Emission Adjustments for Onroad Vehicles in MOVES5

United States
Environmental Protection
Agency

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

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EPA United States
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List of Acronyms

AAA	American Automobile Association
A/C	air conditioning
ABT	averaging, banking and trading
ACCF	air conditioning correction factor
ASM	Acceleration Simulation Mode
CO	Carbon Monoxide
CDB	county database
CF	critical flow factor coefficient
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
CV	coefficients of variation
DPF	diesel particulate filter
ECCC	Environment and Climate Change Canada
EPA	U.S. Environmental Protection Agency
EV	Electric Vehicle
E85	gasoline containing 70-85 percent ethanol by volume
F	Fahrenheit
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GHG	Greenhouse Gases
GVWR	Gross Vehicle Weight Rating
HC	hydrocarbons
HP	horsepower
ICE	Internal Combustion Engine
I/M	Inspection and Maintenance program
IM240	Inspection and Maintenance roadside vehicle driving schedule
KCVES	Kansas City Light-Duty Vehicle Emissions Study

kW	Kilowatt
LA-92	California dynamometer driving schedule for light-duty vehicles
LDT	Light-Duty Truck
LDV	Light-Duty Vehicle
LHDT	Light Heavy-Duty Truck
LLDT	Light Light-Duty Truck
MDPV	Medium-Duty Passenger Vehicle
MOBILE6	EPA Highway Vehicle Emission Factor Model, Version 6
MOVES	Motor Vehicle Emission Simulator Model
MPGe	Miles Per Gallon Equivalent
MSAT	Mobile Source Air Toxics rules
MSOD	Mobile Source Observation Database
NEI	National Emission Inventory
NMHC	Non-Methane Hydrocarbons
NMOG	Non-Methane Organic Gases
NMIM	National Mobile Inventory Model
NO_x	Oxides of Nitrogen
OBD	On-Board Diagnostics
ORD	Office of Research and Development
OTAQ	Office of Transportation and Air Quality
PFI	Port Fuel Injection
PM	Particulate Matter
RIA	Regulatory Impact Analysis
SFTP	Supplemental Federal Test Procedure
SIP	state implementation plan
SRC	selective reduction catalysts
SwRI	Southwest Research Institute
THC	Total Hydrocarbons

US06	A drive cycle that is part of the SFTP
VIN	Vehicle Identification Number
VOC	Volatile Organic Compound
VSP	vehicle specific power

1. Introduction

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

MOVES calculates emission inventories by multiplying emission rates by the appropriate emission-related activity, applying correction and adjustment factors as needed to simulate specific situations, and then adding up the emissions from all sources and regions. The highway vehicle emission rates in the MOVES model represent emissions under a single (base) scenario of conditions for temperature, humidity, air conditioning load and fuel properties. MOVES is designed to adjust these base emission rates to reflect the conditions for the location and time specified by the user. MOVES also includes the flexibility to adjust the base emission rates to reflect the effects of local Inspection and Maintenance (I/M) programs. In addition, adjustments are applied to account for electric vehicle charging and battery efficiency, and to account for fleet-averaging provisions of EPA rules that make the emission limits for internal combustion vehicles dependent on the fraction of electric vehicles sold. This report describes how these adjustments were derived and how they are implemented in MOVES. Adjustments for fuel properties are addressed in a separate report.[1]

This report describes MOVES adjustments that affect running exhaust, start exhaust, and extended idling exhaust emissions for Total Hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$) and energy consumption. The temperature effects that impact these pollutants, also affect the pollutants that are calculated from these pollutants in MOVES, such as volatile organic compounds (VOC)[2] and individual toxics such as benzene[3] (chained to THC), NO_2 (chained to NO_x)[4] [5], elemental carbon (chained to $PM_{2.5}$)[2], and CO_2 emissions (chained to energy).[6] The definitions of these pollutants and the relationship to the primary pollutants are discussed in the cited MOVES reports. The crankcase emission processes[4] [5] are chained to running exhaust, engine start, and extended idling exhaust 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.[7]

For MOVES5, we updated the algorithms for temperature effects related to HD diesel NO_x (see Section 2.4.1). We updated Section 7 to account for the fleet averaging provisions of the recent *Light- and Medium-Duty Multi-Pollutant Rule (LMDV)*[8] and *Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3 (HDP3)*.[9] We also updated information about which pollutants and processes are covered by I/M programs in various counties and calendar years as described in Section 5.4. .

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 two considerations:

1. Ambient temperature
2. The latent engine heat from a previous trip, applied as an adjustment based on the length of time the vehicle has parked since operating (soak time).

This report describes the adjustment based on ambient temperature. Soak time and start emissions are addressed in the light-duty[4] and heavy-duty[5] emission rates reports.

This report addresses temperature sensitivity of emissions from gasoline vehicles in Sections 2.1. through 2.3. Although the gasoline temperature effects are developed based on emissions data from light-duty gasoline vehicles, they 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 diesel 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 non-electric vehicle types in MOVES. These effects are applied only to vehicle starts.

Section 2.7. describes temperature effects on energy consumption from battery and fuel-cell electric vehicles.

2.1. Data Sources for Gasoline Temperature Effects

To determine the impact of ambient temperature on running emissions, our analysis included the Bag 2 emissions of Federal Test Procedure (FTP) tests as well as US06 tests (without engine starts).

For start emissions, measurements from both the Federal FTP and California Unified Cycle (3-phase / 3-bag tests) were used. 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.

The data used in these analyses are from the following sources:

Table 2-1 Summary of Data Sources

Data Source	Test	Temperatures Tested (deg. F)	# of Vehicles	MY Range
MSOD	FTP +	15-110	Hundreds	Pre-2005
ORD (2002)	FTP, IM240	-20, 0, 20, 40, 75	5	1987-2001
MSAT	FTP	0, 20, 75	4	2005
OTAQ	FTP, US06	0, 20, 75	9	2006, 2010
ORD (2021)	FTP	20, 71	3	2014-2015

- ***MSOD -*** *EPA's Mobile Source Observation Database (MSOD) as of April 27, 2005. EPA has 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).*[10]

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.

- ***ORD (2002) –*** *The EPA 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°F.*[11]
- ***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°F. This program was used in the Regulatory Impact Analysis of Final Rule: Control of Hazardous Air Pollutants from Mobile Sources*[12]*, which is referred to as MSAT-2 in this report to distinguish it from an earlier mobile source air toxics (MSAT) rulemaking.*[13] *The MSAT-2 rule required Tier 2 vehicles to meet a non-methane hydrocarbon (NMHC) standard on the FTP cycle of 0.3 g/mile for light-duty vehicles (<6,000 lbs) beginning phase-in for model year 2010 vehicles.*[14]

OTAQ Cold Temperature Program (2012) - EPA's Office of Transportation and Air Quality (OTAQ) contracted the testing of nine Tier 2 vehicles (2006 and 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 0°F. Information on the tested vehicles is summarized in 0 . Note that for the estimation of the THC and CO cold start effects the two GDI vehicles were excluded from the analysis.

ORD (2021) - A recent program was conducted under the auspices of the Office of Research and Development (ORD). In this project, emissions were measured on three vehicles equipped with gasoline direct injection (GDI). All three vehicles are passenger cars, including a Ford Fusion, Honda Accord and Volkswagen Jetta, all in model year 2015. One of the vehicles is naturally aspirated, and the others turbocharged. Mileage at test ranged from 9,000 to 13,000 miles. Emissions were measured on chassis dynamometers over two test cycles, the Federal Test Procedure (FTP) and the US06. For the FTP, results are available by phase. Emissions were measured on a single fuel, a “winter E10” at two temperature levels, 20 and 71°F. A variety of pollutants were measured, including the gaseous criteria pollutants and particulate matter. Particulate matter, as PM2.5, was measured gravimetrically on three replicate filters in a heated box and with sample flows drawn from a constant-volume sampler (CVS). Replicate measurements were also collected from each filter holder.

2.2. Temperature Effects on Gasoline Start Emissions

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

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

- *No adjustment for temperatures higher than 75°F. 75°F is the midpoint of the allowable temperature range (68°F-86°F) per the FTP.*
- *Additive adjustments for temperatures below 75°F. These adjustments are added to the emissions that would occur at 75°F.*
- *Calculate the adjustments as either polynomial (Equation 2-1) or log-linear (Equation 2-2) functions, depending on model year group and pollutant:*

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

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

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

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

2.2.1. THC and CO Start Emissions for Gasoline-Fueled Vehicles

In developing temperature adjustments for THC 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) and MSAT-2 compliant vehicles, which began phase-in starting in 2010. The MSAT-2 rule included the first regulation on low temperature (20°F) non-methane hydrocarbon (NMHC) emissions for light-duty and some medium-duty gasoline vehicles.[14]

Polynomial Fits

The coefficients for THC emissions for pre-2006 gasoline vehicles and CO emissions for pre-2001 gasoline vehicles were calculated with polynomial fits to data processed in the following steps. First, the cold start emissions (grams/start) were calculated as the difference between Bag 1 and Bag 3 emissions for each relevant vehicle test in the MSOD, ORD and MSAT data. 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 (68° to 86°F). The model year groups were aggregated to larger intervals when the less aggregated groups yielded non-intuitive results (e.g., older model year group had lower cold start emissions).

Table 2-2 summarizes the coefficients used with Equation 2-1 (polynomial) to estimate additive start temperature adjustments for older model year gasoline vehicles.

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

	CO		THC	
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 THC 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" THC 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 THC emissions in the more common 0° F to 20°F range. Therefore, the coefficients in MOVES are based on the changes in cold-start emissions for temperatures from zero through 75°. However, these coefficients are applied to all ambient temperatures below 75°F in MOVES.

For CO, the temperature effect developed based on the 1994-2000 model year vehicles was applied to all model years from 1986-2000, because including 1986-1993 model year vehicles in the analysis resulted in cases where older model years were modeled with substantially lower CO emissions than newer model years. Note that the base CO emission rates still vary across this model year range.

To adapt the additive ambient temperature adjustments to account for intermediate soak times, the A and B coefficients for start operating modes other than cold starts were reduced by multiplying by a factor equal to the ratio between emissions at the desired soak time and the cold start emissions for catalyst equipped vehicles as used in MOBILE6.[15] These factors are summarized in Table 2-3.

Table 2-3 Soak Time Multipliers for Additive Start Temperature Effects

Operating Mode ID	Nominal Soak Time (min)	THC	CO	NO_x
108	720	1	1	1
107	540	0.908778	0.91377	1.053118
106	240	0.733962	0.79137	1.117624
105	105	0.64496	0.72996	1.128799
104	75	0.599625	0.6285	1.129778
103	45	0.444825	0.44136	1.02786
102	18	0.208548	0.199678	0.58398
101	3	0.037593	0.035422	0.20508

Log-linear Fits

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

The model parameters were fit using linear mixed models using the function *lme* within the R statistical package *nlme.*[16] 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**

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

[b] We excluded the two GDI vehicles from the OTAQ cold temperature program from the model fit because they 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.

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

$$y = e^{\propto+\beta_1(75-T')} \qquad \textbf{Equation 2-6}$$

$$y = e^{\propto+75\cdot\beta_1}\ e^{\beta_1(-T')} \qquad \textbf{Equation 2-7}$$

$$y = e^{\propto+75\cdot\beta_1}\ e^{\beta_1(Temp-75)} \qquad \textbf{Equation 2-8}$$

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

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 THC and CO, by setting C = -B, yielding Equation 2-2:

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

The initial estimated fixed effects (including p-values) for the linear model fit for CO are displayed in Table 2-4. The model estimates that the Portable Fuel Injection (PFI) MSAT-2 compliant vehicles (Model year 2010) tested in the OTAQ 2012 test program have consistently lower CO start emissions than the pre-MSAT-2 vehicles (pre-2010), as shown by the positive pre-MSAT coefficient (α_2). However, no statistically significant difference in the log-linear impact of temperature (coefficient β) was found between the 2001-2009 and the 2010 model year groups for CO emissions, as shown in Table 2-4 (p-value of the Temperature × pre-MSAT effect is >0.90).

Table 2-4 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 2-5.

Table 2-5 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 2-8. 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.

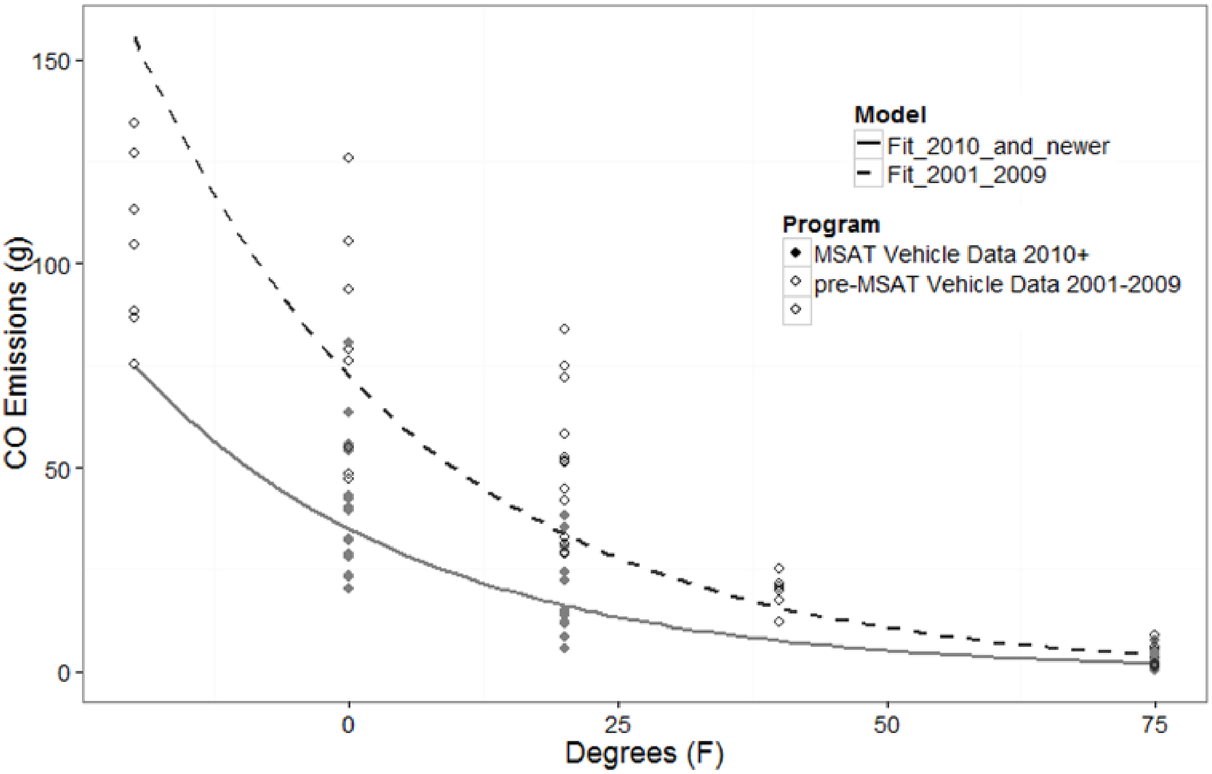


Figure 2-1 FTP CO Start Emissions with Log-linear Model Fit

For THC emissions, a statistically 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 2-6 (p-value of the Temperature × pre-MSAT term is much smaller than 0.05).

Table 2-6. Fixed Effects for the Final THC 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 THC model fit to the cold start emissions data is graphed in Figure 2-2. As shown, the pre-MSAT-2 cold start emissions for THC are much more sensitive to cold temperature than the MSAT-2 compliant vehicles.

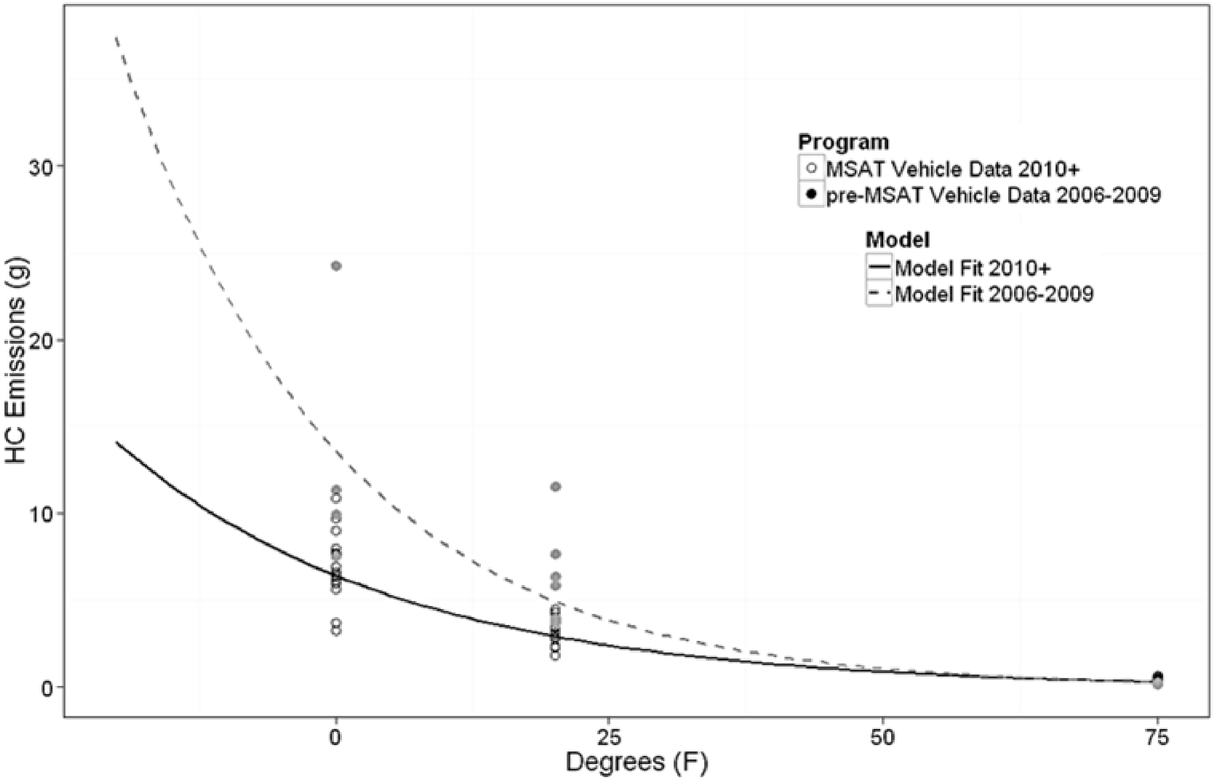


Figure 2-2 FTP THC Start Emissions with Log-linear Model Fit

The differences in the THC 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.[14] Specifically:

- For passenger cars (LDVs) and for the light light-duty trucks (LLDTs) (i.e., those with GVWR up to 6,000 pounds), the composite (combined cold start and hot running) FTP NMHC emissions should not exceed 0.3 grams per mile.
- For light heavy-duty trucks (LHDTs) (those with GVWR from 6,001 up to 8,500 pounds) and for medium-duty passenger vehicles (MDPVs), the composite FTP NMHC emissions should not exceed 0.5 grams per mile.

These cold weather standards are phased-in beginning with the 2010 model year, as shown in Table 2-7.

Table 2-7 Phase-in of Vehicles Meeting Cold Weather THC Standard

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

For the phase-in years, the coefficients for the THC temperature effect equation in the startTempAdjustment table were adjusted linearly according to the light-duty vehicle phase-in. Equation 2-9 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 2-9**

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

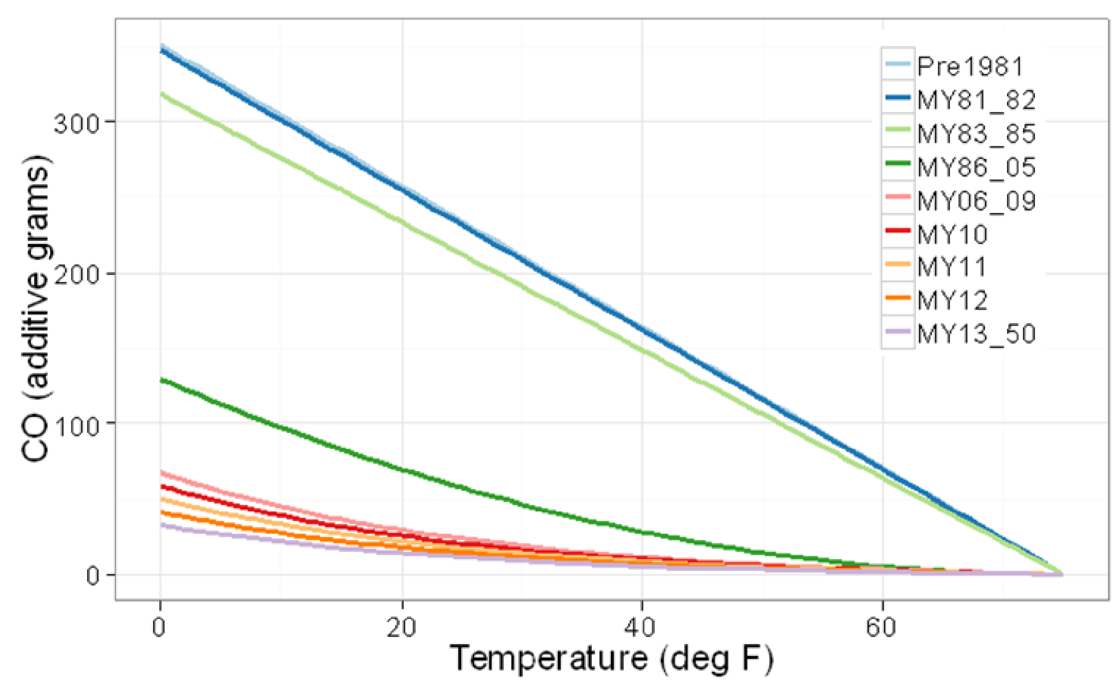
Within the current MOVES design, temperature effects are applied by fuel types and model year vehicles, but not by regulatory class (e.g., LHDTs/MDPVs). As such, the light-duty rates, including the light-duty MSAT-2 phase in are applied to all the gasoline-fueled vehicles in MOVES. No data on LHDTs/MDPVs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

Table 2-8 summarizes the coefficients used with Equation 2-2 (log-linear) to estimate additive start temperature adjustments for more recent model year gasoline vehicles.

Table 2-8. Coefficients Used for Log-linear Temperature Effect Equation for All Gasoline Source Types

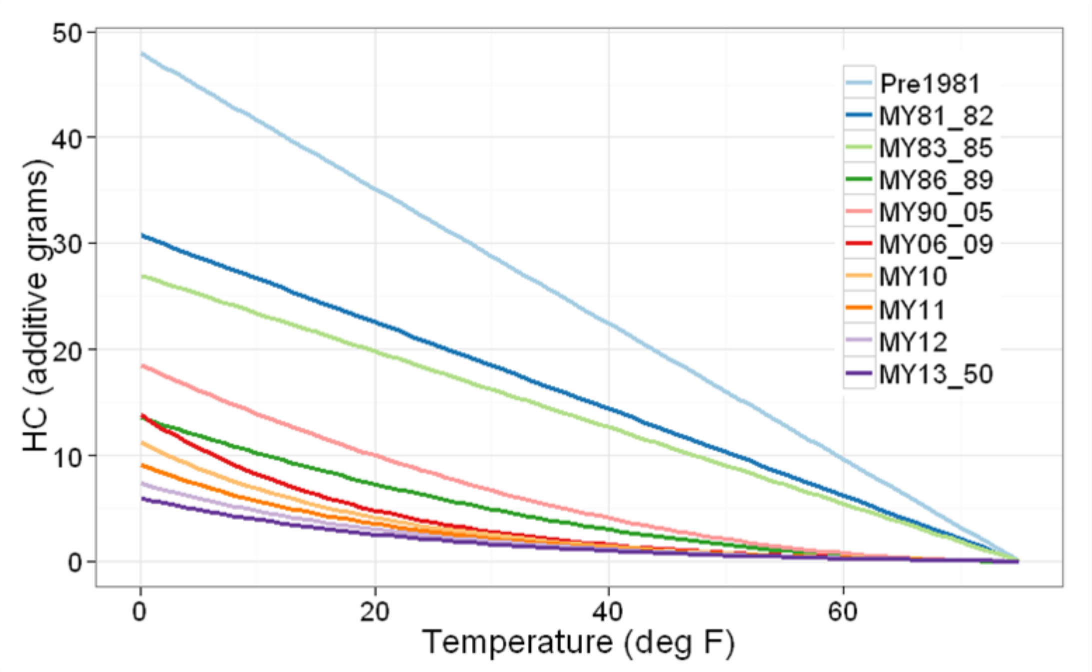
	CO			THC		
Model Year Group	**A**	**B**	**C**	**A**	**B**	**C**
2001-2009	-0.038	4.136	-4.136			
2006-2009				-0.051	0.308	-0.308
2010	-0.038	3.601	-3.601	-0.048	0.315	-0.315
2011	-0.038	3.066	-3.066	-0.045	0.322	-0.322
2012	-0.038	2.531	-2.531	-0.042	0.329	-0.329
2013 & later	-0.038	1.996	-1.996	-0.039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

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



Note: In MOVES, “MY13_50” applies to all model years 2013-2060.

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



Note: In MOVES, "MY13_50" applies to all model years 2013-2060.

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

To adapt the additive adjustments for intermediate soak times, the B and C coefficients for start operating modes other than cold starts were reduced by multiplying by a factor equal to the ratio between emissions at the desired soak time and the cold start emissions for catalyst equipped vehicles as used in MOBILE6[15] as summarized in Table 2-3.

2.2.2. Temperature Effects on Gasoline NO_X Start Emissions

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

Due to the small temperature effects and the variability of the data, the NO_X temperature effect was calculated in MOVES by averaging all the available NO_X results (i.e., the 2005-and-earlier model year data) together across model year groups and then performing regression. Table 2-9 lists the average incremental cold start NO_X emissions, compared to 76.3°F, from the MSOD, ORD, and MSAT programs.

Table 2-9. Average Incremental Cold Start NO_X Emissions by Temperature for Gasoline Vehicles Calculated from the MSOD, ORD and MSAT Programs

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

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

$$NO_X \text{ temperature additive adjustment} = A * (Temp - 75)$$ **Equation 2-10**

Where:

$A = -0.009$
$R^2 = 0.61$

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

Note that Equation 2-10 predicts a decrease in cold-start NO_X emissions for temperatures greater than 75°F, while the data in Table 2-9 indicates an increase in cold-start NO_X emissions as the ambient temperature rises above 90°F. The increase is small and may be an artifact of how these data were analyzed, since only a subset of vehicles was measured above 75°F. Therefore, as with the other temperature adjustments, we have set the NO_X additive adjustment to zero in MOVES for temperatures higher than 75°F.

In addition, we investigated whether different NO_X temperature correction is needed for vehicles subject to the MSAT-2 rule. Figure 2-5 shows a comparison between NO_X start emissions data from OTAQ Cold Temperature Program, including both the port-fuel injection (PFI) and gasoline-direct injection (GDI) 2006-2010 model year vehicles, and the emissions predicted using temperature effects calculated from the MY2005-and-earlier vehicles. Because start emissions compose such a small percentage of total NO_X emissions, the differences between the MOVES temperature effects and the NO_X data from the OTAQ Cold Temperature Program were considered negligible. Thus, we applied the NO_X temperature adjustment estimated in Equation 2-10 for all model years.

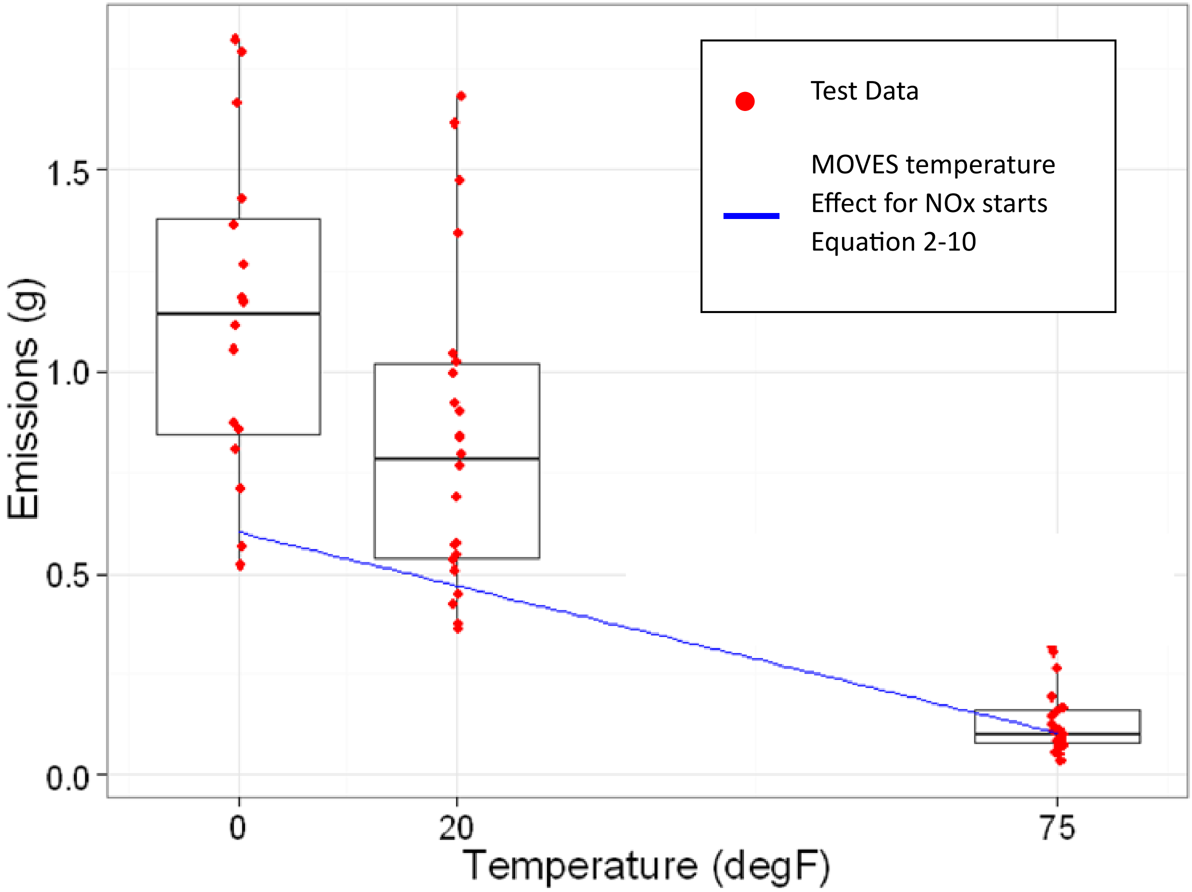


Figure 2-5 FTP Start NO_X Emissions, Bag 1 – Bag 3, Model Years 2006-2010

To adapt the additive adjustments for intermediate soak times, the A coefficients for start operating modes other than cold starts were adjusted by multiplying by a factor equal to the ratio between emissions at the desired soak time and the cold start emissions for catalyst equipped vehicles as used in MOBILE6 and summarized in Table 2-3.

2.2.3. Temperature Effects on Gasoline $PM_{2.5}$ Start Emissions

The temperature effects for particulate matter emissions from gasoline engines were obtained from the Kansas City Light-Duty Vehicle Emissions Study (KCVES)[17], conducted between 2004 and 2005. The KCVES measured emissions from 496 vehicles collected in the full sample, with 42 vehicles sampled in both the winter and summer phases of the program. The EPA conducted an analysis of the temperature effects of gasoline vehicles from the KCVES by estimating the temperature effect on PM emissions from 34 paired vehicle tests that were sampled in both winter and summer ambient conditions (10 paired vehicle tests were removed due to missing values and/or too small temperature differences between the phases) as described in the EPA report[17] and subsequent analysis.[18]

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

Equation 2-11

$$\text{Multiplicative Factor} = e^{\mathbf{A}*(72-\text{Temp})}$$

Where:

Temp = Temperature

A = log-linear temperature effect. A = 0.0463 for cold starts from the KCVES analysis[15][16]

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 that accompanied the rule[12] 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).

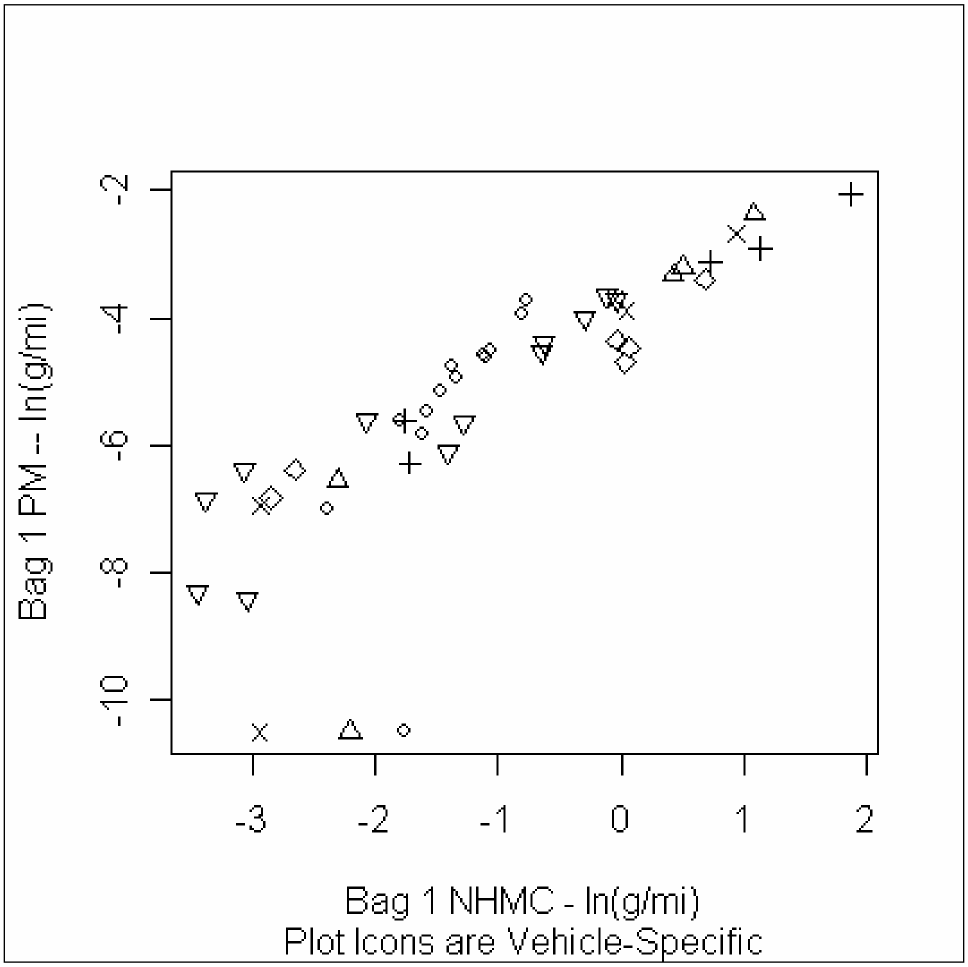


Figure 2-6 FTP Bag 1 PM and FTP Bag 1 NMHC for Tier 2 Vehicles

Therefore, the limitation on cold weather THC (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 20ºF. 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 20° F (for Tier 2 cars and trucks).

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

$$\text{Multiplicative Factor at } 20^{\circ}\text{F for MSAT-2 Vehicles} = 0.7 * e^{0.0463*(72-20)}$$ **Equation 2-12**

$$= 7.8$$

Using Equation 2-12 with the MSAT-2 phase-in schedule from Table 2-7 leads to the following (multiplicative) increases as the temperature decreases from 72° to 20° F:

Table 2-10 Multiplicative Increase in Cold Start $PM_{2.5}$ from 72° to 20° Fahrenheit for Gasoline Vehicles

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

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

Table 2-11 Log-linear Temperature Effect for Start $PM_{2.5}$ Emissions (Coefficient A) for Gasoline Vehicles

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

We confirmed this theoretically derived temperature effect for MSAT-2 compliant vehicles by comparing it to data from the OTAQ Cold Temp Study, which includes only the MY 2010 PFI vehicles(See Appendix B) The temperature effect developed for MOVES fits this data well, as shown in Figure 2-7. Note, as discussed in the light-duty report, we significantly updated the start $PM_{2.5}$ emission rates to account for GDI vehicles in MOVES3 and made additional minor updates in MOVES4,[4] but we did not revisit the temperature effects for start emissions.

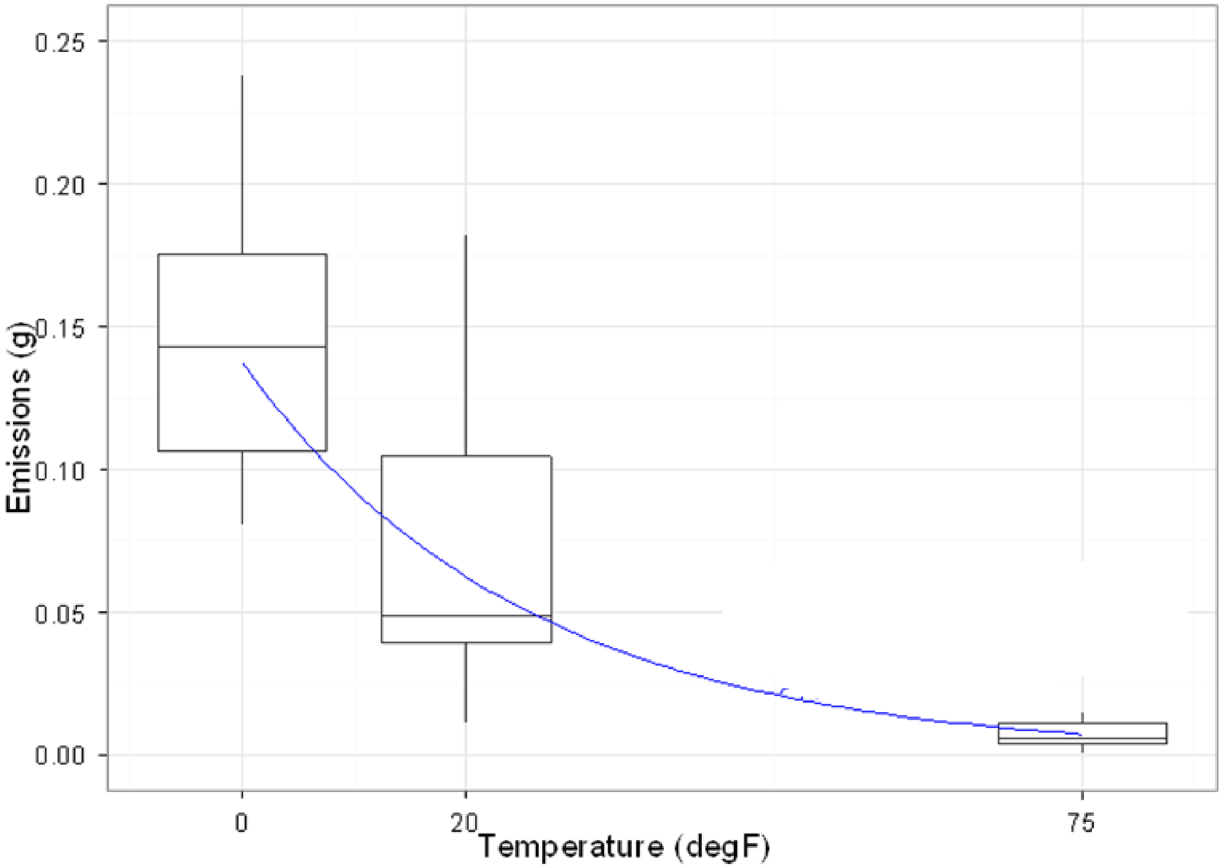
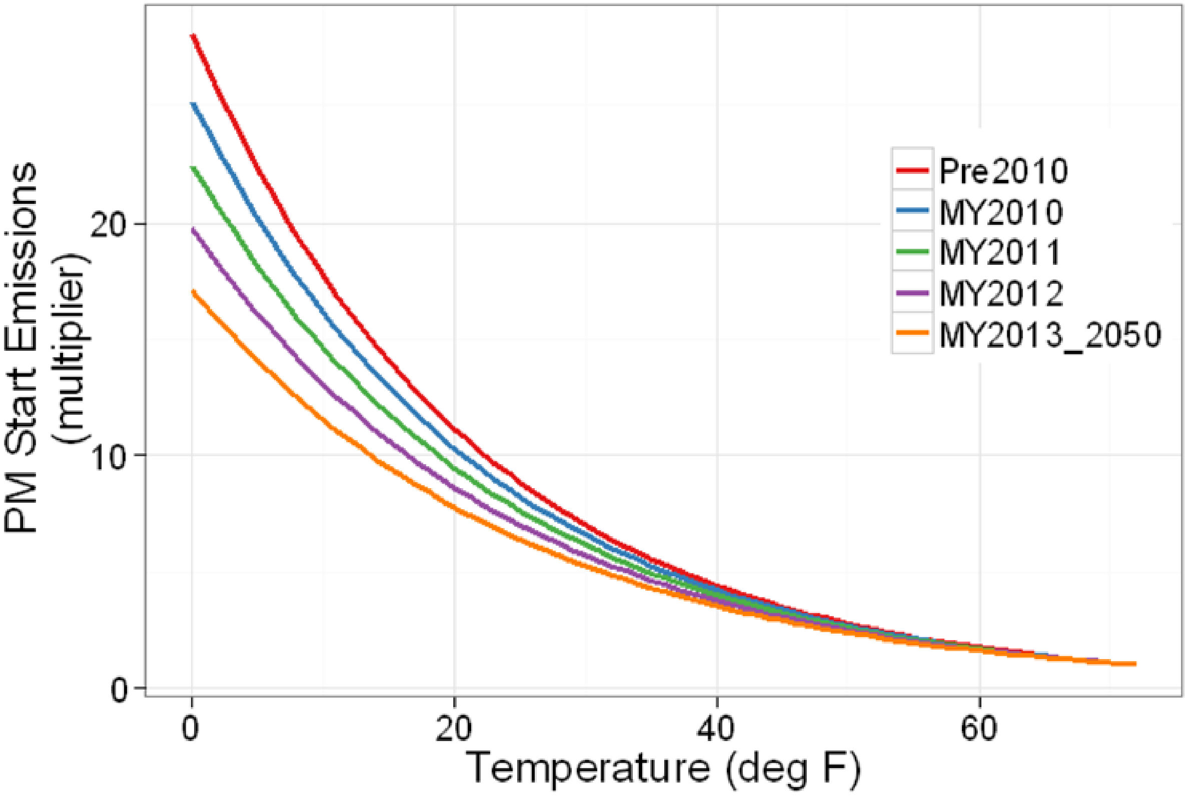


Figure 2-7. FTP $PM_{2.5}$ Start Emissions, MSAT-2 Compliant Vehicles (7 PFI Vehicles, 40 Tests with Nonzero PM Measurements on E10 Fuel) from OTAQ Cold Temperature Program

Figure 2-8 presents the light-duty multiplicative temperature effects using the coefficient from Table 2-11, and the model form of Equation 2-11.



Note: In MOVES, "MY2013_2050" applies to all model years 2013-2060.

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

Because the $PM_{2.5}$ speciation profile for gasoline vehicles did not change significantly between the winter and summer rounds of the KCVES,[19] we apply the same temperature adjustment to each component of the PM emissions, including elemental carbon, organic carbon, sulfate, and other species. The PM start temperature adjustment does not vary with soak time since it is multiplicative.

Effect of Fuel-Injection Technology on Temperature Effects for PM Start Emissions

The adjustment for start emissions described above represents only vehicles equipped with fuel-injection technologies prevalent in 2005, presumably port fuel injection (PFI). Since then, an alternate technology, "gasoline direct injection" (GDI), has entered the market and come to represent a major market share.

This development raises the question as to whether vehicles with GDI would respond differently to cold ambient temperatures than those equipped with PFI. To investigate this question, we combined two datasets, OTAQ (2012) and ORD (2021), which gives a vehicle sample that includes both technologies. Our analysis, explained below, found that a single logarithmic slope term (or rate constant), as in Equation 2-11 above, can be appropriately used as the basis for a temperature adjustment to represent fleets including both PFI and GDI-equipped vehicles.

As detailed in Appendix B , the ORD dataset includes three vehicles, all equipped with GDI. The OTAQ data includes nine vehicles, of which two are GDI-equipped. Combining the two samples gives a total of 12 vehicles, with five GDI-equipped and seven PFI-equipped. This sample enables an analysis designed to test the hypothesis that the trend in PM2.5 with ambient temperature might differ between GDI and PFI.

For this purpose, we used results from the cold-start phase of the FTP cycle (Bag 1). Figure 2-9 shows logarithmically transformed PM, as mg/mi (lnPM) vs. temperature for all 12 vehicles, with those from the recent ORD project distinguished with the prefix “ORD_” and those from the older OTAQ program identified with the prefix “OTAQ_”. In this figure, the view is restricted to the temperatures between 20 and 75°F, despite the fact that some vehicles in the OTAQ program were measured at 0°F. This analysis focused on the question of whether the temperature trend differs between PFI and GDI over this temperature range. A linear trendline is imposed on each panel, which reflects an assumption that the emissions trend is log-linear over this temperature range.

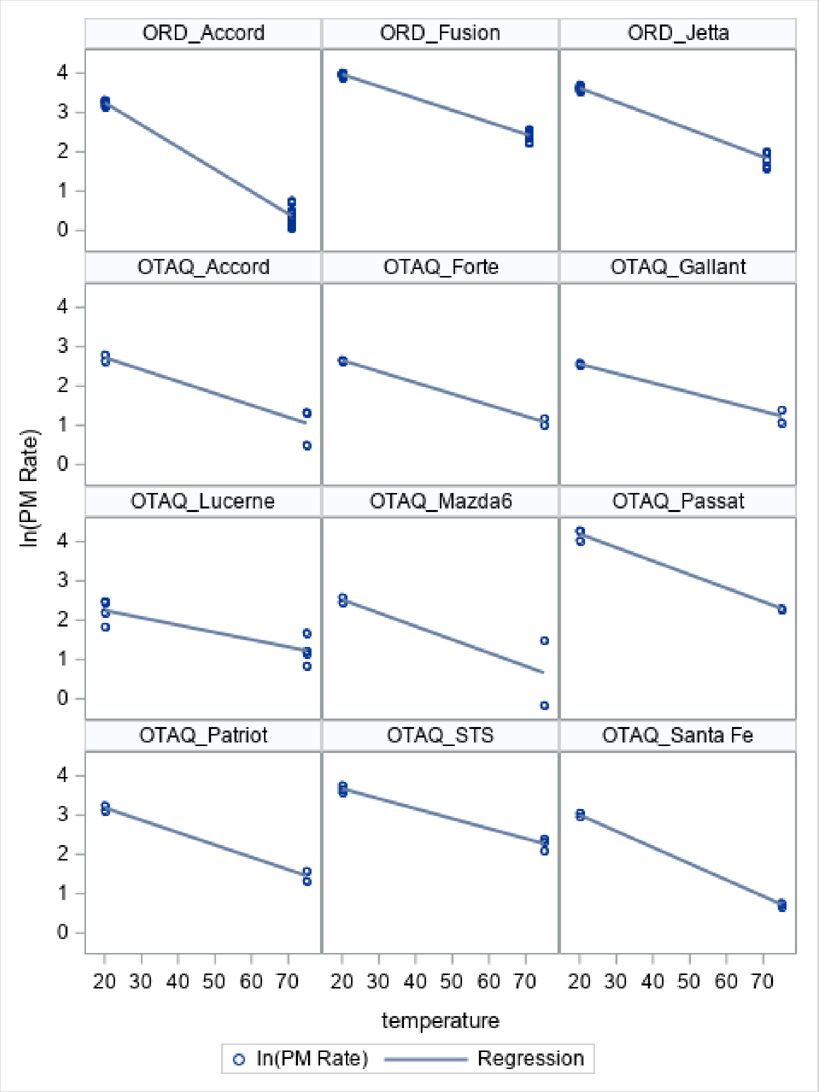


Figure 2-9. lnPM: logarithmically transformed FTP Phase-1 emissions (mg/mi) vs. temperature, by vehicle.

For a more focused comparison of the two fuel-injection technologies, Figure 2-10 shows the data grouped by vehicle and paneled by fuel injection. As a body of data, the GDI data sits higher, with the exception of the ORD Accord, with has the lowest emissions at warm temperature and an apparently steeper trend. With the exception of this vehicle, the two bodies of data have similar slopes.

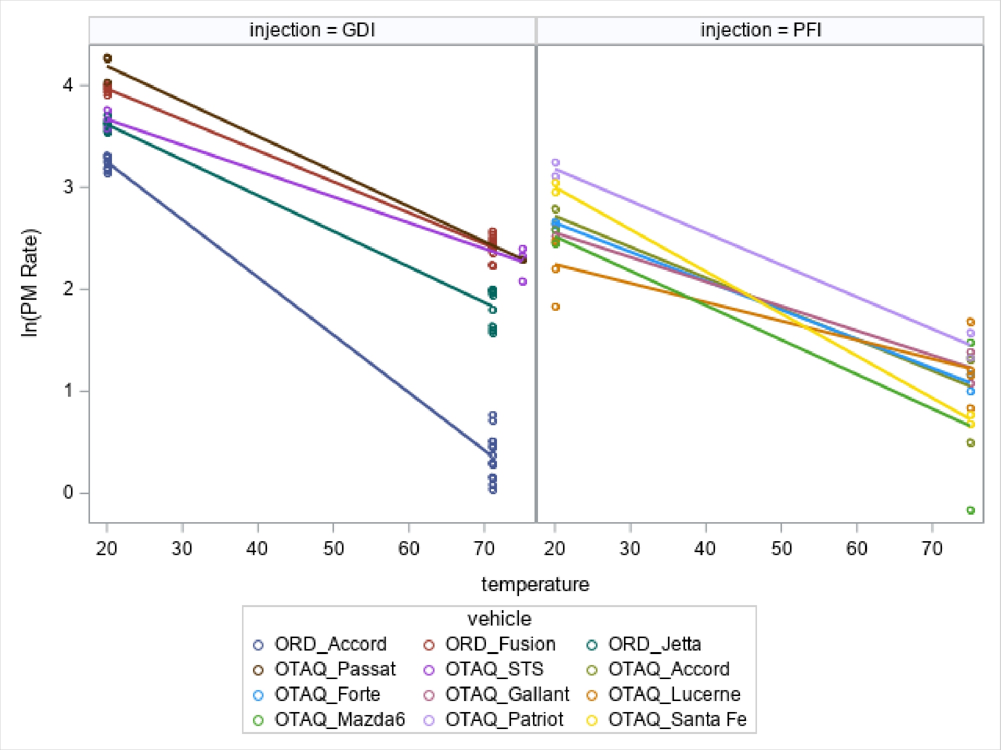


Figure 2-10. lnPM: logarithmically transformed FTP Phase-1 emissions (mg/mi) vs. temperature, by vehicle and fuel-injection technology.

This body of data is sufficient to fit a model to test the hypothesis that the two fuel-injection technologies could have different (logarithmic) trends with temperature over the range of 20-70°F. The mixed-factor 'random coefficients' model includes 'fixed' effects for temperature and fuel injection, as well as 'random' intercepts and slopes for each vehicle.

$$\textbf{lnPM}_{v,r} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1 \boldsymbol{T} + \boldsymbol{\beta}_2 \boldsymbol{\beta}_3 + \boldsymbol{\beta}_2 \boldsymbol{\beta}_4 \boldsymbol{T} + \boldsymbol{b}_{0,v} + \boldsymbol{b}_{1,v} \boldsymbol{T} + \boldsymbol{\varepsilon}_{v,r} \qquad \textbf{Equation 2-13}$$

Where:

lnPM = natural-log transformed PM emissions (mg/mi), for a given replicate for a given vehicle,

T = soak temperature (°F), treated as a continuous variable,

β_0 = a fixed intercept term, reflecting averaging across all vehicles,

β_1 = a fixed slope term, reflecting averaging across all vehicles,

β_2 = a dummy variable indicating fuel- injection technology (0 if PFI, 1 = GDI),

β_3 = an fixed intercept increment representing the effect of fuel injection,

β_4 = a fixed slope increment representing the effect of fuel injection.

$b_{0,v}$ = a "random" increment in the intercept with respect to β_0, for vehicle v, e.g., the individual intercept for vehicle v is $\beta_0 + b_{0,v}$.

$b_{1,v}$ = a "random" increment in the slope with respect to β_1, for vehicle v, e.g., the individual slope for vehicle v is $\beta_1 + b_{1,v}$.

ε_r = residual error variance for replicate r.

Accordingly, when $\beta_2 = 0$, the model for PFI vehicles = $\beta_0 + \beta_1 T$, and when $\beta_2 = 1$, the model for GDI vehicles = $(\beta_0 + \beta_3) + (\beta_1 + \beta_4)T$

As Figure 2-9 and Figure 2-10 suggest, the model fits individual trends (intercepts and slopes) for each vehicle and treats the trends for the vehicles as representing random variation around a mean "fleet" trend.

For this dataset, the random component of the best-fit model contains 14 covariance parameters, including two variances for the random intercepts and slopes, that describe the variance among vehicles, plus individual error variances for each of the 12 vehicles.

The solution for the fixed-effects in the best-fit model is shown in Table 2-12. Additional model-fitting information, including the solution for the random effects, is presented in Appendix F.

Table 2-12. Fixed-Effects Solution for the Best-fit Temperature-effects Model.

Effect	Fuel Injection	Estimate	Standard Error	DF	*t* value	Pr > |*t*|
Intercept (β_0)		3.3669	0.1301	12.5	25.88	<.0001
Temperature T (β_1)		-0.03078	0.003357	14.6	-9.17	<.0001
Fuel injection (β_3)	GDI ($\beta_2 = 1$)	1.1018	0.1833	9.78	6.01	0.0001
Fuel injection	PFI ($\beta_2 = 0$)	0	.	.	.	.
Temperature × Injection (β_4)	GDI ($\beta_2 = 1$)	-0.00563	0.004951	12.7	-1.14	0.2763
Temperature × Injection	PFI ($\beta_2 = 0$)	0	.	.	.	

The initial question in model fitting is whether the interaction term for temperature and fuel injection (β_4) is significant and improves model fit. If this term were significant, it would indicate that the logarithmic slope for GDI-equipped vehicles differed from that for PFI-equipped vehicles. As the table shows, the value for this coefficient is small relative to β_1 and its own standard error, resulting in a small *t* statistic and correspondingly large and insignificant *p*-value. The model fitting thus indicates that both GDI and PFI equipped vehicles can be modeled with the same slope term.

However, the intercept increment for GDI is highly significant, indicating that two logarithmic trends exist for GDI- and PFI-equipped vehicles. These trends have different intercepts but the same slope, i.e., they are parallel, but with the GDI trend sitting higher. If the slope increment for GDI (1.1) is reverse transformed, exp(1.1) = 3.00. This indicates that in this vehicle sample, the PM Phase-1 emissions are three times higher for GDI-equipped than for PFI-equipped vehicles over the measured temperature range.

The overall conclusion from this analysis is that a single logarithmic slope term (or rate constant), as in Equation 2-11 above, can be appropriately used as the basis for a temperature adjustment to represent fleets including both PFI and GDI-equipped vehicles.

2.3. Temperature Effects on Running Exhaust Emissions from Gasoline Vehicles

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

2.3.1. THC, CO, and NO_X Running Exhaust Temperature Effects

We examined the same data described above for starts to evaluate potential running temperature effects. These test data suggest that there is very little effect of temperature on running emissions of THC, CO, or NO_X. Regression analyses found that the coefficients (slopes) were not statistically significant (that is, the slopes were not distinguishable from zero). This contrasts with the significant temperature effect in THC, CO, and NOx Bag 2 of the Kansas City Light-Duty Vehicle Emissions Study (KCVES) with higher emissions at colder temperatures.[17] As discussed for PM emissions in the next subsection, we attribute the temperature effect on THC, CO, and NOx emissions observed in the KCVES to the short duration and mild acceleration of Bag 1 of the LA-92 driving cycle, such that the vehicles had not fully reached hot-stabilized condition by the beginning of Bag 2.

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

Because most of the data sets evaluated did not find a significant temperature effect, and the temperature effect observed in the KCVES is attributed to the test conditions not achieving hot-stabilized running conditions, we do not model temperature effects for THC, CO, and NOx in MOVES for running exhaust for all gasoline vehicles. In MOVES, these effects are coded using polynomial functions as multiplicative adjustments. Therefore, in MOVES, we set all of those adjustments equal to 1.0.

2.3.2. $PM_{2.5}$ Running Exhaust Temperature Effects

The initial analysis of the Kansas City Light-Duty Vehicle Emissions Study (KCVES) data[15] [16] indicated that significant ambient temperature effects existed for both start (Bag1-Bag3) and running (Bag 2) PM emissions on the LA-92 cycle[c]. Thus, MOVES2010 applied a temperature effect for running emissions for

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[c] The temperature effects in MOVES2010 and MOVES2014 for pre-2004 vehicles were substantial. Emissions increased by a factor of 10 between ambient temperatures of 72°F and 0°F.

all model year vehicles based on the Bag 2 measurements from paired vehicles tests conducted in the winter and summer of the KCVES.

For MOVES2014, we updated the PM temperature effect for running emissions for Tier 2 and later model year vehicles (2004+) based on data from the 2012 Cold Temperature Program (documented in Appendix B). Experimental data collected in the 2012 OTAQ program involved measurement of PM emissions on both the FTP (by phase) and the US06 cycles at temperatures of 0, 20 and 75°F of Tier 2 and MSAT-2-compliant vehicles and PFI and GDI (See Appendix B). The results from these programs are plotted against temperature in Figure 2-11. We also fit log-linear models to the data and found the effect of temperature was not statistically significant on either cycle. Based on these results, we removed the temperature effect for Tier 2 vehicles (model year 2004 and later) in MOVES2014.

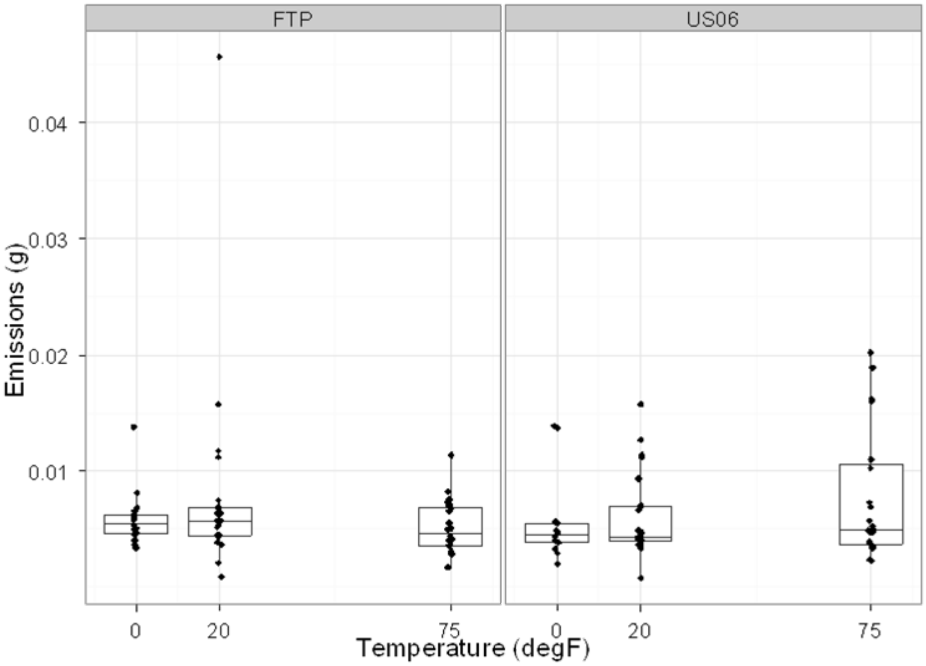

Figure 2-11. Hot-running PM Emissions Measured on Two Cycles (FTP Bag 2, US06) on MSAT-2 Compliant MY 2010 Gasoline Vehicles, Reported as Grams/cycle

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

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

end. In contrast, the cold-start phase of the FTP, used in the Cold Temperature Program is 505 seconds (3.59 miles) in length.

For MOVES3, we conducted a literature review from other studies that measured particulate matter emissions from gasoline vehicles including model years before 2004 at different ambient temperatures. The results are summarized in Table 2-13.

Table 2-13. Literature Review of Temperature Effects on Running $PM_{2.5}$ emissions from Gasoline Vehicles

Study	Vehicles and Test conditions	Findings on $PM_{2.5}$ emissions
Measurements of Exhaust Particulate Matter Emissions from In-Use Light-Duty Motor Vehicles in the Denver, Colorado Area[20 21]	71 light-duty gasoline vehicles from model year 1970 to 1996 tested in the summer of 1996 and winter of 1997 on a chassis dynamometer using bag 2 of the FTP driving schedule.	Linear mixed model was fit and no significant temperature effect was observe.
Comprehensive particle characterization of modern gasoline and diesel passenger cars at low ambient temperature[22]	Two Euro-3 (apply to 2000 -2004 model year vehicles) port-injection gasoline vehicles (Renault Megane and Alfa 406 TS) Tested +23, -7 and -20℃ on a chassis dynamometer on the common Artemis driving cycle (CADC), after warmed up on 50-minute IUFC15 driving cycle.	No temperature effect observed on running emissions.
Characterization of Metals Emitted from Motor Vehicles[23]	Emission rates derived from $PM_{2.5}$ concentrations measured at the entrance and exit concentration of the Howell tunnel in Milwaukee, WI in the summer of 2000 and the winter of 2000-2001. Light-duty vehicles constituted between 90.6 percent to 93.9 percent of the vehicle fleet, with 6.1 percent to 9.4 percent heavy-duty trucks. Chemical mass balance methods were used to estimate the contribution of tunnel emission rates to gasoline tailpipe, diesel tailpipe, brake wear, resuspended road dust, and tire wear emissions.	Carbonaceous $PM_{2.5}$ (EC+OC) emission rates (mg/km) were significantly lower (49-51 percent) in the winter than the summer. Gasoline tailpipe emissions are estimated to be the largest contributors to EC and OC emissions[a]; more than diesel tailpipe, brake wear, and resuspended road dust. The winter tests had comparable or larger PM measurements of inorganic ions and metals (including Na and Cl) presumably due to road salt in the winter.

[a] Gasoline tailpipe and tire wear are combined because they have similar source profiles. However, for the pre-2004 model years covered here, gasoline tailpipe emissions in MOVES contribute a much larger share of $PM_{2.5}$ emission rates (and thus EC and OC) than brake wear emissions.[24]

The result of the literature review (Table 2-13) suggested no temperature effects on PM exhaust emissions, even for model year vehicles similar to the years measured in the KCVES. Thus, we now believe the significant running PM temperature effect in KCVES was an artifact of the measurement conditions of the study, including the short Bag 1 of the LA-92 cycle. Therefore, starting with MOVE3, we have removed the running temperature effect for exhaust particulate matter emissions for all model year light-duty gasoline vehicles.

2.4. Temperature Effects on Diesel Vehicles

With the exception of projections for 2027 and later HD NO_x effects (see Section 2.4.1.3), the data used to evaluate and estimate temperature effects on diesel vehicles were limited to laboratory tests on pre-2007 model year light-duty diesel vehicles. From this analysis, MOVES models a temperature effect only for THC start emissions. The THC start temperature effect estimated from the light-duty diesel was applied to all model year diesel vehicles in MOVES, including heavy-duty diesel vehicles. None of the other pollutants in MOVES have temperature effects for diesel start emissions and MOVES has no temperature adjustments for running emissions.

As described below, we reviewed more recent studies conducted on modern diesel and heavy-duty diesel vehicles, but additional temperature effects data for US light-duty and heavy-duty diesel are needed to fully evaluate the values now in MOVES.

2.4.1. THC, CO, and NO_X Temperature Effects for pre-2027 Diesel Vehicles

For the development of the original diesel temperature effects in MOVES, we were able to identify only 12 diesel vehicles tested on FTP at multiple temperatures (9 passenger cars and 3 light-duty trucks). However, only two of those 12 vehicles were tested at temperatures within the normal FTP range (68° to 86° F). None of these diesel trucks were equipped with aftertreatment devices.

2.4.1.1. Diesel Start Effects

The average start (Bag-1 minus Bag-3) emissions for those tests are shown in Table 2-14. We stratified the test results into four temperature bands which yielded the following emission values (grams per start) and average temperature value:

Table 2-14 Average Light-duty Diesel Vehicle Incremental Start Emissions (Bag 1- Bag3) by Temperature (grams per start)

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

Figure 2-12 shows the plot of mean THC start emissions versus temperature (where the vertical lines represent 90 percent confidence intervals and the "dashed" line represents a linear regression through the data).

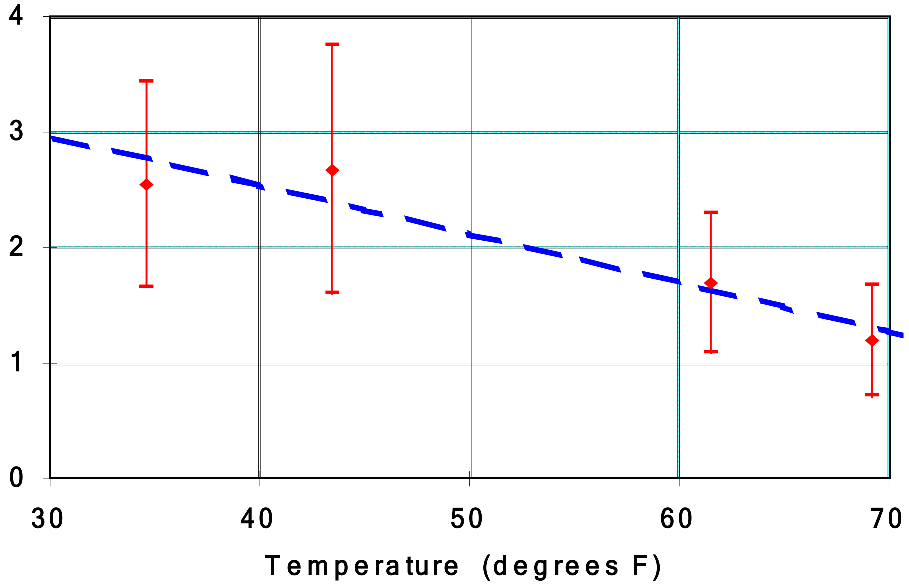

Figure 2-12 Mean Light-duty Diesel Cold-start THC Emissions (in grams, shown on the y-axis) with 90 percent Confidence Intervals vs Temperature

The dashed (blue) line in Figure 2-12 represents a linear regression line:

$$\text{THC} = (-0.04 * \text{Temperature}) + 4.22 \qquad R^2 = 0.90$$

Equation 2-14

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

$$\text{THC additive temperature adjustment} = A * (\text{Temp.} - 75)$$

Where:

Equation 2-15

$A = -0.04$

Temp. is <75° F

The coefficient associated with this temperature adjustment term is statistically significant although its coefficient of variation is relatively large (23 percent). We apply this adjustment to heavy-duty as well as light-duty vehicles due to limited data on heavy-duty diesel starts.

The modified temperature adjustments for diesel THC emissions for starts with shorter soak times (operating modes 101-107) are described in the MOVES heavy duty exhaust report.[5]

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

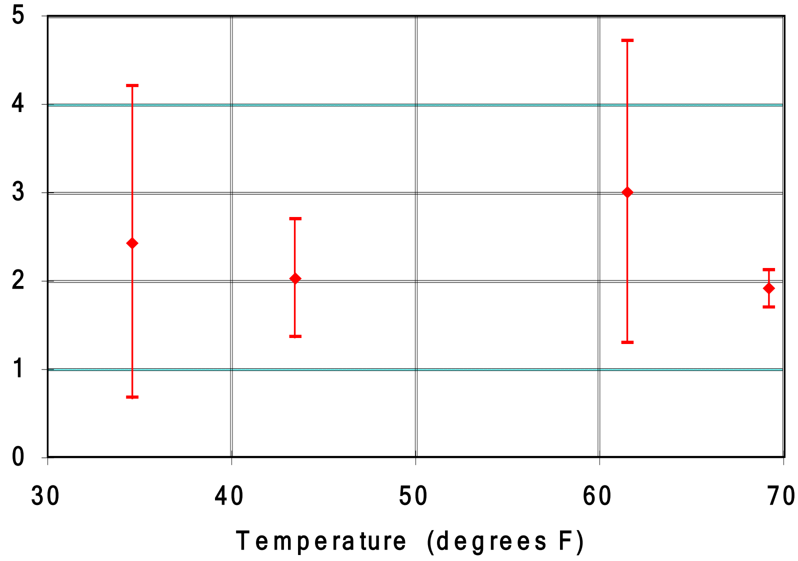

Figure 2-13 Mean Light-duty Diesel Cold-start CO Emissions (in grams) with 90 percent Confidence Intervals vs Temperature

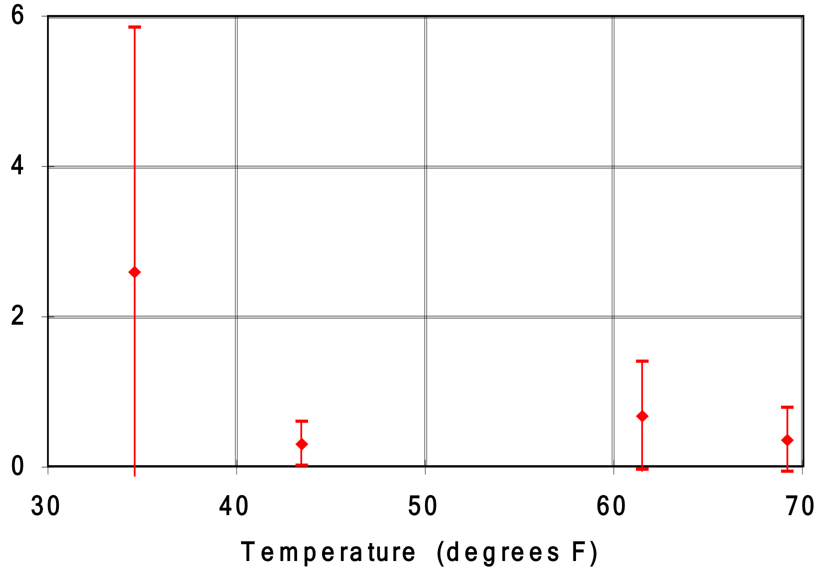

Figure 2-14 Mean Light-duty Diesel Cold-start NO_X Emissions (grams) with 90 percent Confidence Intervals vs Temperature

Statistical analyses of both the diesel cold-start CO and NO_X emissions showed that the coefficients were not significantly different from zero. Therefore, for both cold-start CO and NO_X adjustments for diesel vehicles, we set the temperature adjustment for start emissions to zero.

2.4.1.2. Diesel Running Effects

Since the diesel start temperature effects were either very small or zero, we did not evaluate the diesel running temperature effect for THC, CO, and NO_X for MOVES – we set temperature effects for diesel running exhaust to zero, similar to the gasoline running exhaust adjustments. The exception is NOx emissions for model year 2027 and later, as described below.

We are aware of studies suggesting that diesel NO_x may be underestimated in current US emission inventories during the wintertime[25] and suggesting that there is an increase in heavy-duty diesel NOx emissions at cold temperatures in the US.[26,27,28,29] We will revisit the NO_x temperature effects in MOVES as more data on light-duty and heavy-duty diesels become available.

2.4.1.3. NO_x Temperature Effects for HD Diesel Model Years 2027 and Later

Unlike earlier NOx standards, the HD2027 rule includes off-cycle standards that are a function of ambient temperature; thus, MOVES incorporates cold temperature effects for NO_x from heavy-duty diesel vehicles of model year 2027 and later. This update was based on a 2022 testing program on a prototype engine designed to meet the HD2027 emission standards.[26] The testing was conducted using the CARB Southern Route Cycle at laboratory temperatures (approximately 25°C) and with the ambient temperature between 2 °C and 9 °C. The results from the testing showed that emissions were approximately double at low ambient temperature versus standard laboratory temperature. The tests showed that cold temperatures caused elevated NOx emissions at start and throughout the nearly 6-hour test cycle.

These temperature effects were incorporated into the HD2027 off-cycle NO_x standards as summarized in Table 2-15.

Table 2-15 Temperature Adjustments to the Off-cycle NO_X Standards in the HD2027 Rule (§1036.104 Table 3 to Paragraph (a) (3))[27]

Off-Cycle Bin	NO_x Standard at 25 °C	Temperature[a]-based Adjustment for NO_x
Bin 1	10.0 g/hr	$(25.0-T_{amb})* 0.25$
Bin 2	58 mg/hp-hr	$(25.0-T_{amb})* 2.2$
[a] T_{amb} is the mean temperature in °C over a shift day, or equivalent. The off-cycle NO_x standard for T_{amb} below 25 °C is adjusted by adding the temperature adjustment to the specified NO_x standard in g/hour for Bin 1 and mg/hp-hr for Bin 2.		

For MOVES, we used these values, combined with the temperature-independent duty-cycle standards, to model effective NO_x running and extended idle emission rates for each MOVES operating mode and all relevant regulatory classes (42 thru 48) during in-use operations at both 25°C and 5°C. The details of the HD2027 emission rate calculation process can be found in the MOVES heavy-duty exhaust emissions report[5]

Since MOVES applies the temperature adjustment after all operating mode detail has been aggregated away, we calculated a nationally representative operating mode distribution for each regulatory class, and derived a weighted average emission rate for each regulatory class at both 25°C and 5°C. From this, we calculated a percent increase in NO_x emissions per degree change in temperature. Since MOVES uses the Fahrenheit scale, this was converted to a percent increase in grams of NO_x per degree Fahrenheit below 77°F.

The resulting multiplicative temperature adjustment varies by regulatory class and emissions process, and is calculated for temperatures below 77°F as follows:

$$\text{Adjustment} = \big((77.0 - \text{temperature}) \times \text{tempAdjustTermA}\big) + 1 \qquad \textbf{Equation 2-16}$$

Table 2-16 shows the values of tempAdjustTermA used in the above equation, which are stored in the TemperatureAdjustment table.

Table 2-16 NO_x Temperature Adjustment Coefficients by Regulatory Class and Process

Process (processID)	Regulatory Class (regClassID)	tempAdjustTermA
Running (1)	LHD45 (42)	0.005139
	MHD67 (46)	0.003957
	HHD8 (47)	0.006352
	Urban Bus (48)	0.008397
Extended Idle (90)	Doesn't matter (0)	0.01389

2.4.2. PM Temperature Effects for Diesel Vehicles

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

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

Mathis et al. (2005)[22] 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. Although the researchers observed an increasing trend in particle mass emissions (g/start) from the conventional diesel vehicle at colder temperatures, over the entire drive cycle, the particle number emission rates were not significantly impacted by the cold start contribution. The particle mass emissions from the DPF-equipped vehicle were two orders of magnitude smaller than the conventional diesel engines, but the start contributed the majority of the particle number emissions over the entire test cycle.

Sakunthalai et al. (2014[28]) also reported significant increase in PM start emissions from a light-duty diesel engine tested in a laboratory at +20 and -20°C. 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,[37] [38] 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 in the mobile-source emission inventory. The diesel particulate matter emission temperature effects in MOVES can be revisited in the future as additional data become available.

2.5. Temperature Effects on Compressed Natural Gas Vehicles

MOVES models emissions from heavy-duty vehicles running on compressed natural gas. However, at the time the temperature corrections were developed, no data were available on temperature impacts for compressed natural gas emissions. As discussed in the heavy-duty report,[5] the start emissions for CNG emissions for THC, CO, NO_X and PM are set equal to diesel start emissions. Thus, we also applied the diesel start temperature adjustments on THC emissions to CNG.

2.6. Temperature Effects on ICE Vehicle Energy Consumption

The temperature effects on energy consumption for internal combustion engine (ICE) vehicles in MOVES have not been updated since MOVES2004. No temperature correction is applied to energy consumption from running activity because the analysis documented in the MOVES2004 energy report[29] found no significant temperature effects for warmed-up vehicles. The same report also details the analysis used to derive temperature effects on start energy consumption in MOVES. As presented in heavy-duty report,[5] 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 updated the start energy rates or temperature adjustments in subsequent versions of MOVES.

In this section, we provide a summary of the start temperature effects on energy consumption in MOVES. 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 2-17, which is applied to all ambient temperatures. Unlike the temperature adjustments for criteria pollutants, MOVES does not limit the energy consumption adjustments to only cold temperatures, but also adjusts the energy consumption for hot temperatures. This ambient temperature adjustment is separate from the air conditioning adjustment described in Section 4, below.

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 in the MOVES Greenhouse Gas and Energy report[6] for light-duty vehicles and heavy-duty exhaust report.[5]

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

Equation 2-17

Table 2-17 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, regulatory class, 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.[6] CNG vehicles use the same adjustments as diesel vehicles, because they use the same energy start rates as comparable diesel vehicles. The start energy coefficients do not vary by regulatory class, so regClassID 0 ("doesn't matter") is assigned to these rows.

Table 2-17. Multiplicative Temperature Coefficients for Start Emissions Used in MOVES

tempAdjustTermA	tempAdjustTermB	Fuel types	Model Years
-0.01971	0.000219	Gasoline, E85	1950-2060
-0.0086724	0.00009636	Diesel, CNG	1950-2060

Figure 2-15 displays the multiplicative temperature adjustments for starts as a function of temperature. At 75°F, the multiplicative adjustment is one. Gasoline vehicles have a larger temperature effect than diesel vehicles, increasing to 4.8 at -20°F, while decreasing to 0.64 at 100°F. Whereas, the adjustment for diesel vehicles only increases to 2.7 at -20°F and decreases to 0.85 at 100°F.

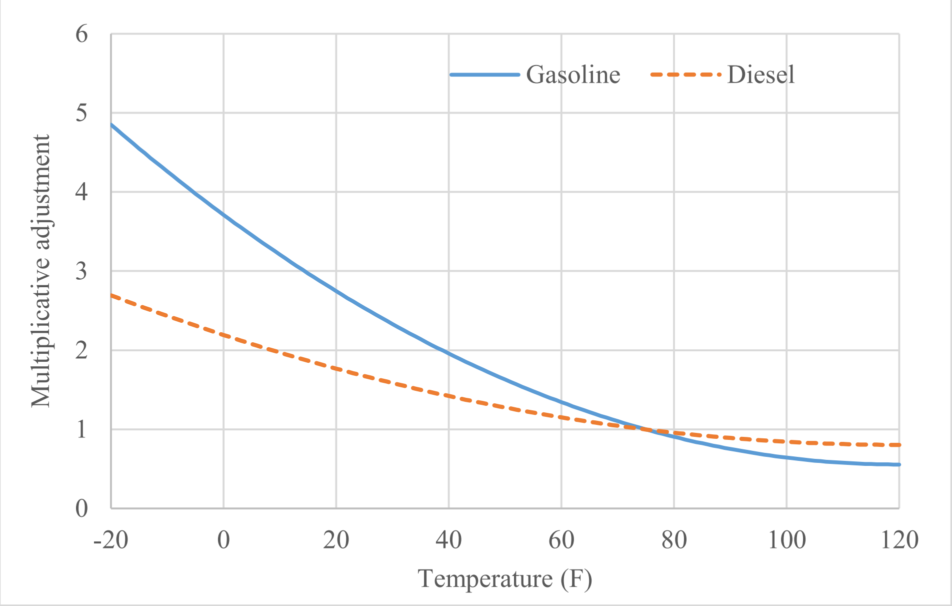

Figure 2-15. Multiplicative Temperature Adjustments for Starts from Energy Consumption as a Function of Ambient Temperature

2.7. Temperature Adjustments for Electric and Fuel-Cell Vehicles

Electric vehicles (EV) do not have exhaust emissions like internal combustion engines, but ambient temperature has a large impact on their energy consumption. Energy consumption can increase due to increased resistance in the drive train and electrical components, but the largest cause for the increase is the use of heating and air conditioning.

Heating is particularly important to consider because EVs cannot scavenge waste heat from the engine like internal combustion engine (ICE) vehicles can. As noted in the sections above, while MOVES does estimate a cold temperature effect on energy consumption from ICE vehicle starts, no direct or cold-weather temperature correction is applied to energy consumption from ICE running activity.

Because MOVES does not estimate energy consumption from starts for electric vehicles, there is no start temperature effect on EV energy consumption.

This sub-section describes how we used the limited available data, as well as existing assumptions on ICE temperature and A/C corrections in MOVES, to develop the appropriate coefficients for the new EV adjustments.

At a heat index above 67°F, MOVES3 and earlier versions of MOVES adjust energy consumption based on ambient temperature via an air conditioning adjustment (see Section 4). The MOVES air conditioning (A/C) adjustments are applied only to passenger cars, passenger trucks, and light commercial trucks. The A/C adjustment algorithm is applied for these vehicle types regardless of fuel type. Therefore, the light-duty EV source types only require a temperature adjustment for temperatures below 67°F. Because heavy-duty EVs lack an A/C adjustment in MOVES, they require both a high and low temperature adjustment for energy.

We use the temperatureAdjustment table in the MOVES default database to adjust EV energy consumption based on ambient temperature. The adjustment is multiplicative, based on Equation 2-18. This quadratic equation matches the basic form of many other MOVES temperature adjustments, such as described in Equation 2-17, where *temperature* represents the ambient temperature in Fahrenheit.

$$\begin{aligned} &\mathit{Multiplicative\ temperature\ adjustment} \\ &\qquad = 1.0 + \mathit{tempAdjustTermA} \times (\mathit{temperature} - 72) \\ &\qquad + \mathit{tempAdjustTermB} \times (\mathit{temperature} - 72)^2 \end{aligned} \quad \textbf{Equation 2-18}$$

At Project Scale, the sign of the adjustment coefficients is flipped if the *meanBaseRate* value is negative; this is a special case to ensure that regenerative braking on electric vehicles is not modeled as generating more energy when electric heaters are running.

The primary data source for the EV temperature adjustments is an American Automobile Association (AAA) study which tested several EV passenger cars on a chassis dynamometer at room temperature, extreme cold (20°F), and extreme heat (95°F).[30] Their testing included a 2018 BMW i3s, 2018 Chevrolet

Bolt, 2018 Nissan Leaf, 2017 Tesla Model S, and a 2017 Volkswagen e-Golf. While all vehicles are passenger cars, they cover a variety of heating and cooling technologies, including both heat pumps (BMW i3s and Nissan Leaf) and resistive heaters (Chevrolet Bolt, Tesla Model S, and Volkswagen e-Golf). All five vehicles were tested at all three temperatures, with the cabin temperature always set to maintain 72°F.

Unlike other potential data sources, the AAA study measures the influence of ambient temperature on EV energy consumption directly through experimental design, rather than through real-world observational data which can have several confounding factors. Therefore, we used the AAA study to derive the exact temperature adjustment for EVs in MOVES. In Appendix D, we show that the temperature adjustment calculated using the AAA study is broadly consistent with observational data.

Relative to room temperature, the AAA found a 39% reduction in miles per gallon equivalent (MPGe) at 20°F and a 17% reduction in MPGe at 95°F, corresponding to a 64% and 20% increase in energy consumption, respectively. Using these changes in energy consumption, a set of linear equations can be derived that allow us to calculate temperature adjustment term A and B for Equation 2-18. They are 0.00225 and 0.00028, respectively.

As noted above, passenger cars, passenger trucks, and light commercial trucks, are already subject to an air conditioning adjustment in MOVES. A typical A/C adjustment during a MOVES run is around 20%, consistent with the AAA study results. To avoid double-counting, Equation 2-18 is applied only when the air conditioning adjustment is not being used. The MOVES air conditioning activity demand function is detailed in the MOVES Population and Activity Report.[31] According to this function, 67°F is the minimum heat index at which an A/C adjustment is applied. In MOVES, this value is hardcoded as the point above which MOVES uses the A/C adjustment algorithm, and below which MOVES uses the temperature adjustment algorithm to scale light-duty EV running energy consumption.

Aside from this exception for light-duty air conditioning, we assume the coefficients derived from the AAA report are representative of all electric vehicles, including heavy-duty. Therefore, they are used for every electric vehicle of every class and EV technology (fuel cell and battery electric). While the adjustments were derived using only the AAA report, we analyzed the adjustments in relation to other published studies and test programs to ensure that the temperature adjustment in MOVES is consistent with many sources, including testing of heavy-duty vehicles. Appendix D evaluates this approach by comparing the resulting energy consumption rates to data from independent studies and shows reasonable agreement. As EV technologies continue to mature and as more temperature effect data becomes available, we hope to revisit both the form and the coefficients for these adjustments.

2.8. Conclusions and Future Research

With improved calibration and temperature management, ambient temperatures generally have less impact on emissions of newer vehicles than older ones but MOVES estimates temperature effects for THC, CO, NO_x and PM start emissions from gasoline vehicles, THC starts for diesel and CNG vehicles, NO_x running emissions for post-2027 heavy-duty diesel vehicles, and running energy consumption for electric vehicles.

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

- Evaluating the benefits of applying log-linear or other mathematical models for pre-MSAT2 gasoline vehicle THC & CO temperature effects and considering whether all temperature effects could be multiplicative rather than using additive effects for THC/CO/NOx start emissions.
- Investigating ambient temperature effects on cold start emissions at temperatures warmer than 75° F.
- Evaluating the interaction of ambient temperature effects and fuel effects.
- Evaluating the interaction of ambient temperature effects and emission control deterioration.
- Analyzing ambient temperature effects for modern (2007 and later) diesel vehicles from recent studies, 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 newer technology gasoline vehicles, including Tier 3 gasoline direct injection, and dual port-fuel and direct injection, stop-start technologies, battery electric vehicles and hybrid technologies.
- Analyzing the effect of temperature on other pollutants estimated in MOVES including ammonia (NH_3).
- Evaluating EV energy used to condition the battery at various ambient temperatures, especially temperatures between 35 and 65°F which are most common in shoulder months.
- Evaluating different EV heating and cooling technologies (such as resistive heating and heat pumps) and their efficiencies at various ambient temperatures.
- Evaluating energy used for EV heating and cooling in a wider range of vehicles, including single-unit and combination trucks. For example, buses and cars need to maintain the climate in close to the full volume of the vehicle, while combination trucks have a much smaller cabin relative to their power requirements and may require a smaller multiplicative temperature adjustment.

3. Humidity Adjustments

Water in the ambient air cools the peak combustion temperature and lowers engine out NO_X emissions. We adjust for this when evaluating source data for MOVES. More specifically, the NO_X exhaust emissions data used to develop emission rates for MOVES are adjusted from actual measurement conditions to a standard humidity; this includes the emissions data from the Evaluation Sample for the Denver Metropolitan I/M Program used to develop NO_x emission rates for MY 1990 and later gasoline vehicles[4] and the emissions data from the Heavy-Duty Diesel In-Use Testing Dataset used to develop NO_x emission rates for MY 2010 and later heavy-duty diesel vehicles.[5] At run time, these base NO_X exhaust emission rates are adjusted from the standard humidity level to the humidity conditions specified by the run spec as described below.

3.1. Humidity Adjustment Equation

In MOVES, the base exhaust emission rates for NOx in all modes and all processes are multiplied by a unitless humidity factor, K. This factor is calculated separately by fuel type, with diesel using one equation and set of coefficients while gasoline, CNG, and E-85 use another equation and set of coefficients.

The equations and coefficients for each fuel type are determined by the Code of Federal Regulations (CFR). The diesel adjustment is based on Part 1065[32] for heavy-duty in-use testing and the adjustment for other fuel types is based on Part 86[33] for light-duty vehicle emissions testing. In each case, the equation specified is the inverse of the adjustment specified in the CFR. This is because the CFR equation is used to adjust emissions to a standard humidity level, while MOVES is taking base rates calculated at the standard humidity level and adjusting them based on the humidity level in the run to calculate a real-world emission rate. In MOVES4 and subsequent versions, the equations and coefficients were updated to better represent this inverse relationship.

Table 3-1 shows the equation coefficients, bounding humidity levels, and humidity units used for each adjustment, as represented in the noxHumidityAdjust table in the MOVES default database. If the specific humidity input is outside the bounding humidity levels, the value of the limit is used to calculate the adjustment. The adjustment for gasoline, CNG, and E-85 vehicles is shown in Equation 3-1 and the adjustment for diesel vehicles is shown in Equation 3-2.

Table 3-1 NO_x Humidity Adjustment Parameters for all Fuel Types

fuelTypeID	CFR Source	Adjustment Equation Terms		Specific Humidity Bounds		Specific Humidity Units
		A	B	Lower Bound	Upper Bound	
1 (Gasoline)	40 CFR 86.144-94	0.0329		3.00	17.71	grams of water / kg of air
2 (Diesel)	40 CFR 1065.670	9.953	0.832	0.002	0.035	moles of water / moles of air
3 (CNG)	40 CFR 86.144-94	0.0329		3.00	17.71	grams of water / kg of air
5 (E85)	40 CFR 86.144-94	0.0329		3.00	17.71	grams of water / kg of air

$$K = 1 - humidityTermA * (specificHumidity - 10.71) \qquad \textbf{Equation 3-1}$$

$$K = \frac{1}{(humidityTermA * x_{H2O}) + humidityTermB} \qquad \textbf{Equation 3-2}$$

MOVES only uses relative humidity as the input source for humidity, either by users or in the default database via the zonemonthhour table. Appendix A6 shows how MOVES calculates specific humidity based on relative humidity, ambient temperature, and barometric pressure.

3.2. Future Research

Future work could investigate whether the real-world emissions impact of humidity is similar to the corrections developed from laboratory testing used in the Code of Federal Regulations. Additional work could evaluate the emission impact of humidity on more recent gasoline, diesel and alternative-fueled engines and consider whether modern engine calibration and emission control technologies impact the humidity effect.

4. Air Conditioning Adjustments

MOVES applies air conditioning adjustments to THC, CO, NO_x and energy consumption from passenger cars, passenger trucks and commercial light trucks. The air conditioning (A/C) effects described below were originally derived for MOVES2010.

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

The MOVES A/C adjustment varies by operating mode for total energy consumption and exhaust running THC, CO and NO_X emissions and applies only to passenger cars, passenger trucks and commercial light trucks. The HD emission rates for conventional vehicles do not require explicit A/C adjustments because they are based on real-world driving that includes A/C usage depending on ambient conditions when the test was conducted. For example, the model year 2010 and later HD diesel energy rates are based on manufacturer-run Heavy-Duty In-Use Testing (HDIUT) data.[5] The impact of air conditioning usage on energy consumption for heavy-duty electric and fuel-cell vehicles is handled as a temperature correction as explained in Section 2.7.

4.1. Air Conditioning Effects Data

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

The data used to develop the MOVES ACCF consisted of emission results from 54 individual cars and light trucks tested over a variety of test schedules. Overall, the database consisted of a total of 625 test cycles and 1,440,571 seconds of emission, speed, and acceleration data. Because of the need to compute vehicle specific power on a modal basis, only test results which consisted of second-by-second data were used in the MOVES analysis. All second-by-second data were time-aligned and checked for errors.

The distribution of test vehicles by model year is shown in Table 4-1. Model years 1990 through 1999 were included. The data set consists of 30 cars and 24 light trucks. No test data were available on other vehicle types (e.g., motorcycles or heavy-duty trucks). The individual test cycles on which the vehicles were run are shown with the test counts in Table 4-2. The data shows a balance between different test cycles and cars and trucks. The individual vehicles are listed in Appendix C.

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

Table 4-1 Distribution of test vehicles by Model Year

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

Table 4-2 summarizes the distribution of test-cycles analyzed. The test-cycles are defined in a MOBILE6 report.[34]

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. Air Conditioning Effects on Emissions and Energy

The data described above was then used to estimate factors to account for increases in emissions and energy consumption with full loading of the air conditioning system. These factors are recorded for running and extended idle emissions by sourcetype, pollutant and operating mode in the fullACadjustment table of the MOVES database. Thus, the same effects are applied for all light-duty fueltypes and model years.

4.2.1. Full A/C Adjustments for THC, CO and NO_X Emissions

Average emissions for each pollutant (HC, CO and NO_x) with and without A/C operation were computed for each of the MOVES light-duty running operating modes as defined using vehicle specific power (VSP).[4] This resulted in 69 (23 VSP bins x 3 pollutants) pairs of emission averages. However, the trends were erratic, and the results were generally not statistically significant. In addition, most of the high-speed bins had little data. An analysis of cars versus light-duty trucks showed no statistical difference between the two. To produce more consistent results, the individual VSP bins were consolidated to three principal bins: Braking / Deceleration, Idle, and Cruise / Acceleration as defined in Table 4-3. These consolidated operating mode bins are quite different in terms of engine operation and emissions performance.

Full A/C adjustments were then generated by dividing the mean “With A/C” emission factor by the mean “Without A/C” emission factor for each combination of consolidated operating mode and pollutant. Full A/C adjustments are shown in Table 4-3. 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 4-3 as “Mean CV of CF.”

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.

Table 4-3 Full air conditioning adjustments for THC, CO and NO_X

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

These adjustments are applied to passenger cars, passenger trucks and light commercial trucks only.

Note the higher air conditioning effect for NO_X at idle. These results are consistent with those obtained from Nam et al. (2000)[35] who showed that at low load conditions, A/C greatly increased NO_X emissions due to reduced residual gas fractions in-cylinder.

4.2.2. 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 CO_2 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 running operating mode and mean values were computed. A separate analysis was done as a function of sourceBinID (combination of vehicle type, fuel type and model year); however, 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 only of running operating mode. The resulting A/C adjustments are shown in Table 4-4.

Table 4-4 Full air conditioning adjustments for energy*

opModeID	A/C Factor	opModeID	A/C Factor	opModeID	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		

* These adjustments are applied to passenger cars, passenger trucks and light commercial trucks only.

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

Fuel economy and GHG regulations are expected to reduce energy consumption with air conditioning. However, because, the MOVES A/C factors are multiplicative adjustments to the running energy rates, a reduction in running energy rates also reduces energy consumption from air conditioning. In MOVES, we project the light-duty A/C improvements of regulatory rules using the running energy rates as documented in the MOVES Greenhouse Gas and Energy Consumption Rates Report.[6]

4.3. Adjustments to Air Conditioning Effects

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

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

Since not all vehicles are equipped with air conditioning and air conditioning is normally not on all 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[36]) of the air outside their vehicles. These MOVES defaults are documented in the Population and Activity report.[31] 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.

$$\text{EmissionRate} = (\text{meanBaseRateACAdj} * \text{ACPenetration}*\text{functioningACFraction}*\text{ACOnFraction}) + \text{meanBaseRate} \qquad \textbf{Equation 4-1}$$

The air conditioning adjustment is applied to the emission rate after it has been adjusted for fuel effects. At Project Scale, the sign of this adjustment is flipped if the *meanBaseRate* value is negative; this is a special case to ensure that regenerative braking on electric vehicles is not modeled as generating more energy when the air conditioning is running.

Air conditioners are also 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.

4.4. Conclusions and Future Research

MOVES applies air conditioning effects to emissions from passenger cars, passenger trucks and commercial light trucks. 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.
- Evaluation of air conditioning effects in the highest operating mode bins.
- Updates to information on the fraction of vehicles equipped with air conditioning and their malfunction rates.

5. Inspection and Maintenance Programs

Inspection and Maintenance (I/M) programs are any state or locally mandated inspection of highway motor vehicles intended to identify those vehicles most in need of emissions-related repair and require repairs of those vehicles. MOVES3.1 and later MOVES versions model an I/M program reduction in emissions of HC, CO and NOx for gasoline and flexible-fueled (E-85) vehicles less than 14,000 pounds (regulatory classes 20, 30 & 41). MOVES does not model emission changes for programs that target diesel or CNG vehicles, Class 4-or-higher heavy-duty vehicles. MOVES does not model an effect for particulate matter.

There is great variation in how vehicles are selected for inclusion in I/M 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.

This section describes the MOVES calculation of I/M benefits for exhaust emissions. The calculation of I/M benefits for evaporative emissions is described in the MOVES Evaporative Emissions report.[7]

5.1. Overview of Exhaust Inspection & Maintenance in MOVES

MOVES uses a number of inputs to estimate the benefits of exhaust I/M programs.

The model starts with two sets of emission rates as a function of age, model year group and regulatory class. The "mean base rate I/M" or "I/M rates" represent emissions for an area with a "reference I/M program." The "mean base rate", or the "non-I/M rates" represent emissions in an area without I/M. The reference I/M program is not the same as the I/M performance standard,[37] but instead is a program used as a data source in MOVES because it provides a large sample of consistent data covering many years. The data analysis used to determine both the I/M and non-I/M rates is detailed in the MOVES light-duty emission rate report.[4] Both sets of rates are recorded in the emissionRateByAge table.

MOVES scales the emission rate between (or potentially beyond) the I/M and non-I/M rate using an "I/M Factor" by source type that accounts for differences in I/M program design, including test type and inspection frequency, as detailed in Section 5.2. The I/M Factor assumes full coverage and compliance.

The result is also modified by the I/M coverage table. For each county and calendar year, the table lists the source types, pollutants and model years that are covered, and the compliance factor which adjusts I/M benefit to account for covered vehicles that are not actually subject to the program, evade testing, or have repairs waived. In MOVES, it is assumed that any repairs attempted on vehicles receiving waivers are not effective and do not result in any reduced emissions.

Mathematically, the IM Factor for the program design and the Compliance Factor for the program characteristics are combined into a single factor, "IMAdjustFract" as shown in Equation 5-1. The Compliance Factor is entered in units of percent and is converted to a fraction.

$$IMAdjustFract = (IMFactor * ComplianceFactor * 0.01) \qquad \textbf{Equation 5-1}$$

MOVES then estimates a net 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 5-2

5.2. Development of MOVES I/M Factors

MOVES is designed to model the different effects of different I/M program designs, specifically different test types and test frequencies. The relative effectiveness of the programs is input into MOVES as the "I/M factor," a value between zero and two, stored in the MOVES IMFactor table. It Is calculated with Equation 5-3.

$$R = \frac{E_p - E_{nonIM}}{E_{IM} - E_{nonIM}}$$

Equation 5-3

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 the I/M Factor, 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."

For our initial version of MOVES (MOVES2010), EPA developed I/M factors based on the information incorporated in MOBILE6.2.[38] These factors have been carried into later versions of MOVES. 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, model year groups and ages. The mean emission results for each combination were extracted from the output and used to compute estimated values for IMFactor.

The IMFactor table includes the following fields[e]:

- Pollutant / Process

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[e] The IMFactor table also includes values for Test Standard "Heavy-Duty Diesel Vehicle Reflash", with "continuous" frequency for other buses and long and short-haul combination trucks (sourcetypes 41, 61 and 62). These values were entered early in MOVES development but are never used. We intend to delete them in a future MOVES version.

- The IMFactor table has rows for HC, CO and NO_x running and start emissions, as well as HC vapor venting.
- Test Frequency
- Annual or biennial
- Test Standard
- See Table 5-1 below
- Source Type
- Passenger cars, passenger trucks, light commercial trucks, single-unit short-haul trucks and motorhomes
- Fuel Type
- Only gasoline and gasoline/ethanol blend fuels are covered
- Model Year Group
- Age Group
- IMFactor

Table 5-1 MOVES I/M Test Standards

testStandardsID	testStandardsDesc	shortName
11	Unloaded Idle Test	Unloaded Idle
12	Two-mode, 2500 RPM/Idle Test	2500 RPM/Idle
13	Loaded / Idle Test	Loaded/Idle
21	ASM 2525 Phase-in Cutpoints	A2525 Phase
22	ASM 5015 Phase-in Cutpoints	A5015 Phase
23	ASM 2525/5015 Phase-in Cutpoints	A2525/5015 Phase
24	ASM 2525 Final Cutpoints	A2525 Final
25	ASM 5015 Final Cutpoints	A5015 Final
26	ASM 2525/5015 Final Cutpoints	A2525/5015 Final
31	IM240 Phase-in Cutpoints	IM240 Phase
33	IM240 Final Cutpoints	IM240 Final
41	Evaporative Gas Cap Check	Evp Cap
42	Evaporative System Pressure Check	Evp Pressure
43	Evaporative System OBD Check	Evp OBD
44	Evaporative Gas Cap and Pressure Check	Evp Cap, Prs
45	Evaporative Gas Cap and OBD Check	Evp Cap, OBD
46	Evaporative Pressure and OBD Check	Evp Prs, OBD
47	Evaporative Gas Cap, Pressure and OBD Check	Evp Cap, OBD, Prs
51	Exhaust OBD Check	Exhaust OBD
61	HDDV Engine Reflash Program	HDDV Reflash

The IMFactor value was computed for all reasonable combinations of the parameters listed in the IMFactor table. MOBILE6.2 runs were done for each parameter combination (Target design, E_p) and a set of runs were done for the reference program (Reference design, E_{IM}). In these runs, the reference program has inputs matching the Phoenix, Arizona I/M program during the time in which the data used in the MOVES2010 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 5-2 below. Each of these runs represents a particular test type and test standard design. 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 THC, CO and NO_X.

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

Table 5-2 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 detailed by age, roadway type, and emission type. This output format necessitated additional processing into composite running and start factors.

The IMFactor (*R*) was then calculated using the mean emission results from the target program, the I/M reference program and the non-I/M reference using Equation 5-3.

5.2.1. Inspection & Maintenance in MOBILE6

Because the IMFactors used in MOVES were generated with MOBILE6.2, it is useful to briefly review MOBILE6 modeling of I/M. Readers interested in a more thorough treatment of the topic are encouraged to review the relevant MOBILE6 documentation. [38] [39] [40]

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. We also modelled 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.

The relative effectiveness of various I/M programs was modeled using “high emitter identification rates” that varied by test type. Since we lacked new data for MOBILE6, the effectiveness of biennial programs as compared to annual programs and the effectiveness of ASM tests relative to IM240 were calculated by running MOBILE5. To determine the high emitter identification rates for the IM240 test, MOBILE6 relied on a database of 910 results from 1981-and-later cars and trucks from EPA emission factor testing in Ann Arbor, Indiana and Arizona in which vehicles were randomly recruited and tested on both a running LA4 test (derived from the FTP test) and the IM240 test. There was little data for OBD and the high emitter identification rate for OBD testing was set at 85 percent.[39]

5.3. I/M Compliance Factors

While the IMFactor (*R*, Equation 5-3)) represents the theoretical effectiveness of a specific I/M program design relative to the reference design, MOVES uses a “compliance factor” to account for I/M program compliance rates, waiver rates, failure rates, and adjustments needed to account for the fraction of vehicles within a source type that are covered by the I/M program (these last adjustments are referred to as the “regulatory class coverage adjustment”).

When modeling for state implementation plans or conformity determinations, EPA guidance recommends that modelers review program descriptive parameters and enter compliance factors which reflect current and expected future program operation.[41]

MOVES values of the I/M compliance factor (*CF*) are specific to individual programs. The compliance factor is entered as a decimal number from 0 to 100 and represents the percentage of vehicles within a source type that actually receive the benefits of the program. The compliance factor is calculated as shown in Equation 5-4.

$$CF = (CR * (1 - WR * FR) * RCCA)$$ **Equation 5-4**

Where:

CF = *Compliance factor*

CR = *Compliance rate*

WR = *Waiver rate*

FR= *Failure rate*

$RCCA$ = *Regulatory class coverage adjustment*

The MOVES Technical Guidance provides instructions for modelers on using I/M program data to calculate each of these values and compute an appropriate compliance factor for use in MOVES.[41]

The default compliance rates in MOVES represent a mixture of state-submitted values and values carried over from MOBILE6. State-submitted values may be based on historic information, including historic regulatory class coverage. For values derived from MOBILE6, the MOBILE6 compliance rate, waiver rate and effectiveness rate were used to determine the default MOVES I/M Compliance Factor. Equation 5-5 shows the relationship.

$$CF = M6ComplianceRate * M6EffectivenessRate * (1 - M6WaiverRate)$$ **Equation 5-5**

5.4. Default I/M Program Descriptions (IMCoverage)

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

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

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

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

- Pollutant / Process
- State / County
- Calendar Year
- Source Use Type
- Fuel Type (only gasoline and ethanol fuels)
- IMProgramID
- Beginning Model Year of Coverage
- Ending Model Year of Coverage
- Inspection Frequency (annual or biennial)
- I/M Test Standards (see Table 5-1)
- UseIMyn
- Compliance Factor

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

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

The 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 National Mobile Inventory Model (NMIM) to compute the National Emission Inventory of 2011. The MOBILE6 data fields listed in Table 5-3 were extracted and processed into the various fields in the MOVES IMCoverage table for each state and county.

As seen in Table 5-3, MOBILE6.2 and MOVES do not have exactly compatible parameter definitions. 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 sourcetype.

Table 5-3 I/M Coverage Table Data from MOBILE6

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

For calendar year 2011 through 2013, the IMCoverage table default parameters were derived using the IMCoverage tables from the county databases (CDBs) provided to EPA for the 2011 National Emission Inventory (NEI) project[42] (Version1). These tables were available for review by states and updated as needed. The I/M program descriptions were extracted from the CDBs and compiled in the default IMCoverage table for calendar year 2011. The I/M descriptions for 2012 and 2013 calendar years were derived from the 2011 I/M descriptions, assuming no changes in the basic I/M program design; however, the model year coverage values were updated to properly account for the existing grace periods in the future calendar years.

The calendar year 2014 and later values were initially derived from the 2014 NEI (Version 1)[43] CDBs following review by the states, with the 2015 and later calendar year values computed assuming no changes in the basic 2014 I/M program design but updating the model year coverage values to properly account for the existing grace periods in the future calendar years. All of the I/M program descriptions were checked using a script to look for cases where a model year coverage either conflicted with other rows in the I/M description or where gaps without coverage were left between model years. This check also looked for cases where the coverage beginning model year occurred 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[44] to resolve conflicts. The county coverage values in some states were also updated for some calendar years. In addition to the updates in the I/M program descriptions, the table was updated to make sure each I/M program covered E85-fueled vehicles in the same way as gasoline in all calendar years. Any program elements claiming benefits for inspections to reduce liquid fuel leaks (pollutant process ID 113) were dropped from the default I/M program descriptions. MOVES does not offer any benefits from inspection programs to detect liquid fuel leaks.

For MOVES3, the table was further updated based on state supplied data through the OBD Clearinghouse website[45] and 2017 National Emissions Inventory (NEI).[46] The updates include adding I/M programs for Ascension Parish, Iberville Parish, and Livingston Parish in Louisiana; for Hamilton County, Tennessee, and for Cache County, Utah. We also updated the program stop years for terminated I/M programs. Terminated programs include programs in Anchorage Borough, Alaska; Grundy County, Illinois; Clark County and Floyd County, Indiana; Shelby County, Tennessee; and seven counties in Minnesota, 26 counties in North Carolina, and six counties in Ohio.

We also deleted the I/M program for Harrison County, Indiana (for all the CY years), since it was confirmed that Harrison County, IN has never been in nonattainment for any National Ambient Air Quality Standards (NAAQS) and does not have a I/M program. We also updated the beginning model year for North Carolina I/M counties to reflect changes to their program for 2020 and later.[47] In addition, to reflect the termination of I/M program in Washington state, I/M programs have been removed from IMCoverage table for all counties in Washington state after CY2019.

California currently has three different I/M programs: an enhanced program, basic program, and ownership change program. These may vary by zip code within a county; however, MOVES lacks this specificity. We mapped California counties with I/M program types by checking all the zip codes in each county. We use the basic program to represent a county if it has mixed programs. This methodology is consistent with previous work. We updated I/M program details for ten counties in California based on our research.

In MOVES3.0.4, we updated compliance factors using data from the 2020 National Emissions Inventory for existing IM programs that match the description in the default database, for year 2020 and after. We also used the 2020 NEI information to update Cache County, UT for calendar year 2020 and beyond. We removed I/M program information for Montgomery County, OH for 2020 and beyond, and removed programs for all counties in Tennessee starting with calendar year 2023. In MOVES4, we further updated information for Montgomery Co, OH for historical years, to reflect that the county had an active I/M program only between 1990 and 2008.

MOVES5 incorporated new I/M information obtained via EPA's 2022v1 Emissions Modeling Platform or through communications with states. New York and Colorado provided information to update all counties within their I/M area starting in calendar year 2022. Georgia changed their evaporative testing from gas cap evap test (testStandardID 45) to evaporative OBD check (testStandardID 43) starting in 2025, and Idaho ceased all I/M operations in 2023, which we reflected by removing all I/M information from calendar year 2024 and forward. Finally, Delaware updated their I/M program and we have updated our defaults to incorporate the information submitted to us by the State with modifications starting on calendar year 2023.

Table 5-4 shows the states with I/M program descriptions in the MOVES5 I/M coverage table and shows the number of counties covered by the programs by calendar year. For example Indiana has four counties with I/M information; two counties were under a program that was active between 1990 and 2007, while the other two counties are under a program that covers 1990 to 2060.

Table 5-4 States With I/M Programs as Listed in MOVES

		Calendar Years		
State	**StateID**	**Minimum**	**Maximum**	**Counties**
Alaska	2	1990	2009	1
		1990	2012	1
Arizona	4	1990	2060	2
California	6	1990	2060	14
		1999	2060	26
Colorado	8	1990	2060	7
	8	2015	2060	2
Connecticut	9	1999	2060	8
Delaware	10	1990	2060	3
District of Columbia	11	1990	2060	1
Georgia	13	1999	2060	13
Idaho	16	1990	2023	1
		2011	2023	1
Illinois	17	1990	2060	10
		1990	2005	1
Indiana	18	1990	2007	2
		1990	2060	2
Kentucky	21	1990	2005	4
Louisiana	22	2000	2060	5
Maine	23	1990	2060	1
Maryland	24	1990	2060	14
Massachusetts	25	1990	2060	14
Minnesota	27	1990	1999	7
Missouri	29	1990	2060	5
Nevada	32	1990	2060	2
New Hampshire	33	2002	2060	3
		2011	2060	7
New Jersey	34	1990	2060	21
New Mexico	35	1990	2060	1
New York	36	1990	2060	9
		2001	2060	53
North Carolina	37	2003	2060	9
		2006	2060	13
		2003	2005	1
		2003	2018	2
		2006	2018	24

		Calendar Years		
State	**StateID**	**Minimum**	**Maximum**	**Counties**
Ohio	39	1990	2008	7
		1990	2060	7
Oregon	41	1990	2060	4
		2001	2060	2
Pennsylvania	42	1990	2060	11
		2001	2060	14
Rhode Island	44	2000	2060	5
Tennessee	47	1990	2016	1
		1990	2022	6
Texas	48	1990	2060	4
		2000	2060	6
		2011	2060	7
Utah	49	1990	2060	4
		2020	2060	1
Vermont	50	1990	2060	14
Virginia	51	1990	2060	10
Washington	53	1990	2019	5
Wisconsin	55	1999	2060	7

5.5. Future Research

For thoughts on potential improvements to the MOVES I/M and non-I/M rates, see the MOVES light-duty report where the calculation of MOVES current rates is explained in detail.[4]

Values for IMFactor are generally based on analysis for MOBILE6 or earlier and should be updated to reflect current vehicle technology and testing practices and to better correspond to the current I/M reference program. An IMFactor update is particularly needed for OBD which is commonplace now but was in its infancy when the current MOVES values were developed.

While county modelers should always review the MOVES default IMCoverage table to assure values are up-to-date for a given county,[41] the default values could be improved with a systematic comparison to state and local I/M program records to assure that all the default values reflect the best information about historical, current and future I/M coverage and compliance data.

In addition, the MOVES algorithm could be improved to allow I/M Coverage by regulatory class to better match program design and the underlying MOVES emission rates. This would eliminate the need for the regulatory class coverage adjustment in computation of the Compliance Factor.

Furthermore, there are vehicle inspection programs not currently modelled in MOVES, including programs to reduce tampering and deterioration of heavy-duty diesel trucks, programs based on remote sensing, and programs intended to reduce emissions of particulate matter. Expanding the scope of MOVES to estimate the benefits of such additional programs would be useful for those considering such programs. However, such expansion would require a significant and long-lasting investment in research and analysis, as illustrated by the difficulty in collecting and updating data to support MOVES current I/M algorithms.

6. Electric Vehicle Charging and Battery Efficiency

MOVES base energy consumption rates include the power needed at the wheels for each operating mode plus energy losses through the drivetrain,[6] but this does not account for an electric vehicle's total demand on the electric power grid. By calculating total energy demand of vehicles on the grid, MOVES can better facilitate the modeling of emissions from power plants and associated air quality changes.[f] This section details how MOVES accounts for charging and battery efficiency when estimating energy consumption for electric vehicles (EVs).

For MOVES purposes, charging efficiency captures the energy lost in the wall charger – essentially the difference between energy drawn from the wall outlet and energy added to the battery. Battery efficiency, meanwhile, captures the relative energy lost in the battery itself – the difference between energy produced at the output terminal and energy added to the battery. Each of these can range from 0 to 1, with higher values being more efficient.

While these efficiencies are related, they depend on different physical components that are engineered independently, so their baseline efficiency and deterioration are likely to be different. MOVES models them individually to account for these differences, but in practice, they are difficult to measure separately. Most studies and lab data report them together in a measure we call "wall-to-output" efficiency.

6.1. MOVES Design and Implementation

The table evEfficiency contains the charging and battery efficiency for electric vehicles. Similar to emissionRateAdjustment,[5] the values in this table are applied once the base rates have been calculated, at the same time as other adjustments and corrections like those for ambient temperature (see Section 2.7.).

MOVES models fuel cell vehicles as vehicles of the "electric" fuelType (fuelTypeID=9), but with a separate engine technology type (engTechID = 40). However, a limitation of this approach is that when charging and battery efficiencies are applied during MOVES runtime, the different EV technologies have already been aggregated together to produce an average EV base energy consumption rate. Therefore, the evEfficiency values implicitly apply to all electric vehicles, including fuel cells. This is not desired, because fuel cell vehicles get their power from the fuel cell rather than the grid. Therefore, the fuel cell base energy consumption rates in emissionRate were scaled down by the appropriate values in evEfficiency. This ensures that the final energy consumption for fuel cell vehicles represents their actual operation, after all adjustments are incorporated.

The evEfficiency table contains separate columns for battery and charging efficiency, with dimensions for pollutant and emission process, source type, regulatory class, model year range, and age range. This design provides maximum flexibility to improve the modeling of chargers and batteries in future versions of MOVES, including by specific vehicle types (regulatory class) and vocations (source type). This

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[f] Similarly, estimating energy consumption of internal combustion engines is useful for estimating the emissions associated with the production and distribution of gasoline, diesel, and other combustion fuels.

flexibility can be used in future MOVES versions to model the impact different driving behaviors, charging behaviors, and drivetrain configurations have on overall EV efficiency.

The adjustments are applied using Equation 6-1.

$$finalRate = \frac{baseRate}{(batteryEfficiency * chargingEfficiency)}$$

Equation 6-1

Consistent with MOVES design for electric vehicles, the only pollutant and process in the table is total energy consumption while the vehicle is running. In MOVES, all electric vehicles use the same efficiencies and deterioration trends, regardless of source type, regulatory class, or model year due to a lack of specific data pertaining to these fields. MOVES design allows more granular efficiency values by source type, regulatory class, and model year, provided sufficient data becomes available.

6.2. Data Analysis and Literature Review

6.2.1. Charging Efficiency

Data on EV charging efficiency is limited, and the technology is evolving rapidly. Our primary data source for charging efficiency is from the Altoona Bus Research and Test Center in the Penn State College of Engineering.[48] They tested battery electric buses from a variety of manufacturers and reported the energy consumption of the bus on various drive cycles as well as the power drawn from the charger for each test. From these, an overall wall-to-output efficiency can be calculated, which represents the combination of charging efficiency and battery efficiency.

The wall-to-output efficiencies vary from approximately 75% to 91% as shown in Figure 6-1 . However, most buses, including the newer model years with better technologies, range from 85% to 91%. Most data reported by Altoona as well as other sources contains wall-to-output efficiency and is not separated by battery and charger efficiency. Therefore, we had to combine the Altoona data with a literature review and engineering judgement to separate the battery and charging efficiency values in MOVES. We assign new EVs a battery efficiency of 95% and a charging efficiency of 94%, which results in a wall-to-output efficiency of 89.3%.

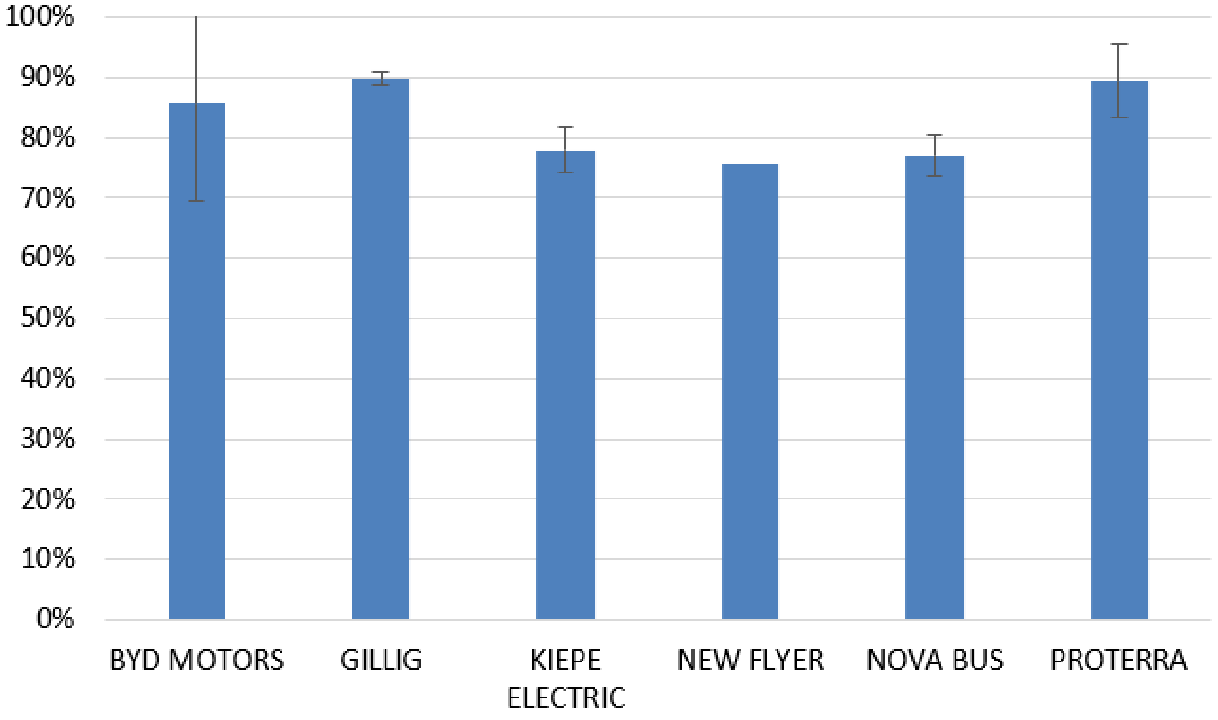

Figure 6-1. Average of wall-to-output efficiencies of electric buses tested by the Altoona Bus Research and Test Center, grouped by manufacturer. Only buses with test reports that included both battery energy levels and total charging energy consumption were included.

Our use of a 94% charging efficiency is informed by a number of factors in combination with engineering judgement based on conversations within the MOVES team and with external experts, including those at the Altoona Bus Research and Test Center. The chosen value of 94% is broadly consistent with a variety of sources for heavy and light-duty vehicles. Tan, et al. (2014)[49] show values ranging from 97% to 98.5% and Kreiger and Arnold (2012)[50] show values ranging from 85% to 95%. Both studies are modeling studies, so we feel they are good confirmation of our efficiency values, but we chose to use observed real-world data to calculate our charging efficiency adjustment. Apostolaki-Iosifidou, et al. (2017)[51] show values ranging from 85% to 98% based in part on observed data. This study contains detailed data, but only for a single charging system and two vehicles, which we feel is adequate to help confirm our adjustment in MOVES but not to calculate the adjustment.

The literature cited above doesn’t report that charging efficiency changes with age, and discussions with experts in the field, including the Altoona Bus Research and Test Center, indicate no physical reason to expect a deterioration with age. Therefore, we assume there is no age trend for EV charging efficiency.

6.2.2. Battery Efficiency

Battery efficiency, however, does deteriorate with age. Loss of EV range as battery ages is well documented, but most studies focus on a loss of capacity. In theory, a loss of capacity can explain reduced range without a drop in efficiency. We could not find any real-world data on the change in battery efficiency with age. However, Yang et al (2018)[52] modeled battery aging in typical driving conditions in each U.S. state to cover a wide range of operational conditions. While their battery model is based on batteries used in most passenger car EVs, the fundamental battery cell technology and specifications are also commonly used in heavy-duty BEVs.

Yang et al. show that internal resistance increases as batteries age, which means that the reduction in EV range with age can be attributed, at least in part, to a change in energy consumption. Energy consumption is related to resistance, as shown in Equation 6-2 where *R* is internal resistance and ε is energy consumption:

$$\Delta\varepsilon = \varepsilon * \frac{1}{1+\Delta R}$$

Equation 6-2

Yang et al show that the average increase in energy consumption related to increased internal resistance is 17.29% over 10 years. Starting with no increase in resistance for new vehicles, we linearly interpolate between ages 1 and 10, binned according to MOVES age groups in the evEfficiency table. Assigning new EVs a battery efficiency of 95% based on engineering judgement and our literature review,[50] [51] [53] we can calculate the average efficiency for each age group using Equation 6-3.

$$batteryEfficiency_{ageGroup} = \frac{0.95}{1+\Delta R_{ageGroup} - 0.95}$$

Equation 6-3

Because electric vehicles are a relatively new technology, there is considerable uncertainty about how batteries age beyond 10 years. While some will continue to deteriorate, other vehicles may get efficiency improvements or battery replacements under warranty. Electric vehicles have an ability to manage battery degradation through software improvements as well, which may also limit battery aging. Therefore, we assume overall battery efficiency doesn't deteriorate beyond the first 10 years. This approach is similar to how we model criteria pollutant emission rate deterioration for ICE vehicles.

6.2.3. Conclusion

The resulting charging efficiency and battery efficiency values used in MOVES are in Table 6-1. We use the same charging and battery efficiency assumptions for all electric vehicles, regardless of vehicle class and model year.

Table 6-1 Battery and Charging Efficiency by Age[g]

Age Group	Battery Efficiency	Charging Efficiency
0-3 years	0.95	0.94
4-5 years	0.903153	0.94
6-7 years	0.874407	0.94
8-9 years	0.847435	0.94
10-14 years	0.828273	0.94
15-20 years	0.828273	0.94
20+ years	0.828273	0.94

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[g] As noted in Section 6.1, the current MOVES code requires application of these values to both BEVs and FCEVs. Thus, the FCEV base energy consumption rates were adjusted ("back-calculated") to generate the correct net energy consumption.

7. Fleet Averaging Provisions

Some EPA regulations allow manufacturers to meet emissions standards through what are known as "averaging, banking and trading" (ABT) provisions. These provisions allow higher emissions from some vehicles in return for lower emissions from others. When EV market share was low, MOVES did not account for these details because it is designed to estimate emissions of "fleet-average" vehicles, rather than individual vehicles or vehicle families. However, with growing EV sales, it is possible for manufactures to sell ICE vehicles with greater emissions due to ABT provisions, so MOVES4 and later MOVES versions have been updated to better account for this impact.

MOVES explicitly accounts for expected increases in the emissions and energy consumption from conventional vehicles when national EV sales increase within any given model year. MOVES does not explicitly model other ABT provisions, such as those that allow credits to be carried across several model years, so we refer to this algorithm as the fleet averaging adjustment instead of an ABT adjustment.

The fleet averaging adjustment is a multiplicative factor applied to the base emission rates in MOVES. It is calculated with the following equation:

$$Adjustment = \frac{1}{1 - \frac{evFraction \times evMultiplier}{(1 - evFraction) + (evFraction \times evMultiplier)}}$$

Equation 7-1

In the above equation:

$evFraction$ is the national fraction of electric vehicles for a given model year, grouped by vehicles that may be averaged together. Except when running with national preaggregation, this calculation does not use user-supplied EV fractions in the AVFT table because compliance with fleet-wide averaging is based on national sales rather than the local fraction of EVs.

$evMultiplier$ is a multiplying factor applied to EV vehicles. This multiplier increases the apparent number of total vehicles sold for the purposes of the adjustment calculation. The values vary with model years as determined from EPA regulations, including the LD Tier 3 rule,[54] the LD GHG Phase 2 rule,[55] The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks,[56] the Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards,[57] the Light- and Medium-Duty Multi-Pollutant Rule (LMDV),[8] and EPA's Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3 (HDP3).[9]

For regulations that do not include an EV multiplier, the adjustment equation reduces to the following form, obtained by inserting a value of 1 for $evMultiplier$:

$$Adjustment = \frac{1}{1 - evFraction}$$

Equation 7-2

In addition, some rules limit how much the effective ICE emission rate may increase due to the presence of EVs in the fleet. For example, LMDV rule limits the emission bins that manufacturers may certify vehicles to, and therefore we limit the ratio of the effective ICE emission rate to the fleet average emission rate in these cases.

The inputs needed for these calculations are stored in the MOVES default database's FleetAvgAdjustment table, which lists the pollutants, emission processes, model year ranges, and fleetAvgGroupIDs affected by the fleet averaging algorithm. The fleetAvgGroupID column, which is defined by regulatory class, is used to group vehicles that may be averaged together. For example, LD vehicles may be averaged together under Tier 3 (among other rules), so regulatory classes 20 and 30 are both assigned fleetAvgGroupID 1. This table contains the following additional fields:

- "evMultiplier", which is described with Equation 7-2. Some pollutants and processes, including criteria pollutants, do not have an EV multiplier. The evMultiplier is set to 1 in these cases.
- "adjustmentCap", which can be used to limit the impact of the fleet averaging adjustments. Some rules do not set an explicit limit to how much more ICE vehicles may emit when there are significant numbers of EVs in the fleet, and so a value of "NULL" in this table represents no adjustment limit. If a value is present in this table, it represents the upper limit to the ratio of the effective ICE emission rate to the fleet average emission rate.

7.1. Fleet Averaging for Criteria Pollutants

7.1.1. Tier 3

Under the Tier 3 rule, fleet averaging provisions are relevant for the NO_X+NMOG (non-methane organic gases) exhaust emission standard, but do not apply to PM or CO. The rule allows averaging electric vehicles exhaust emissions with other light-duty vehicles with a one-to-one weighting. Manufacturers may average across cars and light trucks. Thus, the sale of battery electric vehicles (BEV) in the U.S. light-duty fleet effectively increases the Tier 3 NO_X+NMOG limit for internal combustion LD vehicles. Similarly, the sale of BEV medium-duty vehicles (class 2b and 3 trucks) increases the Tier 3 NO_X+NMOG limit for internal combustion medium-duty vehicles.[54]

We assume manufacturers will take full advantage of these higher effective standards for ICE vehicles because this allows them to reduce costs by applying measures such as installing simpler after-treatment technologies on hybrid vehicles or reducing precious metal loading in catalytic converters. Alternately, they may sell more vehicles in higher Tier 3 emission bins or sell credits to another manufacturer.

Since the rule allows averaging with one-to-one weighting between electric vehicles and internal combustion vehicles, Tier 3 model years appear in the FleetAvgAdjustment table with an evMultiplier value of 1 for running and start exhaust emission rates for NO_X and THC. While the Tier 3 standard and the fleet averaging provisions are for NMOG, we follow the general MOVES practice of modeling relative changes in THC as proportional to changes in the NMOG standard.[4] Additionally, because the fleet averaging applies to light-duty vehicles as well as medium-duty vehicles, entries appear in FleetAvgAdjustment for both fleetAvgGroupIDs 1 (light-duty vehicles) and 2 (medium-duty vehicles). Tier 3 does not provide an upper limit to specifically internal combustion NO_X+NMOG emissions, so Tier 3 entries in the FleetAvgAdjustment table have a value of NULL for the adjustment cap.

Pollutants, processes, fleet average groups, and model years not listed in the table are not adjusted.

7.1.2. LMDV rule

In MOVES, we model LMDV fleet averaging like the Tier 3 averaging described above. However, the LMDV rule provides an upper limit for ICE emissions that we model in MOVES with an adjustment cap. The adjustment caps were calculated as the ratio between the highest allowable certification bin and the model year specific fleet average requirements. Since there are differences between the definition of regulatory classes in MOVES and the grouping of vehicle classes used to define fleet requirements in the rule, for regulatory class 30, we weighted the calculated adjustment caps by the fractional population of LLDT and HLDT based on a historic national vehicle registration dataset, similar to the process described in Section 3.14 of the LD report[58]. Further, since the modeling of fleet averaging in MOVES is applied to regulatory class 20 and 30 as a group, we weighted the relative projected population of each regulatory class for each model year following the information in the default sourcetypepopulation table. The final cap values applied to light-duty and medium-duty vehicles are shown in Table 7-1. These adjustments apply to running and start processes for THC and NO_x.

Table 7-1 Adjustment caps developed for NMOG+NO_x

modelYearID	fleetAvgGroupID	Adjustment Cap
2027	1 (Light Duty)	2.69
2028	1 (Light Duty)	2.88
2029	1 (Light Duty)	3.09
2030	1(Light Duty)	3.92
2031	1 (Light Duty)	4.25
2031+	2 (Medium Duty)	2.27
2032+	1(Light Duty)	4.67

There are no fleet averaging provisions for criteria pollutant emissions for heavy-duty vehicles.

7.2. Fleet Averaging for Energy Consumption and CO_2

Many EPA GHG standards use “electric vehicle multipliers” as a way to promote EVs.[8 9 55 56] They also allow credit trading between light-duty cars and trucks, as well as credit trading between medium-duty vehicles.

Similar to how we model the impact for criteria pollutants, we assume the manufactures will take full advantage of these EV-related benefits with regard to energy and CO_2 emissions.

The FleetAvgAdjustment table contains entries for running energy consumption for light-duty vehicles with the evMultiplier values as shown in Table 7-2. The values vary with model years as determined by EPA regulations, including the LD GHG Phase 2 rule,[55] SAFE,[56] and the revised 2023 and later standards.[57]

Table 7-2 Light-duty Electric Vehicle Energy Adjustment Weights

Model Years	EV Multiplier
2017-2019	2.0
2020	1.75
2021	1.5
2022	1.0
2023-2024	1.3[h]
2025+	1.0

Fleet averaging for CO_2 emissions from medium-duty vehicles is covered by HD GHG Phase 2 for model years 2021 through 2026. HD GHG Phase 2 applies different advanced technology credit multipliers to sales based on technology. Credits for plug-in hybrid electric vehicles are multiplied by 3.5, battery electric vehicles by 4.5, and fuel cell electric vehicles by 5.5.[59] Because MOVES cannot differentiate by engine technology at the point where this adjustment is applied, we can only apply a single value for the evMultiplier for these vehicles. We chose to use the battery electric value of 4.5 because MOVES models plug-in hybrid vehicles as internal combustion vehicles, and battery electric vehicles in this class are more common than fuel cell electric vehicles. For model years 2027 to 2060, the evMultiplier for medium-duty vehicles is reduced to one based on the LMDV rule[8].

We do not account for the fleet averaging provisions applying to heavy-duty vehicles in HD GHG Phase 2 because its impact on ICE emissions is captured in other ways, including updates to roadload coefficients and base emission rate adjustments. We account for fleet averaging for heavy-duty vehicles beginning in model year 2028 based on the HD GHG Phase 3 standards.[9] The Phase 3 rule begins in MY 2027 but retains the advanced technology credit multipliers from Phase 2 for MY 2027 only. Beginning in MY 2028, credits may be traded across vocational and tractor categories so long as they are in the same weight class. The HD fleet average groups are summarized in Table 7-3. There are no advanced technology credit multipliers in HD GHG Phase 3 after MY 2027, so the evMultiplier is set to 1 for each fleet average group.

Table 7-3 Heavy-duty Electric Vehicle Energy Adjustment Weights

MOVES Regulatory Classes	MOVES Fleet Average Group	evMultiplier
LHD45 (regClassID 42)	Light Heavy-Duty (fleetAvgGroupID 3)	1
MHD67 (regClassID 46)	Medium Heavy-Duty (fleetAvgGroupID 4)	1
HHD8 & Urban Bus (regClassIDs 47 and 48)	Heavy Heavy-Duty (fleetAvgGroupID 5)	1

To illustrate the impact of the fleet average adjustment, imagine a MY2024 fleet with 10 percent light-duty EVs and an evMultiplier of 1.3. To compensate for the flexibility allowed in current regulations, the average energy consumption rate for the ICE vehicles would be increased as shown in Equation 7-3 below.

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[h] This value was adjusted from the 1.5 value listed in Table 14 of the Federal Register / Vol. 86, No. 248 [**Error! Bookmark not defined.**] to account for the cumulative cap described in Section 1. ii.b, of the rule.

$$\text{adjustment} = \frac{1}{1 - \frac{0.10 * 1.3}{(1 - .10) + (0.10 * 1.3)}}$$

$$= \frac{1}{1 - \frac{0.13}{(0.90 + 0.13)}}$$

Equation 7-3

$$= \frac{1}{0.874} = 1.144$$

8. References

[1] USEPA (2020). Fuel Effects on Exhaust Emissions from On-road Vehicles in MOVES3. EPA-420-R-20-116. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. 2020. https://www.epa.gov/moves/moves-onroad-technical-reports

[2] USEPA (2023). Speciation of Total Organic Gas and Particulate Matter Emissions from Onroad Vehicles in MOVES4. EPA-420-R-23-006. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023. https://www.epa.gov/moves/moves-onroad-technical-reports.

[3] USEPA (2020). Air Toxic Emissions from Onroad Vehicles in MOVES3. EPA-420-R-20-022. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-onroad-technical-reports.

[4] USEPA (2024). Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES5. EPA-420-R-24-016. Office of Transportation and Air Quality, Ann Arbor, MI. November 2024. https://www.epa.gov/moves/moves-onroad-technical-reports

[5] USEPA (2024). Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES5. EPA-420-R-24-015. Office of Transportation and Air Quality, Ann Arbor, MI. November 2024. https://www.epa.gov/moves/moves-onroad-technical-reports

[6] USEPA (2024). Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES5. EPA-420-R-24-018. Office of Transportation and Air Quality, Ann Arbor, MI. November 2024. https://www.epa.gov/moves/moves-onroad-technical-reports

[7] USEPA (2024). Evaporative Emissions from Onroad Vehicles in MOVES5. EPA-420-R-24-014. Office of Transportation and Air Quality, Ann Arbor, MI. November 2024. https://www.epa.gov/moves/moves-onroad-technical-reports

[8]USEPA (2024). Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles*,* 89 Fed. Reg. 27842, April 18, 2024.

[9] USEPA (2024). Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3, 89 Fed. Reg. 29440., April 22, 2024.

[10] USEPA (2008). Mobile Source Observation Database (MSOD): User Guide and Reference. EPA-420-B-08-017. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. December, 2008. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P10028RC.TXT

[11] Stump, F. D., D. L. Dropkin, S. B. Tejada, C. Loomis and C. Pack (2002). *Characterization of Emissions from Malfunctioning Vehicles Fueled with Oxygenated Gasoline-Ethanol (E-10) Fuel -- Part III*, US EPA's National Exposure Research Laboratory (NERL), U. S. Environmental Protection Agency, Washington, D.C., EPA Report Number EPA/600/R-01/053 (NTIS PB2004-106735), July 2002.

---

[12] USEPA (2007). "Regulatory Impact Analysis for Final Rule: Control of Hazardous Air Pollutants from Mobile Sources" EPA Report Number EPA420-R-07-002, February 2007, Chapter 2, pages 2-15 to 2-17. Available at: https://nepis.epa.gov/Exe/ZyPdf.cgi?Dockey=P1004LNN.PDF

[13] USEPA (1994). Regulation of Fuels and Fuel Additives: Standards for Reformulated and Conventional Gasoline 59 Federal Register: Issue 32. February 16, 1994, Docket Number: AMS-FRL-4817-8.

[14] USEPA (2007). Control of Hazardous Air Pollutants From Mobile Sources 72 Federal Register 8428.February 26, 2007 . https://www.govinfo.gov/content/pkg/FR-2007-02-26/pdf/E7-2667.pdf

[15] E. Glover and D. Brzezinski, (2001) Exhaust Emission Temperature Correction Factors for MOBILE6: Adjustments for Engine Start and Running LA4 Emissions for Gasoline Vehicles, EPA Report Number EPA-420-R-01-029 (M6.STE.004), April 2001.

[16] Jose Pinheiro, Douglas Bates, Saikat DebRoy, Deepayan Sarkar and the R Development Core Team (2013). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-109.

[17] USEPA (2008). Analysis of Particulate Matter Emissions from Light-Duty Gasoline Vehicles in Kansas City, EPA Report Number EPA420-R-08-010, April 2008. Available at: https://www.epa.gov/moves/mobile-source-emission-factors-research

[18] Nam, E.; Kishan, S.; Bauldauf, R.; Fulper, C. R.; Sabisch, M.; Warila, J. Temperature Effects on Particulate Matter Emissions from Light-Duty, Gasoline-Powered Motor Vehicles. Environ. Sci. Technol. 2010, 44, 4672-4677.

[19] Sonntag, D. B., R. W. Baldauf, C. A. Yanca and C. R. Fulper (2013). Particulate matter speciation profiles for light-duty gasoline vehicles in the United States. *Journal of the Air & Waste Management Association,* 64 (5), 529-545. DOI: 10.1080/10962247.2013.870096.

[20] Cadle, S. H., et al. (1998). Measurements of Exhaust Particulate Matter Emissions from In-Use Light-Duty Motor Vehicles in the Denver, Colorado Area. CRC Project E-24-1 CRC Project E-24-1. Coordinating Research Council. March 24, 1998.

[21] Cadle, S. H., et al. (1999). Composition of Light-Duty Motor Vehicle Exhaust Particulate Matter in the Denver, Colorado Area. *Environ Sci Technol,* 33 (14), 2328-2339. DOI: 10.1021/es9810843.

[22] Mathis, U., M. Mohr and A.-M. Forss (2005). Comprehensive particle characterization of modern gasoline and diesel passenger cars at low ambient temperatures. Atmospheric Environment, 39 (1), 107-117. DOI: http://dx.doi.org/10.1016/j.atmosenv.2004.09.029.

[23] Schauer, J., et al. (2006). Characterization of Metals Emitted from Motor Vehicles. Health Effects Institute Research Report Number 133 Health Effects Institute Research Report Number 133. https://www.healtheffects.org/system/files/Schauer.pdf

---

[24] Sonntag, D., et al. (2018). Modeling Brake and Tire Wear Emissions in Regulatory Models in the United States. 2018 ISES-ISEE Joint Annual Meeting. Ottawa, Canada.

[25] McDonald, B., et al. (2019). Quantifying Urban Emissions Influencing Wintertime Ammonium Nitrate Formation. AQUARIUS (Air Quality in the Western US). Salt Lake City, UT.

[26] USEPA (2022). Chapter 3 of Regulatory Impact Analysis for Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards, Office of Transportation and Air Quality. US Environmental Protection Agency, Ann Arbor, MI., December 2022. EPA-420-R-22-035 https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf

[27] 40 CFR 1036.104

[28] Sakunthalai, R. A., et al. (2014). *Impact of Cold Ambient Conditions on Cold Start and Idle Emissions from Diesel Engines*. SAE Technical Paper.

[29] USEPA (2005). *Energy and Emissions Inputs.* EPA-420-P-05-003. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. March, 2005. https://www.epa.gov/moves/moves-onroad-technical-reports

[30] American Automobile Association, Inc. (2019). *AAA Electric Vehicle Range Testing. AAA proprietary research into the effect of ambient temperature and HVAC use on driving range and MPGe.* American Automobile Association, Inc. https://www.aaa.com/AAA/common/AAR/files/AAA-Electric-Vehicle-Range-Testing-Report.pdf

[31] USEPA (2024). Population and Activity of Onroad Vehicles in MOVES5. EPA-420-R-24-019. Office of Transportation and Air Quality, Ann Arbor, MI. November 2024. https://www.epa.gov/moves/moves-onroad-technical-reports

[32] 40 Code of Federal Regulations 1065.670 (a)(Page 230). Available online: https://www.govinfo.gov/content/pkg/CFR-2017-title40-vol37/pdf/CFR-2017-title40-vol37-sec1065-670.pdf

[33] 40 Code of Federal Regulations 86.144-94(c)(7)(iv-viii)(Page 706). Available online: https://www.govinfo.gov/content/pkg/CFR-2015-title40-vol19/pdf/CFR-2015-title40-vol19-sec86-144-94.pdf

[34] USEPA (2001). Air Conditioning Correction Factors in MOBILE6. EPA-420-R-01-055. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2011.

[35] Nam, E. K., Understanding and Modeling NOx Emissions from Air Conditioned Automobiles, SAE Technical Paper Series 2000-01-0858, 2000.

---

[36] National Oceanic and Atmospheric Administration (2014). The Heat Index Equation. Weather Prediction Center. National Weather Service http://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml

[37] USEPA(2022) Performance Standard Modeling for New and Existing Vehicle Inspection and Maintenance (I/M) Programs Using the MOVES Mobile Source Emissions Model, USEPA Office of Transportation and Air Quality, Transportation and Climate Division. EPA Report Number EPA-420-B-22-034 October 2022. Available at: https://www.epa.gov/state-and-local-transportation/vehicle-emissions-inspection-and-maintenance-im-policy-and-technical

[38] USEPA (2002) User's Guide to MOBILE6.1 and MOBILE6.2 Mobile Source Emission Factor Model, USEPA Office of Transportation and Air Quality, Assessment and Standards Division. EPA Report Number EPA-420-R-02-028 October 2002.

[39] USEPA (2002) MOBILE6 Inspection / Maintenance Benefit Methodology for 1981 through 1995 Model Year Light Vehicles, USEPA Office of Transportation and Air Quality, Assessment and Standards Division. EPA Report Number EPA420-R-02-014 (M6.IM.001) March 2002. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi/P10022PN.PDF?Dockey=P10022PN.PDF

[40] USEPA (2001) Determination of NOx and HC Basic Emission Rates, OBD and I/M Effects for Tier 1 and later LDVs and LDTs Final Report M6.EXH.007, USEPA Office of Transportation and Air Quality, Assessment and Standards Division. EPA Report Number EPA-420-R-01-056 (M6.EXH.007) November, 2001.

[41] USEPA (2024). MOVES5 Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity, USEPA Office of Transportation and Air Quality, Assessment and Standards Division. EPA Report Number EPA-420-B-24-043. November 2024.

[42] USEPA (2011). 2011 National Emission Inventory - https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

[43] USEPA (2016). 2014 National Emission Inventory. https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

[44] USEPA (2013), I/M Program Data, Cost and Design Information, Final Report, Prepared by ERG for EPA, Project No.: 0303.00.009.001, August 2, 2013.

[45] OBD Clearinghouse (2019) "I/M Jurisdiction Report," https://www.obdclearinghouse.com/Jurisdiction/jurisdictionPDFs?

[46] USEPA (2020). 2017 National Emission Inventory. https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

---

[47] USEPA (2019), Air Plan Approval; NC: Revision to I/M Program & Update to Charlotte Maintenance Plan for the 2008 8-Hour Ozone NAAQS, Federal Register/Vol. 84, No. 176/Wednesday, September 11, 2019/Rules and Regulations.

[48] LTI Bus Research and Testing Center (2012-2020). Bus Testing Report. https://www.altoonabustest.psu.edu/bus-list.aspx

[49] Tan, K., Yong, J., and Ramachandaramurthy, V. (2014). Bidirectional battery charger for electric vehicle. 2014 IEEE Innovative Smart Grid Technologies. DOI: 10.1109/ISGT-Asia.2014.6873826.

[50] Elena M. Kreiger and Craig B. Arnold. (2012). Effects of undercharge and internal loss on the rate dependence of battery storage efficiency. Journal of Power Sources 210 (2012) 286-291. DOI: 10.1016/j.jpowsour.2012.03.029

[51] Apostolaki-Iosifidou, E., Codani, P., and Kempton, W. (2017). Measurement of power loss during electric vehicle charging and discharging. Energy 127 (2017) 730-742. https://doi.org/10.1016/j.energy.2017.03.015

[52] Yang, F., Xie, Y., Deng, Y., and Yuan, C. (2018). Predictive modeling of battery degredation and greenhouse gas emissons from U.S. state-level electric vehicle operation. Nature Communications. DOI: 10.1038/s41467-018-04826-0.

[53] Kostopoulos, E., Spyropoulos, G., Kaldellis, J. (2020). Real-world study for the optimal charging of electric vehicles. Energy Reports, Vol. 6, 418-426. DOI: https://doi.org/10.1016/j.egyr.2019.12.008.

[54] 40 CFR § 86.1811-17

[55] USEPA(2012), 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, Federal Register, 77 FR 199.

[56] USEPA(2020), The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks, Federal Register, Vol.85, No.84.

[57] USEPA (2021) Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards, 86 FR 74434, December 30, 2021.

[58] USEPA (2024). Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES5. EPA-420-R-24-016. Office of Transportation and Air Quality, Ann Arbor, MI. November 2024. https://www.epa.gov/moves/moves-onroad-technical-reports

[59] 40 CFR 1037.150(p)

Appendix A Derivation of Temperature, Humidity and Meteorology Calculations

The MOVES default database includes default ambient temperature and humidity values for every county, month, and hour. If modelers do not enter local data, MOVES will use these values to calculate the temperature and humidity adjustments described in the main body of this report. These values were derived from 10-year average temperature and relative humidity values from calendar years 2001 through 2011 by month and by hour (standard time) for each county in the United States for all calendar years.

Due to the limited number of hourly observation stations (about 200 sites), interpolation of the available data was required. This interpolation will not always produce accurate results, particularly in areas where climate can vary significantly over distance, such as in mountainous terrain and near coastlines or deserts. Moreover, it is important that the diurnal range of the average hourly temperatures match those of the average monthly minimum and maximum values. This aspect arises due to the averaging process and to the fact that daily maximum and minimum temperatures do not always occur at the same hourly observation time.

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

Note, temperature and humidity data are one of the many inputs that are averaged for simplified national and state level onroad MOVES runs. The algorithms for this averaging ("aggregation") are described in the MOVES code documentation at https://github.com/USEPA/EPA_MOVES_Model.

A1. Data Sets and Quality Control

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

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

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

In addition to the hourly temperature and dew point data, the identification number and geographic location (latitude and longitude) for all available weather stations across the United States, Puerto Rico, and the Virgin Islands were obtained from the NCDC files. Using Geographical Information System (GIS) software, the locations of the hourly weather observation stations were validated. To resolve duplicate IDs and latitude/longitude issues, careful analysis of the station history files and conversations with state climatologists and National Weather Service offices were made. Our contractor, Air Improvement Resource Inc. (AIR), hand-edited the IDs and latitude/longitude data and supplied updates to our data and to the NCDC.

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

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

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

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

A2. County Temperature Assignment

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

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

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

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

A3. Temperature Recalculation

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

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

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

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

Where:

h is hour of the day,

$AdjTemp_h$ is the adjusted hourly temperature,

$Temp_h$ is the hourly temperature in the profile,

AMin is the average monthly minimum temperature,

AMax is the average monthly maximum temperature,

PMin is the minimum temperature based on the averaged 24 hourly temperatures in the profile,

PMax is the maximum temperature based on the averaged 24 hourly temperatures in the profile.

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

A4. Relative Humidity Recalculation

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

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

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

A5. Calculation of 10 Year Averages

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

A6. Calculation of Specific Humidity

While the MOVES default humidity is stored as relative humidity, the humidity adjustment uses specific humidity. The adjustment for diesel fuel type uses specific humidity expressed as a molar fraction, while the adjustment for other fuel types uses specific humidity expressed as grams of water per kilogram of air.

MOVES uses the following equations to calculate specific humidity based on pressure, relative humidity, and ambient temperature.

Inputs:

T_F is the temperature in degrees Fahrenheit, T_K is the temperature in degrees Kelvin

P_B is the barometric pressure, in inches of mercury

H_{rel} is the relative humidity

First, MOVES calculates the vapor pressure of water at the saturation temperature in kPa.

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

Next, MOVES calculates the molar fraction of water in the air. This is the molar fraction used to calculate the NO_x adjustment for diesel vehicles.

$$x_{H2O} = \frac{\left(\frac{Hrel}{100}\right)\cdot P_{H2O}}{P_B * 3.38639}$$

Finally, MOVES calculates specific humidity in grams of water per kilogram of air using the following two equations (1 inHg = 3.38639 kPa).

$$PV(kPa) = \left(\frac{Hrel}{100}\right)\cdot(P_{H2O})$$

$$specificHumidity = \frac{621.1 * PV}{(P_B * 3.38639) - PV}$$

A7. Calculation of Heat Index

MOVES air conditioning demand is calculated as a function of the heat index as described in the MOVES Population and Activity report.[31] In MOVES, the heat index is a function of temperature and relative humidity. For temperatures below 78° Fahrenheit, the heat index is equal to the temperature. For temperatures above 78, the following equation (which is a simplification of the National Weather Service heat index equation[i]) is used,

$$\begin{aligned} Heat\ Index = \min\big(\big(&-42.379 + 2.049015237T + 10.14333127H \\ &- 0.22475541TH - 0.00683783T^2 - 0.05481717H^2 \\ &+ 0.00122874T^2H + 0.00085282TH^2 \\ &- 0.00000199T^2H^2\big), 120\big) \end{aligned}$$

Where:

T= temperature

H = relative humidity

T >=78°F

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[i] National Weather Service, Weather Prediction Center, The Heat Index Equation, May 2014. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml

Appendix B OTAQ Light-duty gasoline 2012 Cold Temperature Program

EPA's Office of Transportation and Air Quality (OTAQ) contracted the testing of nine Tier 2 vehicles (2006 and 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. Note: we excluded the two GDI vehicles (Cadillac STS and the VW Passat) from the estimation of the THC and CO cold starts[b] as mentioned in Section 0.

Information on the tested vehicles is summarized in Table B-1.

Table B-1 Vehicles Tested in 2012 Cold Temperature Study

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 C Air Conditioning Analysis Vehicle Sample

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.

Table C-1 lists the vehicles in the test program.

Table C-1 Vehicle Sample for the Air Conditioning Analysis

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

Model Year	Make	Model	Vehicle Class	Weight
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 Consistency of MOVES EV Temperature Adjustment with Other Sources

As explained in Section 2.7. , MOVES applies a temperature adjustment to energy consumption from electric vehicles. While the adjustments were derived using only values from the AAA report[30], we analyzed the adjustments in relation to other published studies and test programs to ensure that the temperature adjustment in MOVES is consistent with many sources.

D1. North American Transit Bus Study

Henning, Thomas, and Smyth published a paper which included observational data from both battery electric and fuel cell urban buses[j]. The data was collected by eight transportation agencies in North America, ranging from California to Minnesota, meaning they were able to collect data at a wide range of ambient temperatures. The data was collected at the daily level, comparing daily energy consumption, daily mileage, and daily temperature.

This means their observed temperature effects are approximate and not experimentally derived. Attributing average change in energy consumption versus ambient temperature is difficult because of a number of confounding factors, the most important of which is the uncertainty introduced by daily averaging. Over the course of a day, temperature can change by as much as 20-30 degrees Fahrenheit and this is not reflected in the data. However, the data is still precise enough to provide a general comparison to the existing MOVES temperature adjustment and confirm that the adjustment is not fundamentally different for HD EVs compared to the passenger cars measured in the AAA study.

Their data shows a similar temperature impact for both fuel cell and battery electric EVs, with fuel cells possibly having a smaller impact. Despite the uncertainties in the data, it is possible to calculate a more precise temperature effect, but we believe the difference is small enough that creating additional complexity in MOVES to apply different temperature adjustments for each engine technology is unwarranted.

Henning, Thomas, and Smyth note a drop in MPGe with decreasing temperature. For battery electric buses, the average MPGe drops from 18.8 at 65°F to 14.4 at 32°F. This corresponds to a 27% increase in energy consumption, while the MOVES temperature adjustment estimates a 29% increase. Henning, Thomas, and Smyth report an average increase of about 6% at higher temperatures (80-95°F), which is smaller than the MOVES' high temperature adjustment and the AAA findings of a 20% increase, but directionally consistent with the AAA finding of less impact at warm than at cold temperatures (20 – 32°F).

Table D-1 shows Henning, Thomas, and Smyth's observed temperature impacts on fuel economy of both fuel cell and battery electric buses.

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[j] Henning, Mark; Thomas, Andrew R.; and Smyth, Alison, "An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses" (2019). Urban Publications. 0 1 2 3 1630. https://engagedscholarship.csuohio.edu/urban_facpub/1630.

Table D-1. Fuel Economy Reductions for EV Buses observed by Henning, Thomas, and Smyth

Ambient Temperature Range	Fuel Cell Reduction	Battery Electric Reduction
22 – 32 F	28.6%	32.1%
50 – 60 F	0%	0%
70 – 80 F	6.6%	6.4%

D2. Japanese Passenger Car Study

In 2018, Liu et al collected GPS and real-world energy consumption data from 68 passenger car EVs being driven across Japan, at a wide range of ambient temperatures[k]. They used the data to fit an EV energy consumption model based on several factors, of which two key variables are the ambient temperature and accessory load usage, which are related.

Because the energy consumption model is calibrated based on real-world data and temperature is a key component of the model, it can be used to attribute an increase in energy consumption to a change in temperature. First, they show that a quadratic equation similar to Equation 2-16 is a good fit for their data. Second, they show that their quadratic fit is close to the MOVES adjustments, although it is a bit steeper (a doubling of energy consumption, relative to about 65°F, at about 23°F instead of MOVES' estimated 8°F).

We did not use this paper as a direct source for a MOVES temperature adjustment for three reasons. First, the EVs in the study were owned and operated in Japan, and therefore may not be representative of the American fleet or American driver behavior. Second, the attribution of a change in energy consumption to temperature is done via a calibrated model, and not direct measurement. The AAA study source is a more direct observation of the effect of temperature on EV efficiency via controlled experimental design, which is a better input to MOVES. Third, the paper does not provide enough data to calculate a temperature effect at the level of precision required by MOVES. Nonetheless, we should expect the temperature effect modeled by Liu et al. to be broadly consistent with other sources such as MOVES, and it is.

D3. Canadian Passenger Car Study

Environment and Climate Change Canada (ECCC) performed on-road, real-world testing of a 2018 Chevrolet Bolt in January and July of 2019, collecting energy consumption data at a frequency of 2 Hz from the battery terminal[l]. Their instrumentation was able to collect energy consumption of various components as well, and they show that HVAC is the dominant factor increasing energy consumption at

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[k] Liu, K., et al. (2018). Exploring the interactive effects of ambient temperature and vehicle auxiliary loads on electric vehicle energy consumption. Applied Energy, 227, 324-331. DOI: https://doi.org/10.1016/j.apenergy.2017.08.074.

[l] Emissions Research and Measurement Section (Environment and Climate Change Canada) and ecoTechnology for Vehicles Program (Transport Canada), Government of Canada.

extreme temperatures. The vehicle was driven on similar routes each day of testing, and therefore the results of several trips are directly comparable.

There were only eight days' worth of testing, and the temperatures tended to be either extreme cold (below 35°F) or at room temperature and above. Therefore, it is not appropriate to fit a quadratic curve to the data and calculate an exact temperature effect. However, Figure D-1 shows that, given the expected variance that exists between individual tests, the ECCC data generally agrees with the MOVES adjustments, including the A/C adjustment and light-duty EV cold temperature adjustment.

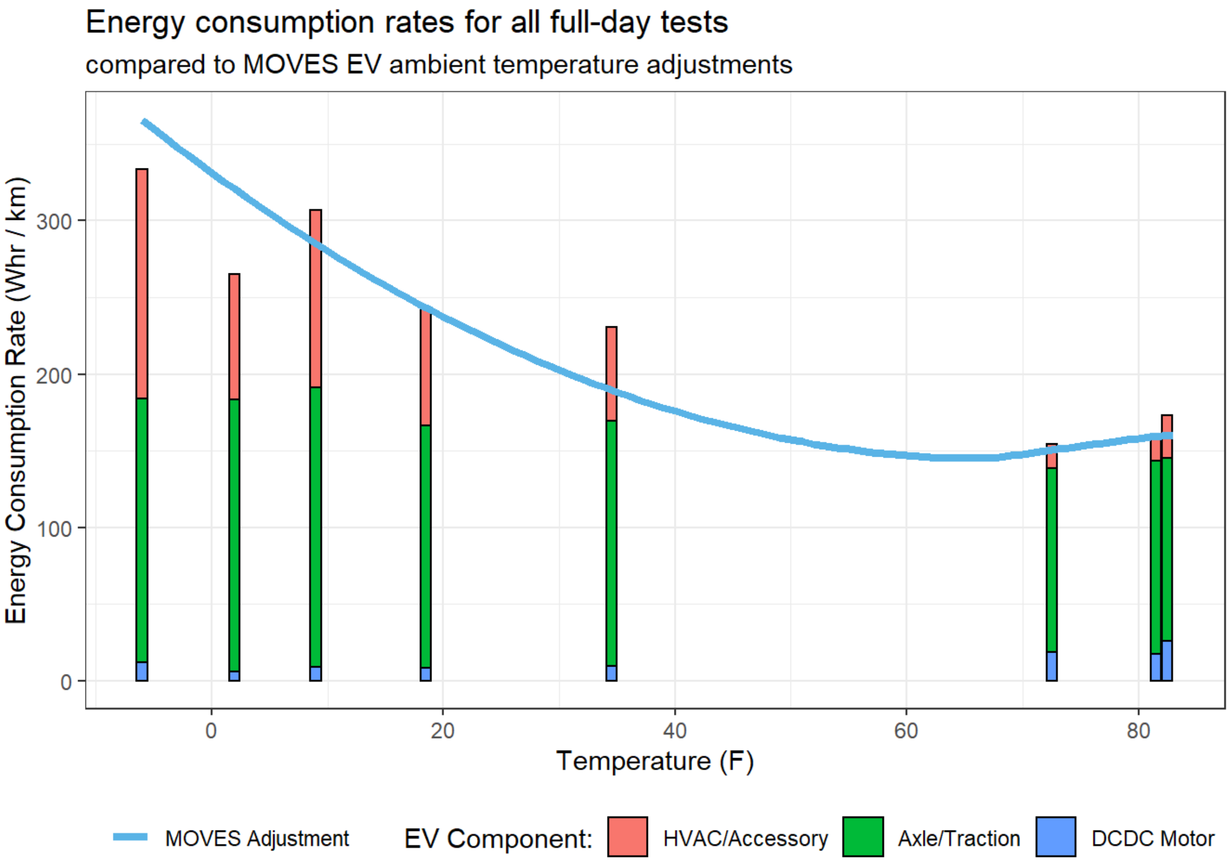

Figure D-1 Comparison of ECCC test data and MOVES EV energy consumption with temperature adjustment.

D4. Conclusion

Overall, the MOVES EV temperature adjustment algorithm is generally consistent with the limited available real-world data on changes in total energy consumption with temperature for electric vehicles of all classes and technologies.

Appendix E Vehicles in the 2021 ORD Cold-temperature Program

The vehicles measured in this program, designated as ORD (2021) in Section 0, are described in <T.

Table E-1. Vehicles Measured in the 2021 ORD Cold-Temperature Program

ID	MY	Make/Model	Inertial Weight (lb)	Displ. (L)	Mileage	Aspiration	GDI
Veh 1	2014	Honda/Accord	3,500	2.4	12,700	Natural	Wall-guided
Veh 2	2015	Ford/Fusion	3,750	1.5	10,500	Turbo	Spray-guided
Veh 3	2015	VW/Jetta	3,375	1.8	9,200	Turbo	Combo Wall/air-guided

Appendix F Model-Fitting Information for Analysis of Fuel-Injection Technology

The following tables include additional model-fitting information for the for the model presented in Table 2-12, on page 30.

Table F-1. Dimensions for the best-fit Model

Covariance parameters	14
Columns in X	6
Columns in Z per Subject	2
Subjects	12
Maximum observations per subject	27

The ‘subjects’ are the 12 vehicles. The total number of observations was 112.

The table below presents the 14 covariances associated with the ‘random’ component of the best-fit model. These include variances for the random intercepts and slopes for the vehicle subjects, as well as individual residual error variances for each vehicle.

Table F-2. Covariance Parameters for the best-fit model

Parameter	**Subject**	**Group**	**Estimate**
Intercept (σ^2_{b0})	vehicle		0.1028
Temperature (T) (σ^2_{b1})	vehicle		0.000079
Residual (σ^2_{ε})		(ORD) Accord	0.03175
Residual (σ^2_{ε})		(ORD) Fusion	0.006631
Residual (σ^2_{ε})		(ORD)_Jetta	0.01786
Residual (σ^2_{ε})		(OTAQ) Accord	0.1275
Residual (σ^2_{ε})		(OTAQ) Forte	0.007208
Residual (σ^2_{ε})		(OTAQ) Gallant	0.02544
Residual (σ^2_{ε})		(OTAQ) Lucerne	0.1377
Residual (σ^2_{ε})		(OTAQ) Mazda6	0.4537
Residual (σ^2_{ε})		(OTAQ) Passat	0.01273
Residual (σ^2_{ε})		(OTAQ) Patriot	0.02139
Residual (σ^2_{ε})		(OTAQ) STS	0.01867
Residual (σ^2_{ε})		(OTAQ) Santa Fe	0.004494

The following table includes ‘random’ intercepts and slopes for the 12 vehicles included in the analysis. See Equation 2-13 and discussion on page 29.

Table F-3. Solution for the Random Effects for the Best-fit Model

Vehicle	Effect	Estimate	Std. Err. Pred.	d.f.	*t* value	Pr > |*t*|
(ORD) Accord	Intercept (b_0)	-0.1100	0.1604	9.17	-0.69	0.5099
	Slope (b_1)	-0.01970	0.004186	10.7	-4.71	0.0007
(ORD) Fusion	Intercept (b_0)	0.1084	0.1507	7.42	0.72	0.4939
	Slope (b_1)	0.005961	0.004069	9.65	1.47	0.1747
(ORD) Jetta	Intercept (b_0)	-0.1434	0.1554	8.27	-0.92	0.3823
	Slope (b_1)	0.001323	0.004143	10.3	0.32	0.7558
(OTAQ) Accord	Intercept (b_0)	-0.01107	0.2345	11.3	-0.05	0.9632
	Slope (b_1)	-0.000003.44	0.004952	16.1	-0.00	0.9995
(OTAQ) Forte	Intercept (b_0)	-0.1180	0.1577	11.6	-0.75	0.4693
	Slope (b_1)	0.001859	0.003860	13.3	0.48	0.6380
(OTAQ)_Gallant	Intercept (b_0)	-0.2306	0.1810	10.3	-1.27	0.2306
	Slope (b_1)	0.005038	0.004207	13.5	1.20	0.2517
(OTAQ)_Lucerne	Intercept (b_0)	-0.3904	0.2127	16.2	-1.83	0.0849
	Slope (b_1)	0.006119	0.004741	18.7	1.29	0.2126
(OTAQ) Mazda6	Intercept (b_0)	-0.07965	0.2717	9.79	-0.29	0.7755
	Slope (b_1)	-0.00304	0.006207	14.3	-0.49	0.6321
(OTAQ) Passat	Intercept (b_0)	0.3832	0.1628	9.02	2.35	0.0429
	Slope (b_1)	0.002394	0.004266	11.1	0.56	0.5859
(OTAQ) Patriot	Intercept (b_0)	0.3810	0.1766	10.5	2.16	0.0550
	Slope (b_1)	0.000341	0.004139	13.1	0.08	0.9356
(OTAQ) STS	Intercept (b_0)	-0.2382	0.1681	9.7	-1.42	0.1878
	Slope (b_1)	0.01003	0.004297	11.5	2.33	0.0387
(OTAQ) Santa Fe	Intercept (b_0)	0.4486	0.1533	11.7	2.93	0.0130
	Slope (b_1)	-0.01032	0.003798	13	-2.72	0.0176