indicates 2000 and later.

RESPONSE: We added shading to Table 2-2, to make it clear the intended model year groups for the CO and HC temperature effects between 1990 and 2005 model year vehicles.

10/3: doubtful that "raw" data were used – the data probably underwent QA. Use a different descriptor

RESPONSE: We removed "raw"

10, last paragraph, "linear mixed models" is not defined and should be explained. The term "mixed" seems to refer to a mix of continuous and categorical variables. Avoid using the word "nature" as in "paired nature" and "unbalanced nature" – these terms are vague.

RESPONSE: These changes have been made.

11: start emissions have units (e.g., grams). Always show units with numbers and in defining numbers.

RESPONSE: Units have been added.

12: figures 2-1 and 2-2. Do not rely only on color to distinguish lines for two different series… use different line styles also. The legend does not clearly define the data points. Is 2010 and new the same as MSAT? Using two different descriptors for the same time period is confusing. Be consistent.

RESPONSE: Labels have been updated and colors have been accompanied by shading/linestyle differences

13/1/1: for clarify, was the value of A similar for both model year groups (i.e. did not have a statistically significant difference)?

Response:. Yes, we have clarified derivation of A using Table 2-3 and Table 2-4. There was no significant difference to the β_1X MSAT-2 interaction term that we added to the model. We then refit the data without a β_1X MSAT-2 interaction term, to derive the A, B, and C terms used in MOVES2014. Because A is derived from β_1, there is no difference in the A term between the 2001-2009 and 2010 and later model year group vehicles.

13/1: Why is Table 2-3 cited before Table 2-2?

RESPONSE: Table citation removed.

13/2/4: "is used to representative" seems incorrect.

RESPONSE: Reworded to "effect represents the impact of Mobile…"

13/2: the explanation of the MSAT-2 rule is very helpful, but should be given earlier since this rule is mentioned previously.

RESPONSE: We added an explanation of the MSAT-2 rule to the chapter overview

13/3 – please explain what is "composite FTP NMHC emissions". Does this mean it includes both cold start and hot stabilized emissions?

RESPONSE: Yes, we added to the report for clarification in section …

13 – near bottom of page: "startTempAdjustment" table – please define or explain what this is. Similarly, define or explain a2010, apre, and apost. Also explain/define HLDT and MDPV. This seems to start a new section on other regulatory classes and thus should have a new header.

RESPONSE: These abbreviations are defined in the bullets above. An explanation has been included for the other terms.

Table 2-3: caption should be clear as to the applicability of these data – i.e. for all source types? Or just LDGV?

RESPONSE: Caption has been changed to specify that the effects apply to all gasoline source types.

14… why "not unexpectedly"? What was the expectation and its basis?

RESPONSE: This misleading term has been removed.

Figure 2-3: for what vehicle type is this applicable? Also, the "data" plotted here is confusing. Does each "point" in the graph at a given temperature and model year range represent one measurement, or is it the average of all (how many) measurements at that temperature for that model year group? If the latter, then why not show the individual vehicle data, or show a range of values associated with each average?

RESPONSE: The graphic is based on an older analysis that is not used in MOVES2014. We removed Figure 2-3, and kept the discussion of the analysis that is relevant to the NOx effects used in MOVES2014.

Table 2-4 is for what type of vehicle? Fuel? Range of model years? Are these empirical data or predictions from a model? If from a model, what model? i.e. be more specific. Figures and tables should be self-documenting. Also, what is the "Emission Result" – is this an increment of cold start emissions for cold starts at temperatures other than 75 oF? The caption is unclear, and thus the data are highly likely to be misinterpreted.

RESPONSE: We added clarification that it is the average incremental cold start emissions from gasoline vehicles calculated from the MSOD, ORD, and MSAT programs

Page 16, equation: please justify that the "tempAdjustTerm" should have 7 significant figures. Also, the R2 can be reported as 0.61 or maybe 0.611, but 6 decimal places is not necessary nor justifiable.

RESPONSE: The number of significant figures has been reduced

Page 16 "the actual data indicate that the cold start NOx emissions increase as the ambient temperature rises above 90 oF. Therefore…. " "set to zero." What precedes the "therefore" does not actually explain why values that show an increase with higher temperatures should be set to zero. Provide an explanation/justification for this decision. As an aside, what are "actual" data? does this refer to "measurements"?

> *RESPONSE: The averaged cold start data in Table 2-8 indicate that the cold start NOx emissions increase above 90. We add text to qualify that this may be an artifact of the data since only some vehicles were measured above 75 F. We also state that we are not adjusting temperatures above 75F to be consistent with the other temperature effects.*

Page 16, last paragraph: "evaluated" how or in what way? "small" and "too minor" means what, exactly… are these not statistically significantly different from zero incremental change, or are these such a small percentage of baseline emissions as to be negligible. Justify, preferably quantitatively.

> *RESPONSE: An explanation has been added to the report to explain why the NOx change was evaluated as negligible, because the start NOx emissions are a small percentage of the baseline NOx emissions.*

Figure 2-4: Should also show mean values. Also indicate sample size.

> *RESPONSE: The sample size is indicated by the data points, and an overview of the program is given in Appendix A.*

Page 17: "report4"?

> *RESPONSE: We verified the citation to the EPA report is active to the Kansas City Study.*

Page 18: for the equation given, report the R2 value for each case mentioned.

> *RESPONSE: The R^2 value is not available in the cited reports. Additionally, the R^2 value for the log-transformed data, is not directly comparable to the model predictive power in real-space, and does not add substantial value for the average reader.*

Page 18 – please either explain way it is necessary or preferred to imply 6 to 7 significant figures for these ratios, or use a reasonable number of significant figures (probably 2 or 3). Furthermore, it is not really clear how one arrives at the ratio from a 30% NMHC reduction, which should be explained or shown.

> *RESPONSE: The numbers have been reformatted to 3 significant digits. We also an example calculation at how the multiplicative increases were reduced by 30%.*

Table 2-5 and Table 2-6 [Now Table 2-9, and Table 2-10]: are these results specific to any particular vehicle type or fuel? Significant figures?

RESPONSE: We added 'gasoline vehicles' to the heading of Table 2-9 and Table 2-10 , and have reduced the significant figures.

Page 19: last two lines of second paragraph- cannot figure out what this is about (unclear)

> *RESPONSE: These sentences are not needed in this report and are removed. The concept is covered in the light-duty vehicle emission rate report.*

Figure 2-6 [now Figure 2-7]: is this for total PM, PM10, PM2.5? It is useful to show mean values also. Also indicate sample size.

> *RESPONSE: We added PM2.5, and the sample size to the heading of Figure 2-7. For purposes of the qualitative comparison, we believe that showing the distribution of the data, without the mean, is sufficient to show that the data compare well.*

Page 20: please indicate if this section is for all model years or is applicable to a particular range of model years. Also please indicate sample size in Figure 2-7, and the range of model years of the data shown.

> *RESPONSE: We added text at the beginning and end of Section 2.3.1 to specify that the effects apply to all model year vehicles. We also added information on the sample size of the KCVES in the beginning of Section 2.2.3, and in Section 2.3.1 with regard to the sample size in Figure 2-7.*

Page 21, 1st few lines: previous text indicates that there is no effect; thus, in such a context, this text is confusing in that it seems to be contradictory. However, it ends with zero change. This could be rewritten to make clear that MOVES was designed to allow for modeling of an effect, but given that there is no observed effect, the coefficients are set to zero…

> *RESPONSE: We added text to the beginning of Section 2.3.1 stating that MOVES is design to allow for modeling temperature effects for running-exhaust for HC, CO, and NOx, but the data does not support it. This point is re-emphasized at the end of Section 2.3.1.*

Page 21 – middle of page says "no significant temperature effect is observed in either cycle." Figure 2-8 gives some hint that there may be an effect for the US06 cycle. However, if there is an effect, it may be on the mean rather than the median "emissions". Is this total emissions or some kind of emissions increment… not very clear. If this is a hot running emissions, why is it not in units of mass per mile? In general, it is helpful to indicate sample sizes of data sets and to also indicate the mean value in box and whiskers plots.

> *RESPONSE:. We added text explaining that we fit log-linear models to the data, and found no statistically significant temperature effect. The units .*
>
> *We specify the units in the heading as grams per cycle.*

Page 23: After rereading this a few times I think I finally understood the logic here, but for one thing the graphs are very hard to read, and thus it is hard to follow what is being stated in the text. The text seems to deal with this later, but on page 23 my thought was that a real world trip can be on the order of 500 to 1000 seconds, so even if somehow bag 2 emissions included a delayed cold start effect, if there really was such an effect, then it needs to be considered somehow in the emission inventory. Thus, it may not be "wrong" if it is averaged into the hot stabilized emission rate for the purpose of improving the accuracy of the inventory for trips of similar lengths. This seems to be the point made on page 24 in the first of the paragraphs numbered as "2."

> *RESPONSE: We clarified the heading of Figure 2-11 to mention that it is the average of sec/sec data. We also added text immediately following Figure 2-11, to help transition the discussion to the statistical tests using the same data. We also added text to better*

explain the results in Table 2-11, and added reference to the form of the equation used in the statistical tests.

Page 25: first line of section 2.3, please clarify if these are light duty diesel vehicles. Even the term “diesel trucks” later in this paragraph is not very clear… are these light duty trucks? – i.e. be more specific as the types of vehicles represented here.

RESPONSE: We clarified that the diesel trucks refer to light-duty diesel trucks. We also specified in the overview following Section 2 that we only tested light-duty diesel vehicles, but apply the effects in MOVES to all diesel vehicles.

Table 2-8… please be clear as to what type of diesel vehicle is represented here (see above). Also, explain the basis of the confidence intervals shown in Figure 2-10 – are these actually CI on the mean, or are they a range of variability in the data?

RESPONSE: We added text to Table 2-9 heading stating that the data are from light-duty diesel vehicles. We also added text on Figures 2-10, 2-11, and 2-12 stating that the graph plots the means, to reflect the definition of the confidence interval on the mean as stated in the text.

25/equations: significant figures. When a number is reported such as 4.22477812, it implies precision of 4.22477812±0.000000005, which seems implausible.

RESPONSE: The numbers were reduced to 3 significant digits.

Figures 2-11, 2-12: indicate the model year range and vehicle type.

RESPONSE: We specified in the Figure heading text that the data are for light-duty diesel vehicles.

28: not clear on what basis it is reasonable to extrapolate results for gasoline vehicles to diesel vehicles. This needs more explanation/justification.

RESPONSE: We revised the text to state that we did not evaluate the diesel running temperature effect, but we set it to zero, similar to what was done for the gasoline vehicle effects.

D.7.2 Dr. Joe Zietsman

In my review of Chapter 2 of the report documenting temperature adjustments for MOVES 2014, I found the methods and assumptions to be overall reasonable and adequate. There are obviously significant constraints, specifically with regard to available data, and I have touched upon these limitations in my specific answers to the questions.

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[30] USEPA (2010). *MOVES2010 Highway Vehicle Temperature, Humidity, Air Conditioning, and Inspection and Maintenance Adjustments* EPA-420-R-10-027. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. December, 2010. http://www.epa.gov/otaq/models/moves/documents/420r10027.pdf.