Exhaust Temperature, Air Conditioning and Inspection and Maintenance Adjustments in MOVES2010a

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Highway Vehicle Temperature, Humidity, Air Conditioning, and Inspection and Maintenance Adjustments

(EPA-420-R-10-027)

http://www.epa.gov/otaq/models/moves/420r10027.pdf

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Exhaust Emissions Temperature Adjustments

Outline (Temperature Adjustments)

- Test Data
- Analysis
- Operating Modes (Soak Time)
- Results

Test Data Used

- **“Bagged” Emission Tests**
  - Paired vehicle tests.
  - Each vehicle tested at multiple temperatures.
  - FTP, LA92 and US06 test procedures.
- **Second-by-Second Test Data**
  - I/M testing in Chicago (IM240s).
  - Used to validate effects on running emissions.

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Data Sources

- **Mobile Source Observation Database (MSOD).**
  - Repository for past EPA and non-EPA test program results.
  - Tests used as the basis for the earlier MOBILE6 model.
  - Temperatures range from 15 to 110 degrees F.
- **Kansas City Study (2008).**
  - LA92 test procedures at ambient temperatures.
- **EPA Office of Research and Development (ORD).**
  - Five vehicles tested down to -20 degrees F.
- **EPA testing at Southwest Research Institute (SwRI).**
  - 2005 model year vehicles tested down to zero degrees F.

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Data Sources - Tests

Model Years	MSOD	ORD	SwRI	Kansas City
Pre-1981	233			34
1981-1982	502			
1983-1985	874			18
1986-1989	1760	5		85
1990-1993	227	5		91
1994-1999	128	5		220
2000-2005		10	12	99

Stratifying Test Data

- **Fuel Type / Emission Process**
  - Gasoline / Diesel
  - Engine start / Hot running
- **Regulatory Class**
  - LDV / LDT / HDV
- **Model Year Groups:**
  - **1960 – 1980**
  - **1981 – 1982**
  - **1983 – 1985**
  - **1986 - 1989**
  - **1990 - 2004**
  - **2005 and later**

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Data Analysis Technique

- **Estimate the hot running and cold start emissions for each test.**
  - MOVES divides trip exhaust emissions into engine start and hot running processes.
- **Determine the appropriate stratum for the data.**
- **Regression analyses of emissions versus temperature within each stratum.**

Running Emission Processes

- **Hot running emissions includes all engine operation, excluding the effects of engine starts.**
  - Derived from adjusting the hot start emissions.
- **Engine start emissions are the increment in emissions between a trip with an engine start and the same trip without an engine start.**
  - Derived by subtracting the hot running emission rate from the cold start emission measurement.

Adjustment Methods

- Most adjustments to base emission rates in MOVES are using multiplicative adjustments:

  Adjusted Rate = Base Rate * Adjustment Factor

- Some adjustments can be better done using additive factors:

  Adjusted Rate = Base Rate + Adjustment Factor

Additive Temperature Adjustments

- **Additive adjustments make sense when:**
  - The additional emissions are <u>not necessarily proportional </u>to the base emission rate.
  - The quantity of additional emissions is <u>much larger </u>than the base emission rate.
- **Additive adjustments will prevent small changes in the base emission rate from causing massive changes in the temperature adjusted emissions.**

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Running Exhaust Emissions Temperature Adjustments

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Particulate Matter (PM) Data

- **Kansas City (LA92) testing (261 Round 1 and 278 Round 2 with 43 vehicles in both).**

  "Analysis of Particulate Matter Emissions from Light-Duty Gasoline Vehicles in Kansas City", (EPA420-R-08-010, April 2008).

  http://www.epa.gov/oms/emission-factors-research/420r08010.pdf

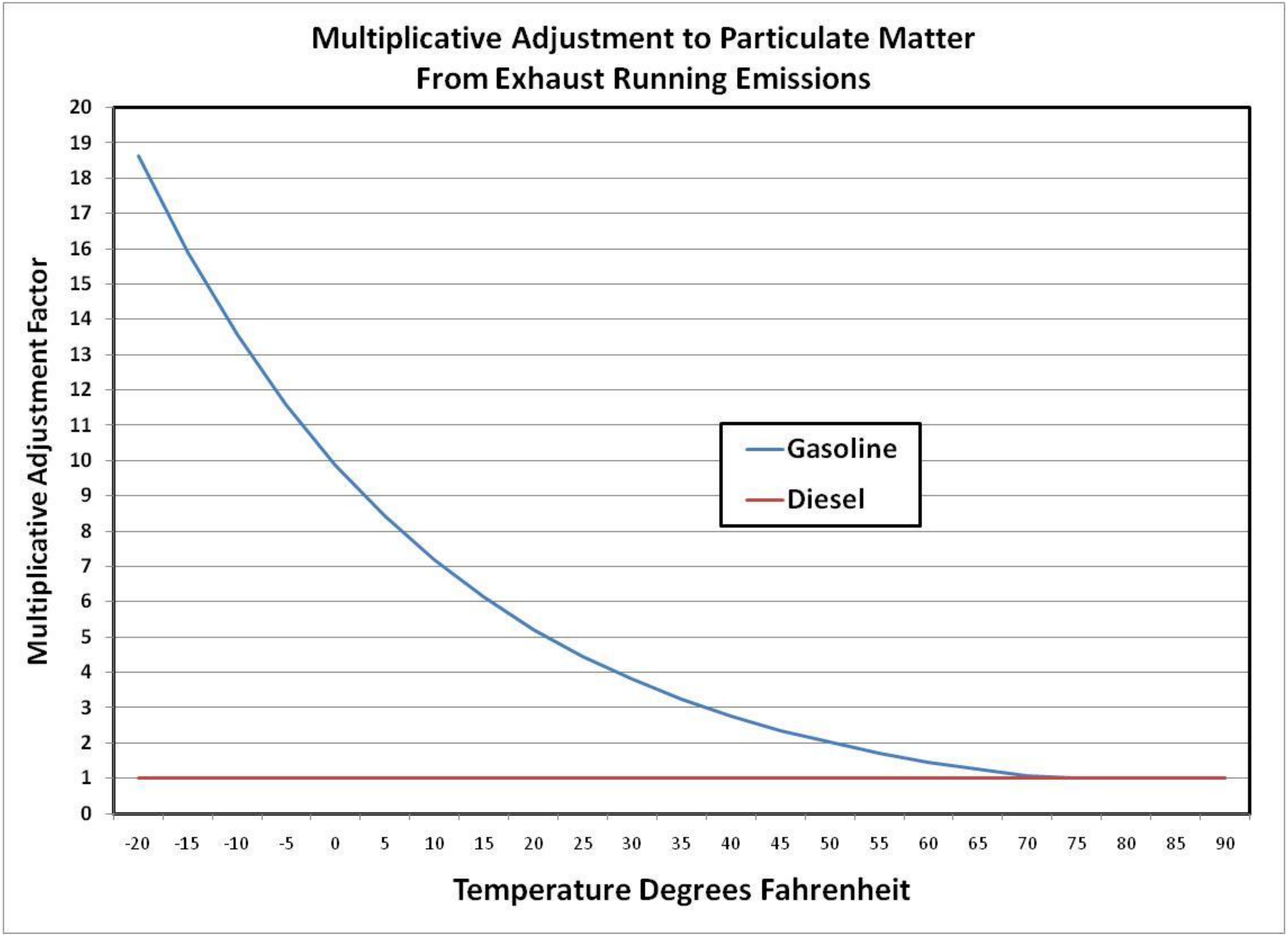
- **Office of Research and Development (ORD) testing (5 vehicles).**

  "Characterization of Emissions from Malfunctioning Vehicles Fueled With Oxygenated Gasoline-Mtbe Fuel Part 1", (EPA/600/R-03/028, 2000).

  http://www.epa.gov/nerl/mtbe/paper-1.pdf

Analysis Results for PM Running Emissions

- PM running emission adjustments are multiplicative.
- Gasoline PM increases exponentially as temperature decreases.
- The effect of temperature on exhaust running PM above 72 degrees is not significant.
- PM emissions from diesel vehicles are not adjusted for temperature in MOVES.


Multiplicative Adjustment to Particulate Matter
From Exhaust Running Emissions
Multiplicative Adjustment Factor
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
Temperature Degrees Fahrenheit
Gasoline
Diesel

Analysis Results for Other Running Emissions

- **The analysis found very little variation in the exhaust running emissions for Energy, HC, CO, or NOx in the available data.**
  - MOVES has no temperature adjustment for these emissions.
  - Diesel running emissions have no temperature adjustment.

Engine Start Emissions Temperature Adjustments

Cold Start Emissions Analysis

- **Estimating Cold Start emissions.**
  - Cold start is not a reference to ambient temperature, just the soak time between engine starts.
- **Calculating change in Cold Start (relative to 75 F).**
- **Analyzing changes in Cold Start.**

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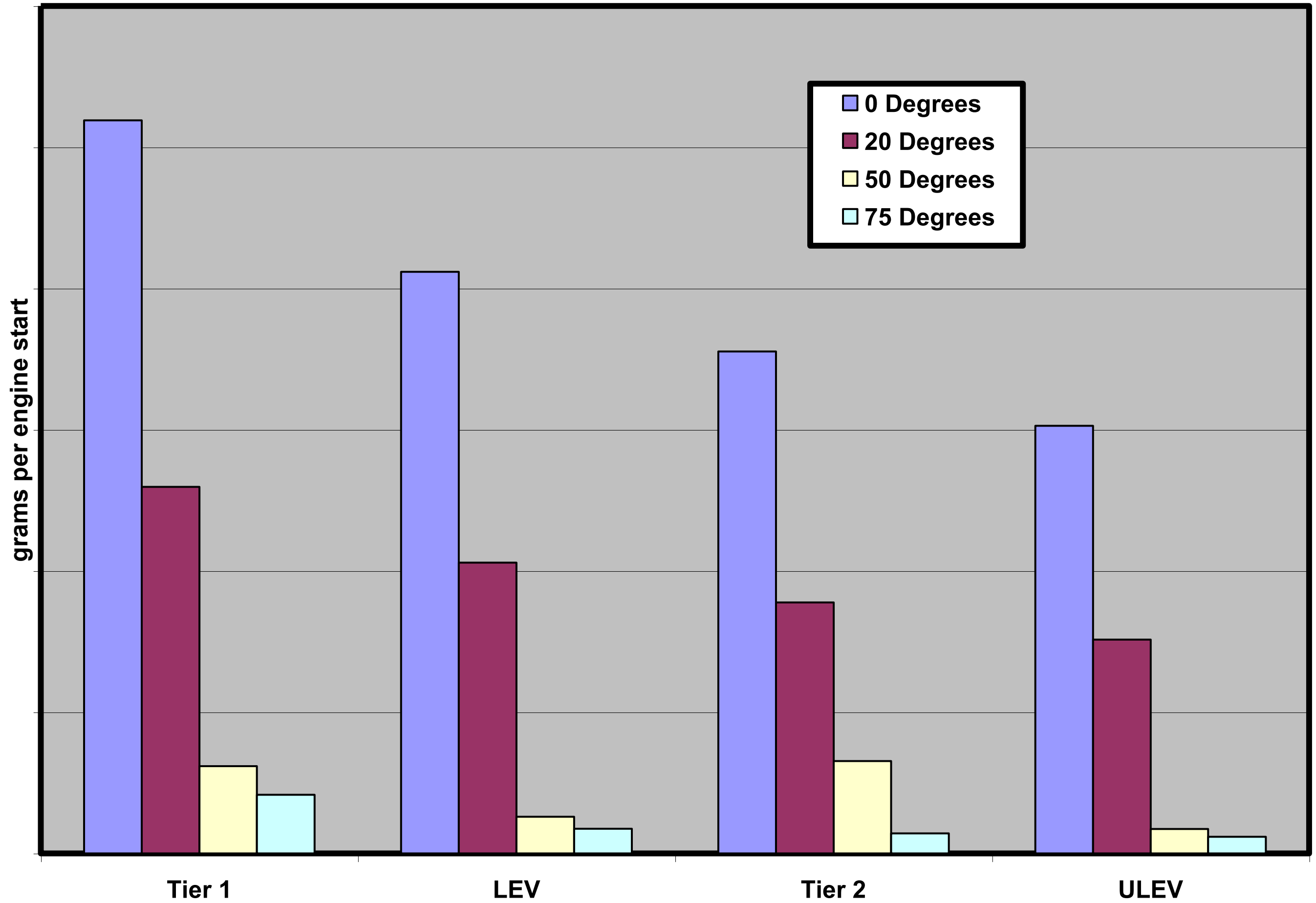
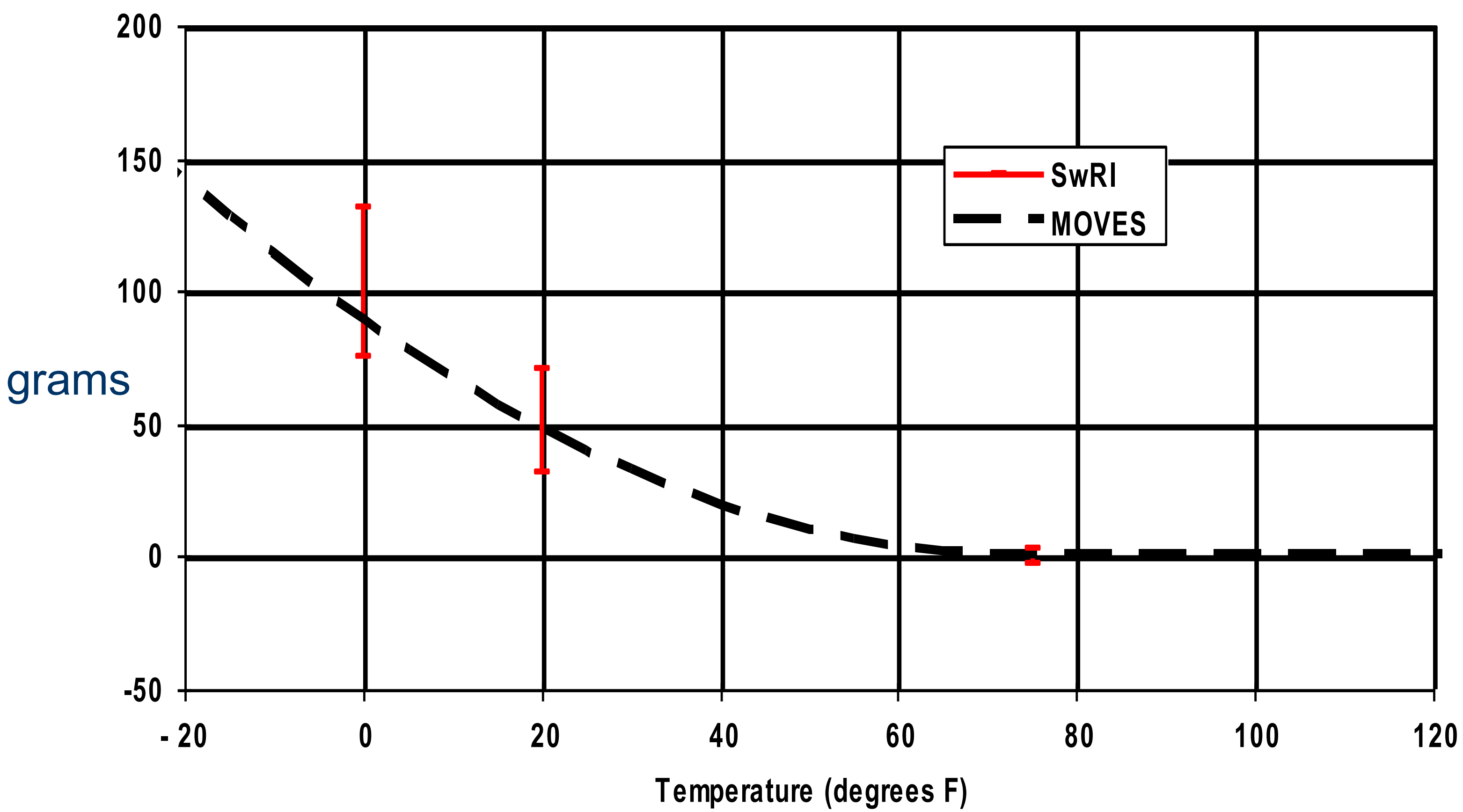
Engine Start Emissions Additive Temperature Adjustments

- Engine start emissions at the coldest temperatures are much larger (orders of magnitude) than the base emission rate at 75 degrees Fahrenheit.
- The observed ratio of engine start emissions at colder temperatures to the base emission rate is not the same for different base rates.
- MOVES will use additive adjustments for the effects of temperature on engine start emissions for HC, CO and NOx emissions below 75 degrees Fahrenheit.

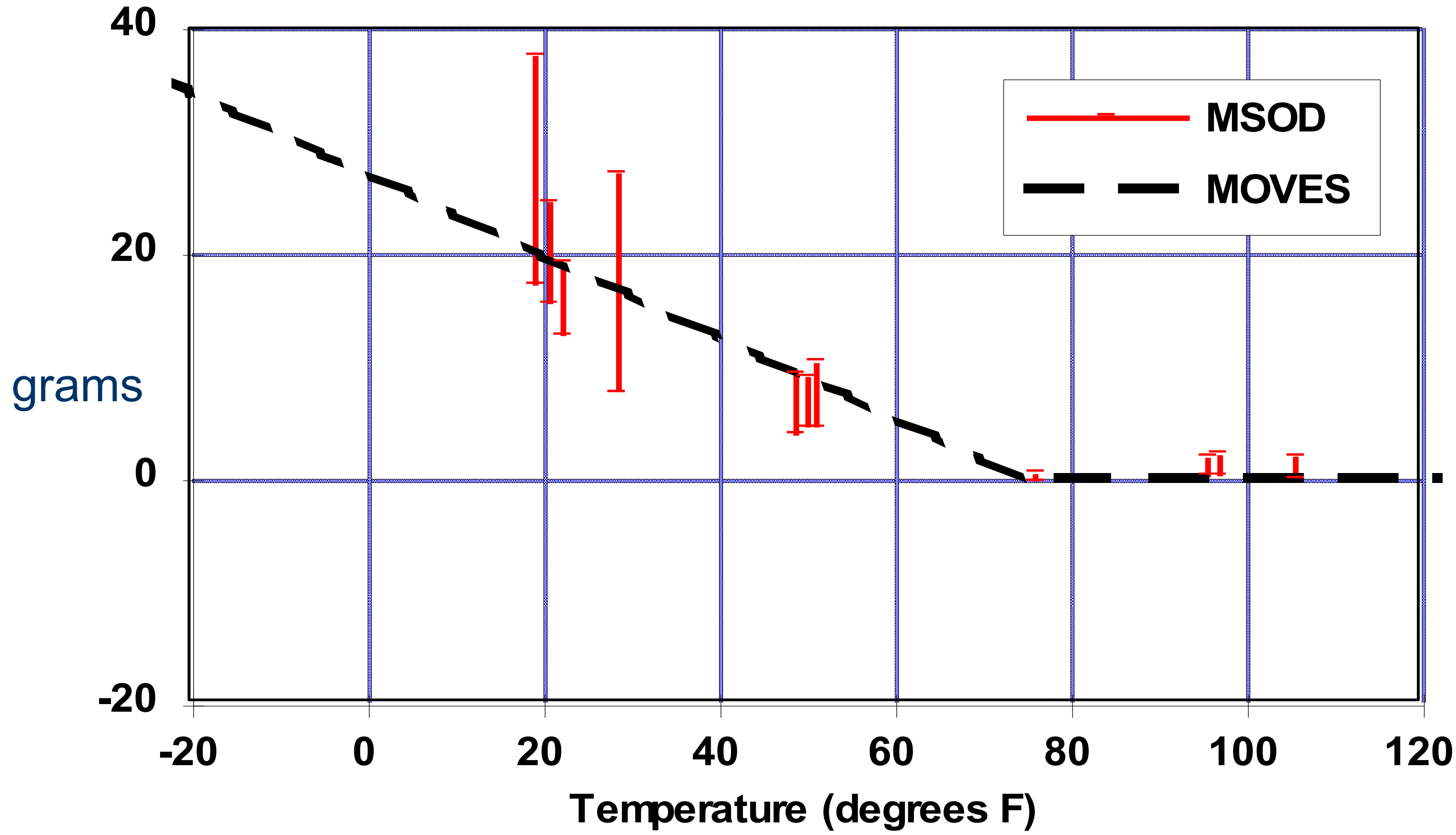
Example Engine Start HC Emissions Versus Temperature



Change in Cold-Start CO Emissions
Tier-2 Vehicles



Change in Cold-Start HC Emissions 1983-85 Model Year Group



Diesel Temperature Effects

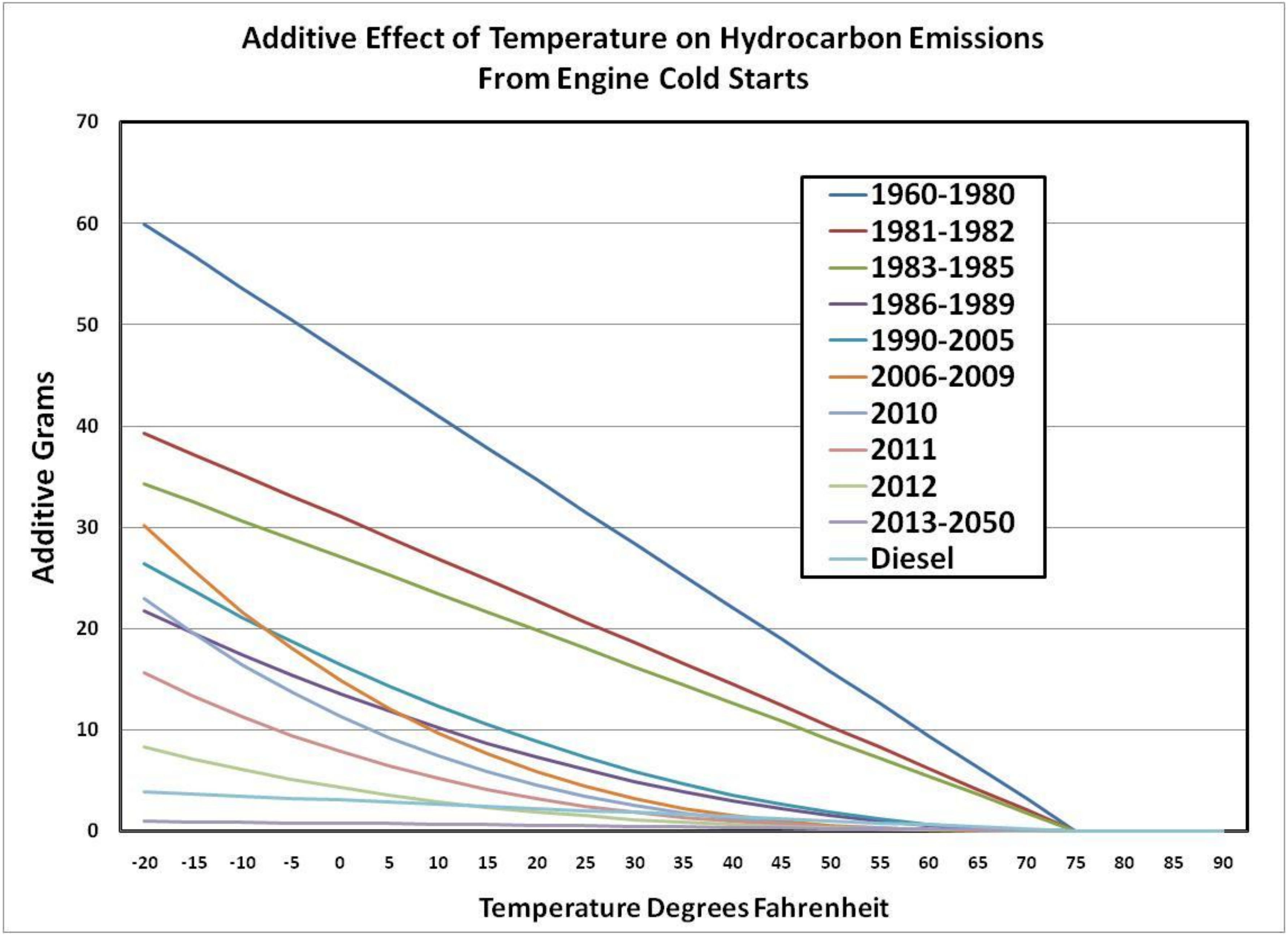
- **Limited sample of diesel vehicles with multiple temperature measurements.**
  - Nine passenger cars and 3 light duty trucks.
  - None with after-treatment devices.
- **Limited temperature range.**
  - 30 to 75 degrees Fahrenheit.
- **Results used for all diesel vehicles of all classes and model years.**

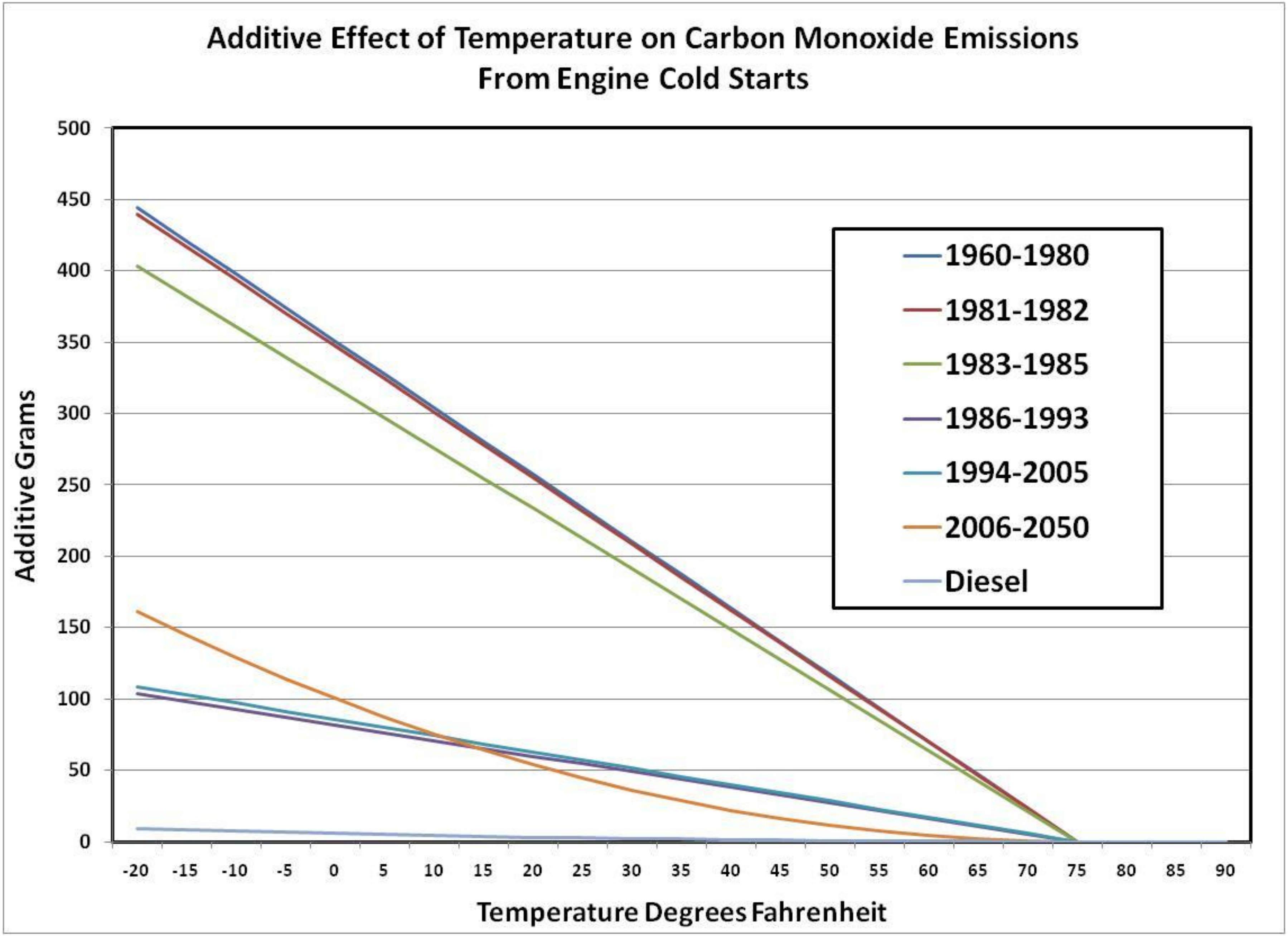
Analysis Results for Engine Start Emissions

- **The effects of temperature on engine starts for HC, CO and NOx emissions are additive.**
- **The effects of temperature on engine start emissions above 75 degrees Fahrenheit are not significant.**
  - MOVES does not adjust engine start emissions for temperatures above 75 degrees.
- **Compressed Natural Gas (CNG) vehicle emissions are assumed to be unaffected by temperature for both engine starts and running exhaust.**

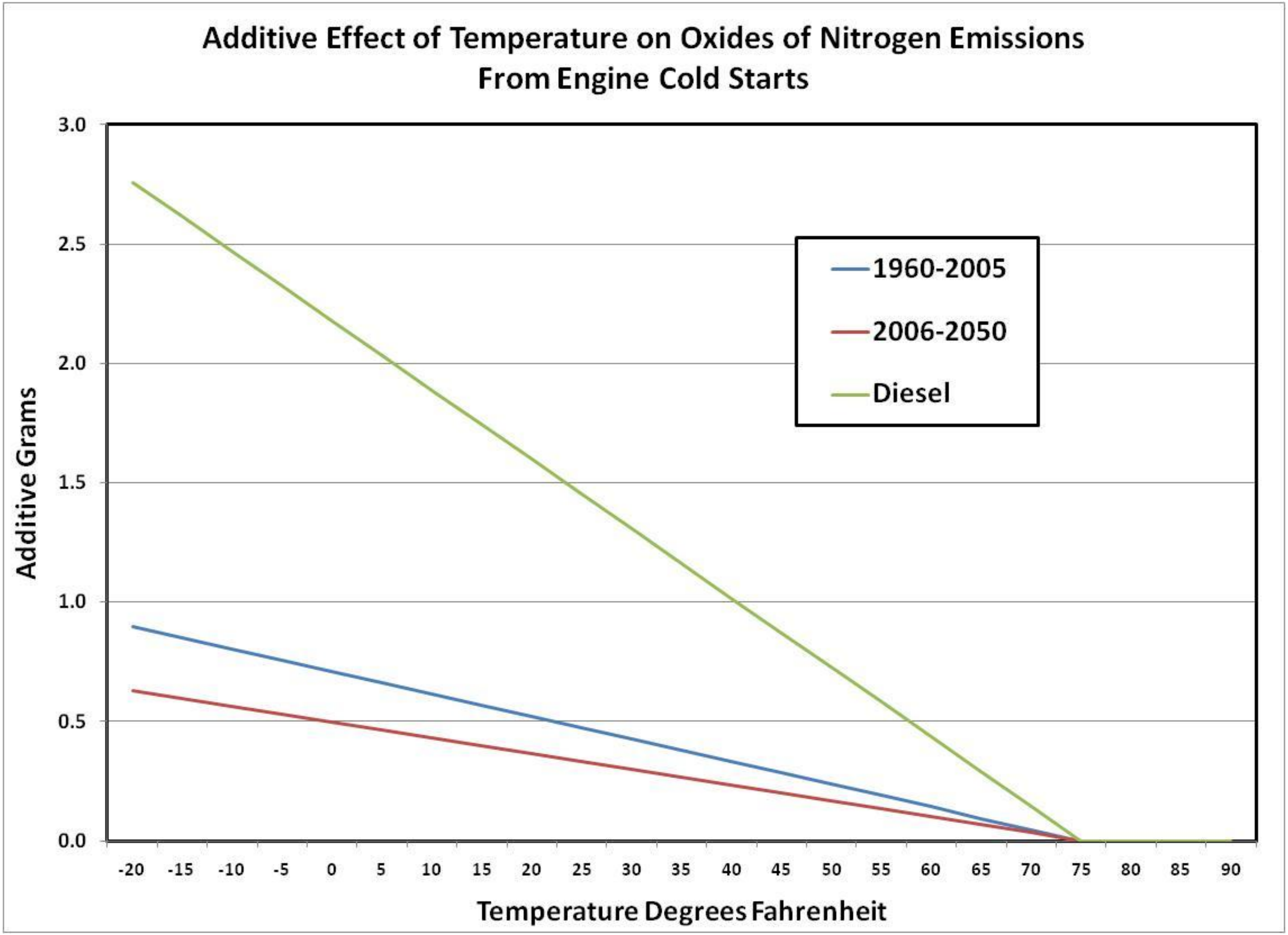
Adjustment for MSAT Cold Temperature HC Standard

- **The Mobile Source Air Toxic (MSAT) rule establishes cold temperature HC standards beginning with the 2010 model year.**
  - MOVES assumes MSAT will only affect engine start emissions.
  - Running emissions in MOVES have little or no temperature dependency.
- **The additive impact on engine start emissions at and below 20 degrees was reduced on vehicles required to meet the new standard.**


Additive Effect of Temperature on Hydrocarbon Emissions
From Engine Cold Starts
Additive Grams
Temperature Degrees Fahrenheit
0
10
20
30
40
50
60
70
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
1960-1980
1981-1982
1983-1985
1986-1989
1990-2005
2006-2009
2010
2011
2012
2013-2050
Diesel

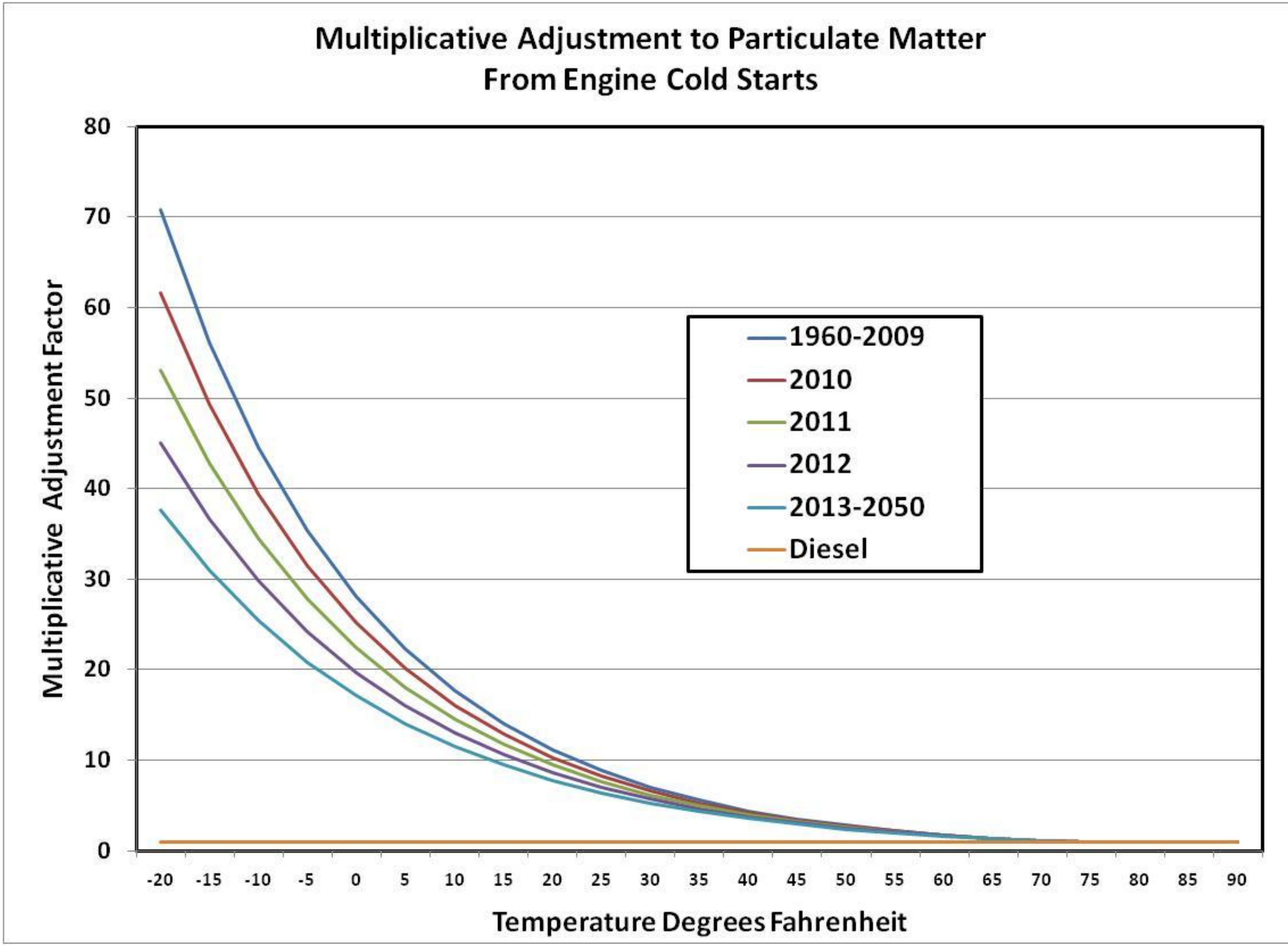


Additive Effect of Temperature on Carbon Monoxide Emissions
From Engine Cold Starts
Additive Grams
500
450
400
350
300
250
200
150
100
50
0
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Temperature Degrees Fahrenheit
1960-1980
1981-1982
1983-1985
1986-1993
1994-2005
2006-2050
Diesel


Additive Effect of Temperature on Oxides of Nitrogen Emissions
From Engine Cold Starts
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Additive Grams
1960-2005
2006-2050
Diesel
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Temperature Degrees Fahrenheit

Analysis Results for PM Engine Start Emissions

- **Gasoline engine start PM increases exponentially as temperature decreases.**
  - For every 20˚F drop, PM doubles.
- **The effect of temperature on exhaust running PM above 72 degrees is not significant.**
- **2010 and newer PM start emissions were adjusted for the impact of MSAT cold temperature HC standards.**
- **Engine start PM emissions from diesel vehicles are not adjusted for temperature in MOVES.**

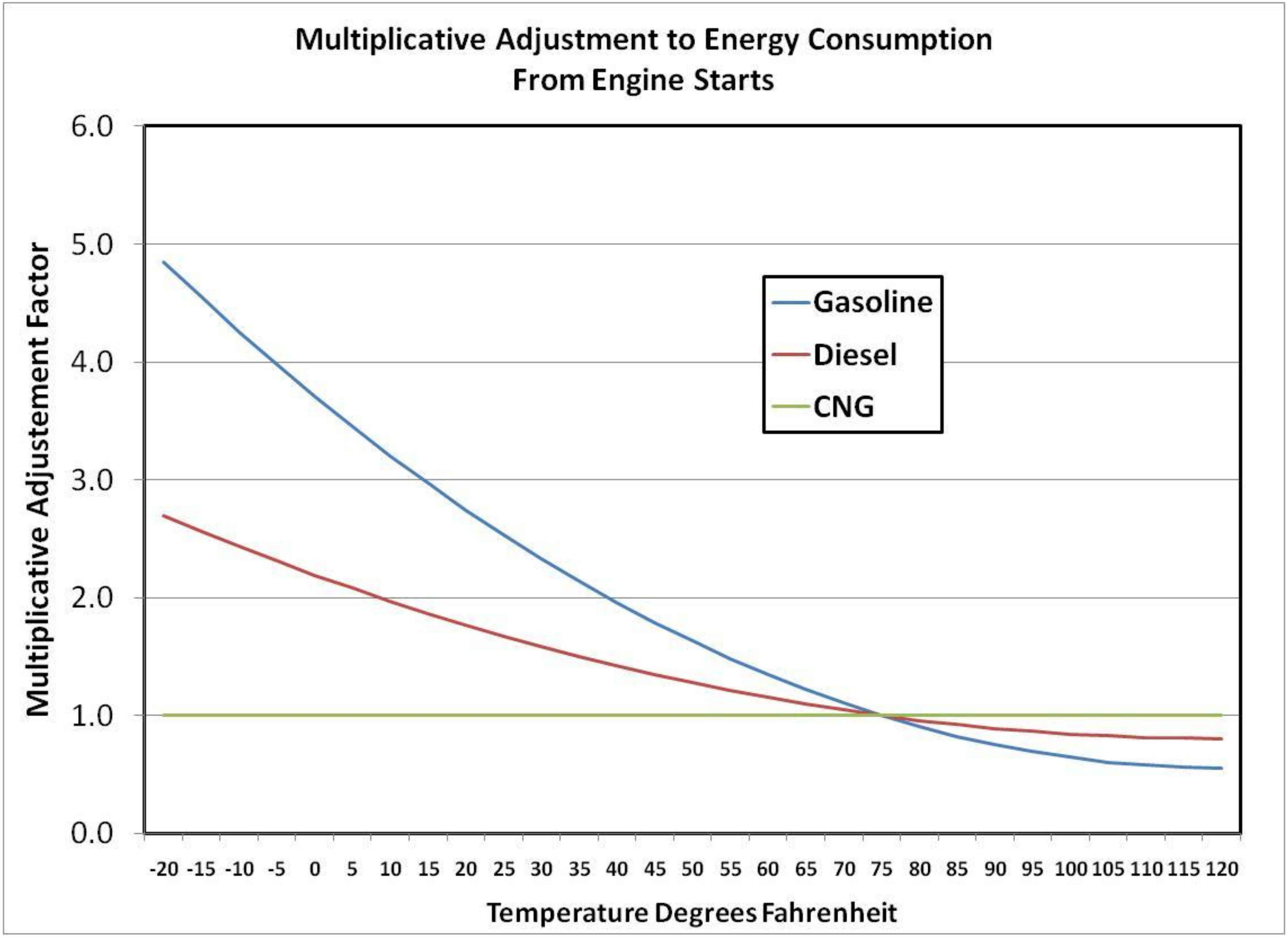

Multiplicative Adjustment to Particulate Matter
From Engine Cold Starts
Multiplicative Adjustment Factor
80
70
60
50
40
30
20
10
0
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Temperature Degrees Fahrenheit
1960-2009
2010
2011
2012
2013-2050
Diesel

Effects of Temperature on Fuel Consumption

- The effect of temperature on energy (fuel) consumption were carried over from earlier versions of MOVES (MOVES2004).
- The effect of temperature on start energy consumption is multiplicative.
- Energy consumption is affected both above and below 75 degrees Fahrenheit.
- Both gasoline and diesel vehicles are affected, but not CNG.

"MOVES2004 Energy and Emission Inputs" (EPA420-P-05-003, March 2005)

http://www.epa.gov/otaq/models/ngm/420p05003.pdf


Multiplicative Adjustment to Energy Consumption
From Engine Starts
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Multiplicative Adjustement Factor
Gasoline
Diesel
CNG
-20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120
Temperature Degrees Fahrenheit

Engine Start Soak Effects

- **Engine start emissions are maximum after at least a 12 hour period (soak) between engine operations (cold start).**
  - Cold start is not a reference to ambient temperature, just soak time.
- **Most engine starts occur after a short period of time.**
- **Cold soak emission rates must be adjusted to reflect the distribution of soak times.**

Engine Start Operating Mode

- **MOVES uses distinct start emission rates for different "modes".**
- **Modes are defined in terms of soak time:**
  - Under 6 minutes
  - At least 6 minutes but under 30 minutes.
  - At least 30 minutes but under 60 minutes.
  - At least 60 minutes but under 90 minutes.
  - At least 90 minutes but under 120 minutes.
  - At least 120 minutes but under 360 minutes.
  - At least 360 minutes but under 720 minutes.
  - At least 720 minutes ("cold start").

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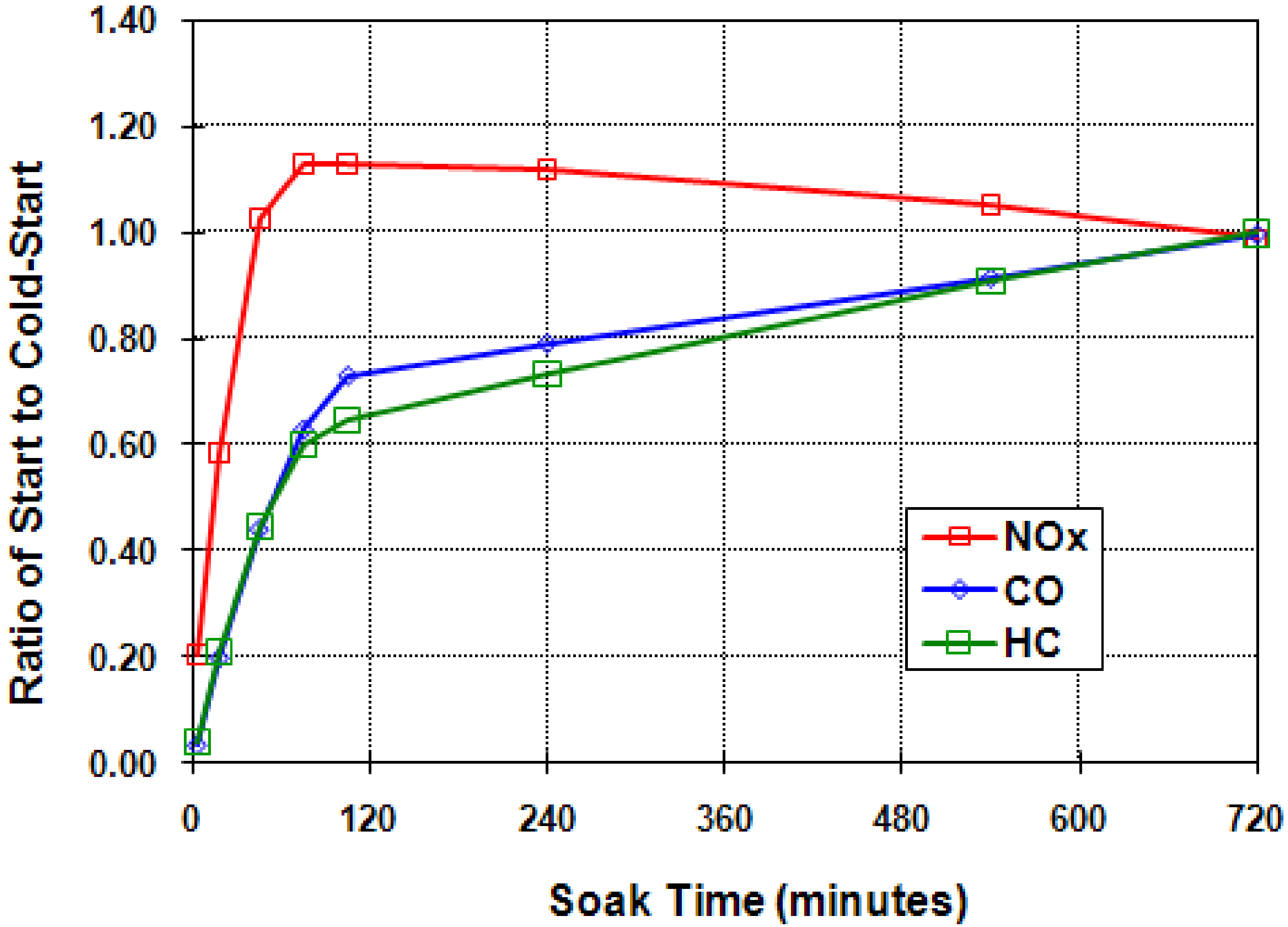
Adjusting for Length of Soak

- **The start emission rates for each soak time were calculated using factors developed by ARB applied to the base (12 hour soak) emissions.**
- **Those same ARB soak-time factors were applied to the additive temperature adjustments.**
  - Starts with shorter soak times will have smaller engine start emissions and proportionally smaller adjustments for temperature.

ARB Soak Curves



Adjustments for Air Conditioning

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Outline (Air Conditioning)

- Test Data
- Data Analysis
- Adjustments to air conditioning effects

Air Conditioning Data

- **Testing included:**
  - A variety of test driving cycles.
  - 625 total test cycles on individual vehicles.
  - Over 1.4 million seconds of emission measurements.
  - 75 and 95 degrees Fahrenheit.
- **Vehicles included:**
  - 1990 through 1999 model year vehicles.
  - 30 passenger cars and 24 light trucks.
- **Matched tests AC-on and AC-off.**

Mapping Data to VSP

- Vehicle Specific Power (VSP) was determined for each second.
- The VSP was used to assign each second to one of the MOVES operating modes.
- The VSP and operating modes definitions are the same as used for MOVES exhaust running emission rates.

Air Conditioning Effects

- **The "with AC" emission rates are divided by the "without AC" emission rates for each operating mode.**
- **The ratio defines the "full" AC adjustment for that operating mode.**
- **The AC effects for HC, CO and NOx:**
  - Affect only passenger cars, passenger trucks and light duty commercial vehicles.
  - Affect all fuel types.
- **AC effects on energy also affect HD vehicles.**

Summary of “Full” Air Conditioning Adjustments

Pollutant	Operating Mode	Full A/C Adjustment
HC	Braking / Decel	1.0000
HC	Idle	1.0796
HC	Cruise / Accel	1.2316
CO	Braking / Decel	1.0000
CO	Idle	1.1337
CO	Cruise / Accel	2.1123
NOx	Braking / Decel	1.0000
NOx	Idle	6.2601
NOx	Cruise / Accel	1.3808

Full Air Conditioning Effect on Energy Consumption by Operating Mode

opModeID	fullACAdjustment	Description
0	1.34224	Braking
1	1.36463	Idling
11	1.31407	Low Speed Coasting; VSP< 0; 1<=Speed<25
12	1.25383	Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25
13	1.18743	Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25
14	1.16615	Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25
15	1.15418	Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25
16	1.12809	Cruise/Acceleration; 12<=VSP; 1<=Speed<25
21	1.29417	Moderate Speed Coasting; VSP< 0; 25<=Speed<50
22	1.22319	Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50
23	1.18678	Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50
24	1.16695	Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50
25	1.15742	Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50
27	1.12661	Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50
28	1.12661	Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50
29	1.12661	Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50
30	1.12661	Cruise/Acceleration; 30<=VSP; 25<=Speed<50
33	1.20457	Cruise/Acceleration; VSP< 6; 50<=Speed
35	1.15559	Cruise/Acceleration; 6<=VSP<12; 50<=Speed
37	1.13716	Cruise/Acceleration; 12<=VSP<18; 50<=Speed
38	1.13716	Cruise/Acceleration; 18<=VSP<24; 50<=Speed
39	1.13716	Cruise/Acceleration; 24<=VSP<30; 50<=Speed
40	1.13716	Cruise/Acceleration; 30<=VSP; 50<=Speed

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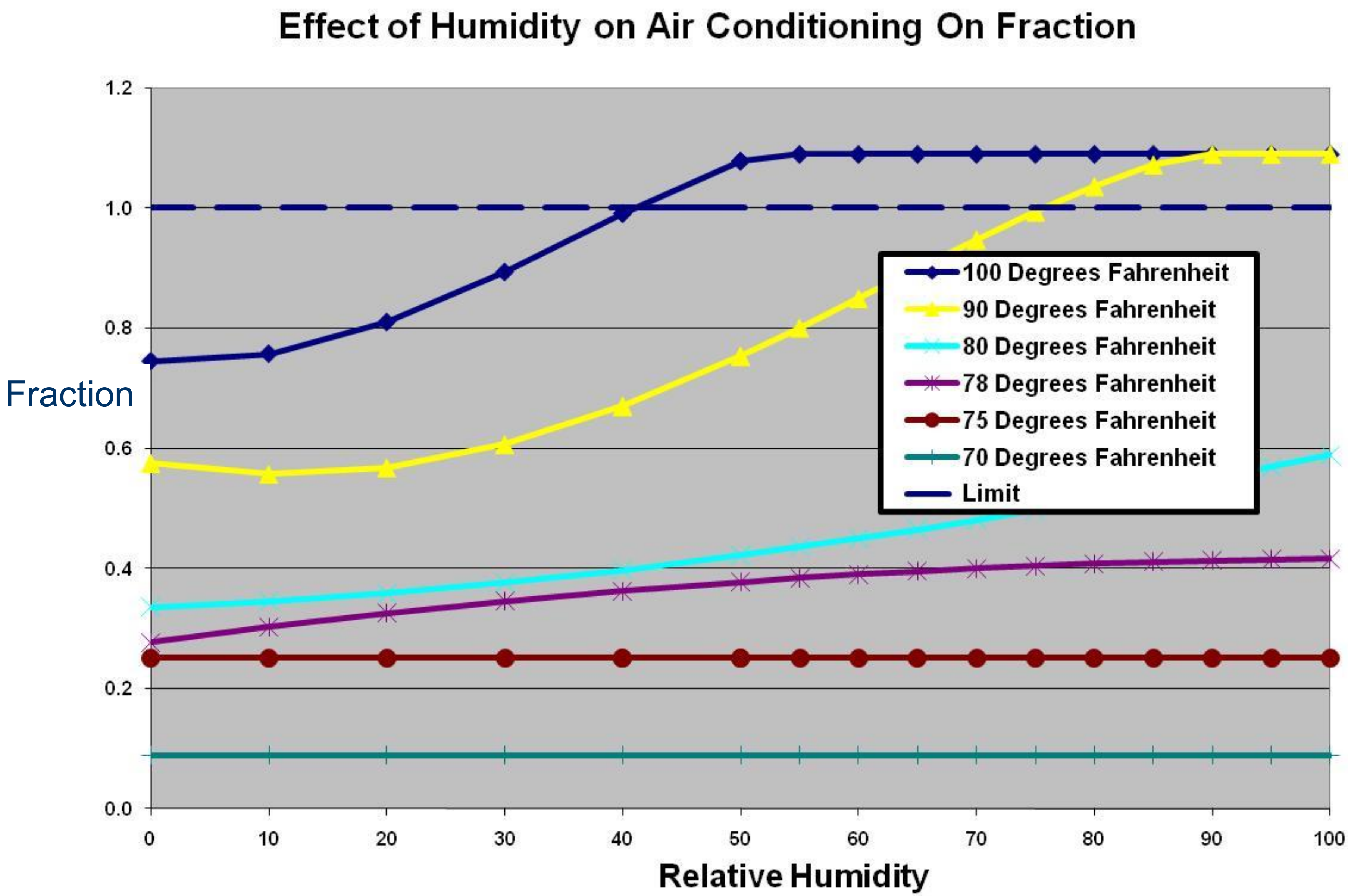
Adjustments to Air Conditioning

ACAdjustment =
1
+ ((FullACAdjustment - 1)
* ACPenetration
* functioningACFraction
* ACOnFraction)

Adjustments to Air Conditioning

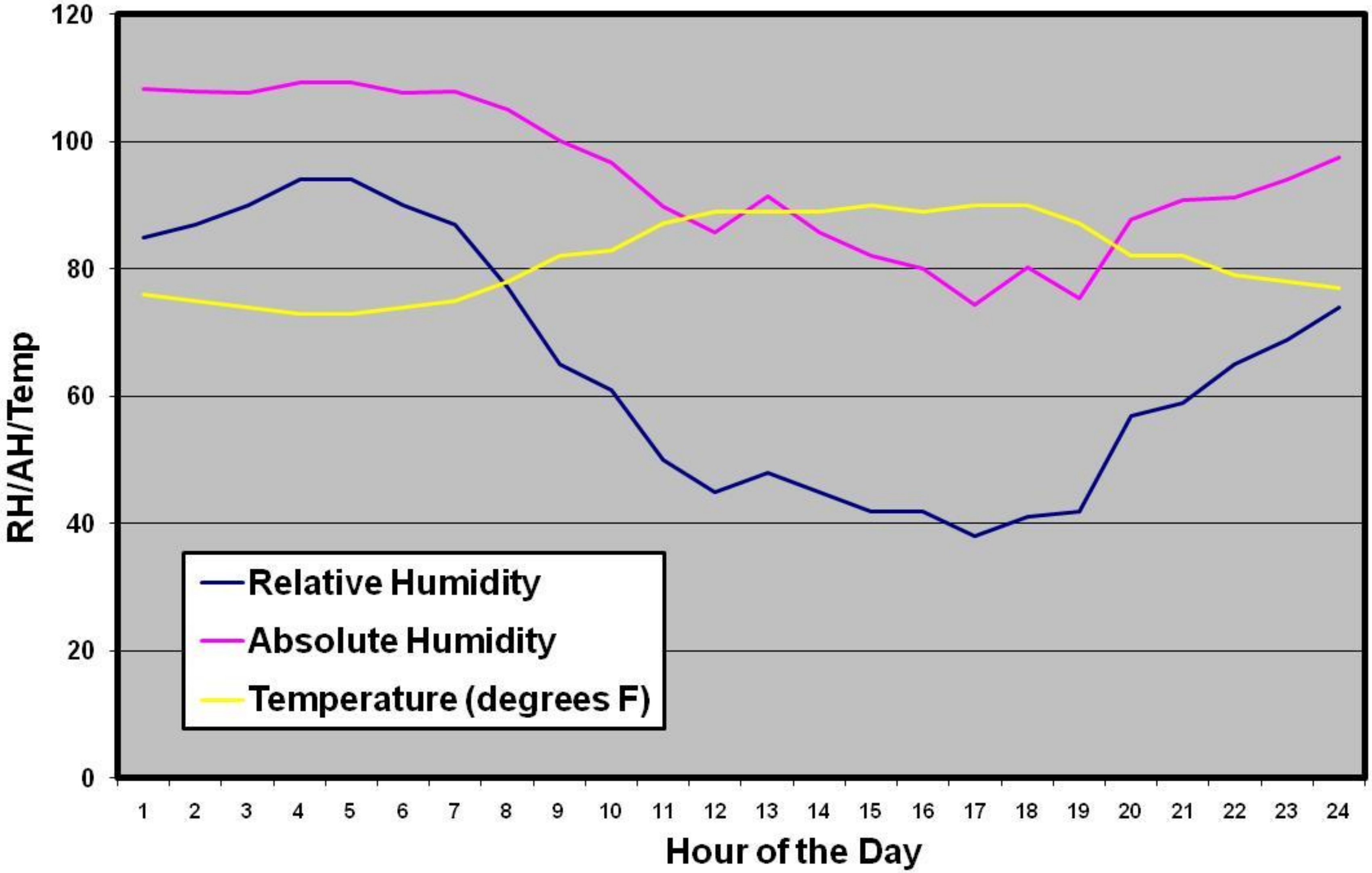
- **Not all vehicles are equipped with air conditioning.**
  - 53% of 1985 model year trucks have A/C.
  - 98% of 2000 model year passenger cars have A/C.
- **Not all air conditioning equipment is operational.**
  - Fraction is a function of vehicle age.
  - 95% of 18 year old air conditioning still working.
- **Temperature and humidity affect air conditioning usage.**
  - Temperature and humidity combined into a heat index.
  - No air conditioning usage assumed below a heat index of 67.

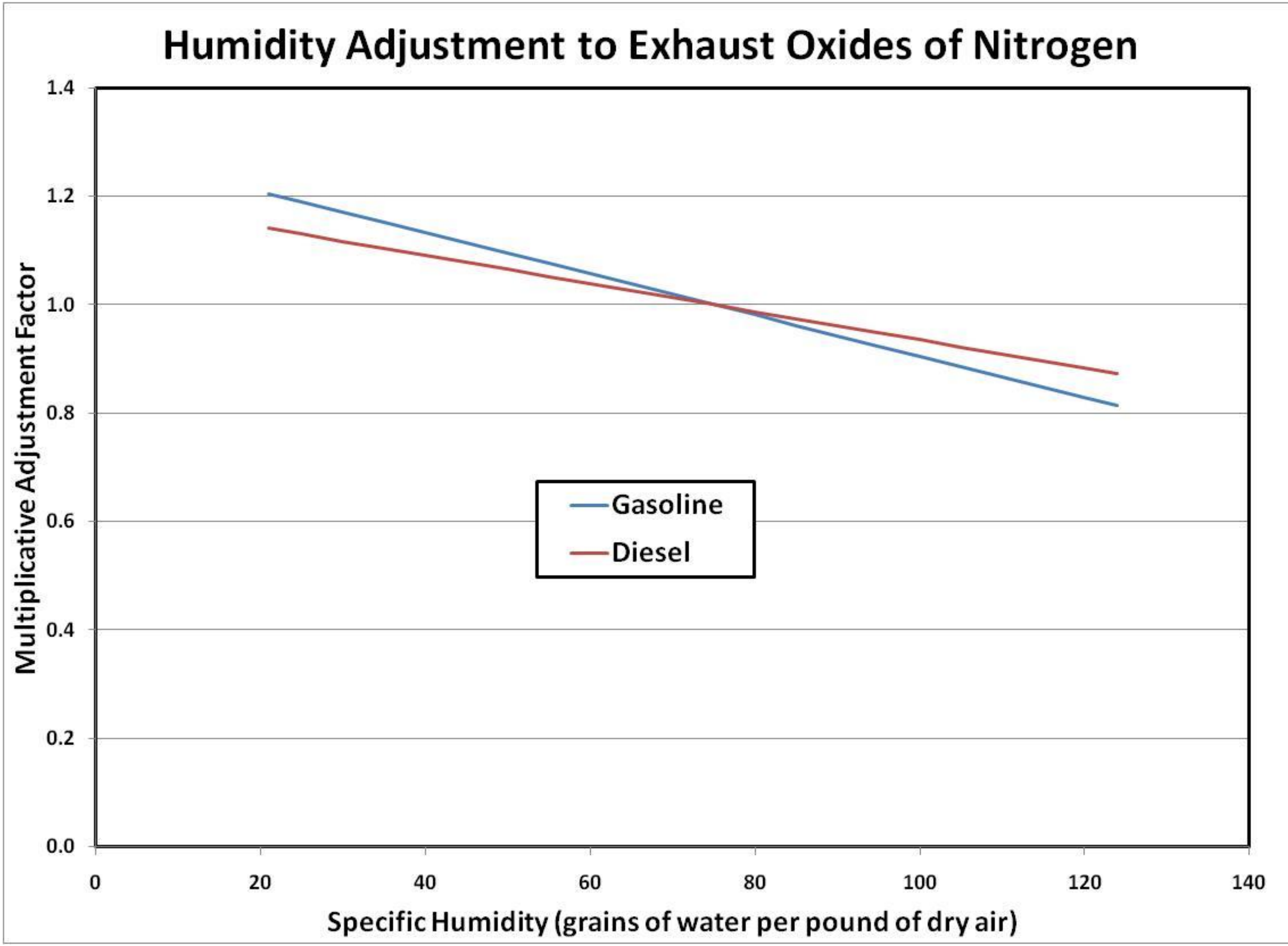

Effect of Humidity on Air Conditioning On Fraction
Fraction
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70
80
90
100
Relative Humidity
100 Degrees Fahrenheit
90 Degrees Fahrenheit
80 Degrees Fahrenheit
78 Degrees Fahrenheit
75 Degrees Fahrenheit
70 Degrees Fahrenheit
Limit

Humidity Adjustment

- **Ambient humidity has a significant effect on exhaust NOx emissions.**
  - Humidity NOx adjustments are taken directly from the Federal Test Procedure for gasoline and diesel.
- **Humidity can affect other pollutants.**
  - Humidity affects the heat index which affects the amount of air conditioning usage, which can affect all pollutants and energy consumption.

Example Relationship Between Relative and Specific Humidity




Humidity Adjustment to Exhaust Oxides of Nitrogen
Multiplicative Adjustment Factor
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
Specific Humidity (grains of water per pound of dry air)
Gasoline
Diesel

Adjustment Interactions

- **Even when there is no temperature adjustment, variation of temperature will affect the specific humidity, which will affect NOx emissions.**
  - Constant relative humidity is not the same as constant specific humidity.
- **Air conditioning load may affect any pollutant and is a function of both temperature and humidity.**
- **Engine start temperature effects are additive and are not affected by driving activity (speed, VMT).**
- **Temperature will also significantly affect non-exhaust (evaporative) emissions.**

Adjustments for Inspection and Maintenance

Inspection and Maintenance

- **Inspection and Maintenance (I/M) programs:**
  - Mandatory.
  - Periodic inspection of vehicles.
  - Require repairs.
- **Benefits depend on:**
  - Inspection frequency.
  - Inspection stringency.
    - Test procedure.
    - Test limits (cutpoints).
  - Scope (region, vehicles, ages, etc.).
  - Enforcement and Waivers.

I/M Benefits in MOVES

- Benefits for I/M programs in MOVES are derived from emission rates from areas without programs compared to the emission rates in an area (Phoenix, AZ) with an I/M program.

$$Ep = R*Eim + (1-R)*Enonim$$

Ep = program emission rate
R = aggregated program adjustments
Eim = reference I/M emission rate
Enonim = non-I/M area emission rate

Adjustments to I/M Benefits

- **Separate adjustments for each:**
  - Pollutant/process.
  - Vehicle/regulatory class.
  - Technology/model year grouping.
  - Age group.
- **Adjustments account for:**
  - Inspection frequency.
  - Inspection test procedure.
  - Test standards (cutpoints).

Developing I/M Adjustments

- **Adjustments to I/M program benefits were derived from credits originally developed for MOBILE6.**
  - The reference I/M program was simulated using MOBILE6.
  - Each program design was also simulated using MOBILE6.
- **The base I/M program adjustment factor (Rp) is the ratio of the target program emission results to the reference program results.**

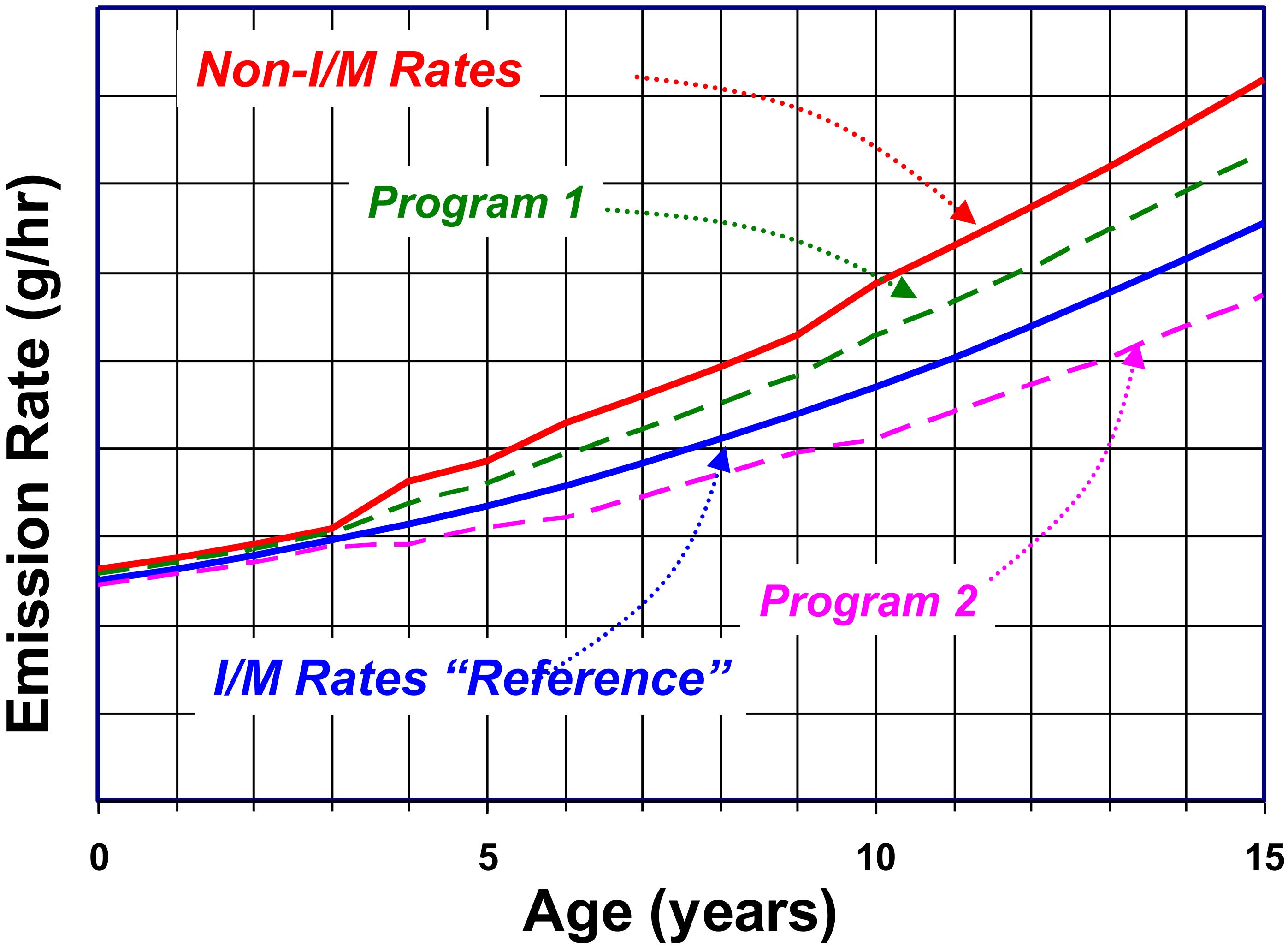
$$Rp = Ep / Er$$

Other I/M Adjustments

- **User supplied I/M program information is used to make further adjustments to I/M benefits.**
  - Compliance rates account for both non-participation in the I/M program and waiver provisions.
  - Vehicle and model year coverage will limit benefits.
- **Use "Technical Guidance on the Use of MOVES2010 for Emission Inventory Preparation in State Implementation Plans and Transportation Conformity" (EPA-420-B-10-023)**

http://www.epa.gov/otaq/models/moves/index.htm

Example: Reference Rates by Age



Limits of I/M Benefits

- **MOVES does not calculate benefits for:**
  - Diesel fueled vehicles.
  - Heavy duty vehicles or buses.
  - Inspection frequencies greater than annual or less than biennial.
  - Testing procedures or standards not addressed in MOBILE6.
  - Remote sensing inspections.
  - Voluntary inspections.
  - Particulate matter emission rates.