

# **MOVES Sensitivity Analysis: The Impacts of Temperature and Humidity on Emissions**

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## **ABSTRACT**

The U.S. Environmental Protection Agency has released MOVES2010 designed to estimate emissions from on-road mobile sources under user-defined conditions such as time periods, geographical areas, vehicle types, pollutants, and road types, using a default database which includes information relevant to emissions for the entire United States. Furthermore, MOVES2010 allows users to import data specific to their unique needs and goals. Reconciling analytic goals and model capabilities with limitations of time and resources requires some knowledge about behavior of various input parameters and the degree to which they affect emission results. Because of the number of input parameters and the complexity of their interactions, this paper focuses primarily on temperature and humidity analyzing the changes in emissions from variations of these parameters in isolation, and compares the impact of each individual parameter on emission results by quantifying percent change in emissions.

## **INTRODUCTION**

U.S. EPA has recently released the latest version of **MO**tor **V**ehicle **E**mission **S**imulator (MOVES2010) which is used to estimate national, state, and county level inventories of criteria air pollutants, greenhouse gas emissions, air toxics, and energy consumption (total, petroleum-based, and fossil-based) from on-road mobile sources (1). It is approved for use in official state implementation plan (SIP) submissions to EPA and for conformity emissions inventory development outside of California. Furthermore, it can be used to estimate on-road vehicle emissions for a variety of different purposes: to evaluate the national and local emissions trends, to compare different emission scenarios, to analyze the benefits from mobile source control strategies, and to provide inputs for air quality modeling.

MOVES2010 provides substantially expanded capabilities relative to its predecessor, MOBILE6. These expansions are achieved through fundamental redesign, combined with extensive updating of model inputs. In addition, the model facilitates estimation of emissions under user-defined conditions by allowing users to replace national defaults with local inputs through the county-data-manager feature. The locality specific data can have considerable influence on the estimates of emissions and thus, it is essential that users are knowledgeable of the input parameters and their relative sensitivity to emissions. Relevant input parameters include meteorology, vehicle population, age distributions, vehicle miles travelled (VMT), average speed distributions, road type distributions, ramp fractions, fuel supply, and I/M program parameters. However, as an initial effort to examine MOVES' sensitivity to input parameters, this paper will focus on emissions changes due to variations of temperature and humidity.

Although MOVES database includes default average hourly temperature and humidity data for every county in the country based on 30 year averages from the National Climatic Data Center over the period 1971 – 2000, EPA does not recommend using the default meteorology table for the purposes of SIP and regional conformity analysis. Rather, for these analyses, EPA suggests that users substitute local temperature (degrees Fahrenheit) and relative humidity (%). Therefore, understanding the degree to which temperature and humidity affect emissions results will have substantial benefits to MOVES users.

Ambient temperature and humidity are known to have significant impact on most pollutant processes for on-road vehicles. In MOVES2010, temperature and humidity affect emissions mainly through three mechanisms: 1) direct effect via temperature adjustment on emission rates; 2) direct effect via humidity correction factor for NO<sub>x</sub>; 3) indirect effect via air conditioning adjustment – temperature and relative humidity are used to populate heat index (see A-1) which in turn is used to calculate the fraction of vehicle fleet with air conditioning turned on. The detailed analyses describing how these adjustments are derived, calculated, and applied can be found in MOVES technical report (2).

The current analysis examines relationships among meteorological parameters and emissions for: gasoline and diesel for all sourcetypes and roadtypes. Although a strong association exists between temperature and relative humidity, efforts were made to examine each input parameters in isolation. Emissions considered include hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and total particulate matter (PM<sub>2.5</sub>). For CO, NO<sub>x</sub>, and PM<sub>2.5</sub>, emissions include cold start emissions and hot stabilized running emissions; for HC, emissions comprise evaporative emissions (fuel vapor venting, permeation, fuel leaks, refueling spillage loss, and refueling displacement vapor loss) in addition to running and starts. The emission estimates in this paper are obtained using MOVES2010a, the version of MOVES released in September, 2010.

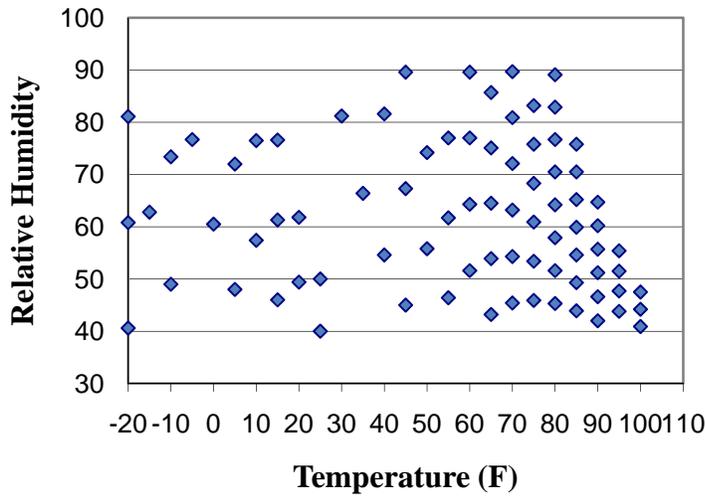
## **METHODS**

### *Temperature*

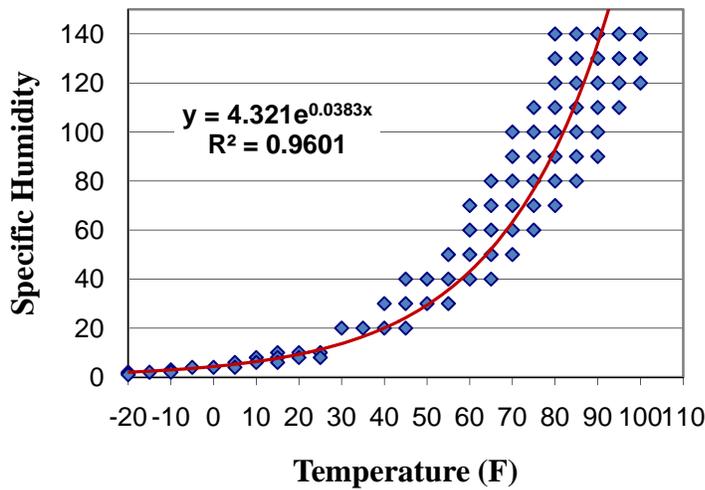
MOVES was run at a “national” scale keeping all parameters constant except for temperature in increments of 10 degrees Fahrenheit from -40 to 120 degrees. Although MOVES default temperature ranges from -24.5 to 107.5 degrees, extreme temperatures were included to test MOVES’ ability to produce reasonable estimates in those conditions. Because temperature and relative humidity are both input in each model run, the relationship between temperature and humidity was examined, using the default values in MOVES’ ZoneMonthHour table (see Figure 1). However, due to the close coupling between temperature and relative humidity, relative humidity was converted to specific humidity using Equation A-2, in order to clarify the relationship between temperature and humidity (see Figure 2), allowing the two to be varied independently while recalculating appropriate levels of relative humidity for given temperatures.

For each temperature profile, the associated specific humidity was calculated using the regression line from Figure 2, translated to relative humidity, and inputted to the model. This approach was necessary because varying temperatures while keeping relative humidity constant would have produced unrealistic meteorological parameters and emission results with no environmental relevance.

**Figure 1. Temperature vs. Relative Humidity.**



**Figure 2. Temperature vs. Specific Humidity.**



### *Humidity*

MOVES was run at a “national” scale. At a given temperature, relative humidity was varied in increments of 10 percent from 0 to 100, while keeping all other parameters constant. Relative humidity from MOVES default database ranges from 11.5 to 95.3 percent. The temperature profiles for the analysis ranged from 25 to 100 degrees Fahrenheit.

## **RESULTS AND DISCUSSION**

### *Temperature*

Percent changes in emission in relation to incremental changes in temperature are illustrated in Figure 4 and 5 for gasoline and diesel vehicles, respectively. The percent change in emissions was

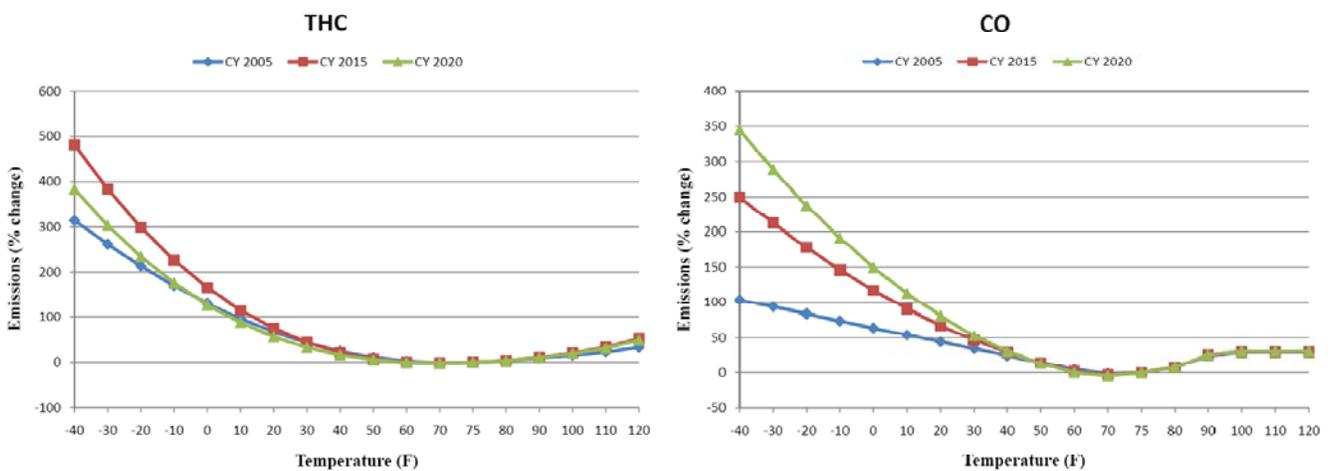
calculated using 75 degrees F (i.e., the nominal temperature of EPA’s FTP test) as the base. Emission estimates are aggregates of all sourcetypes, processes, and roadtypes (see Figures A.1 – A.6 in the Appendix for sensitivity by emission processes).

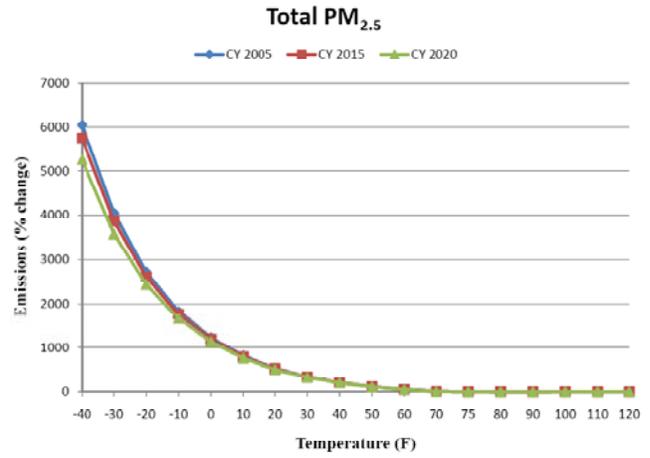
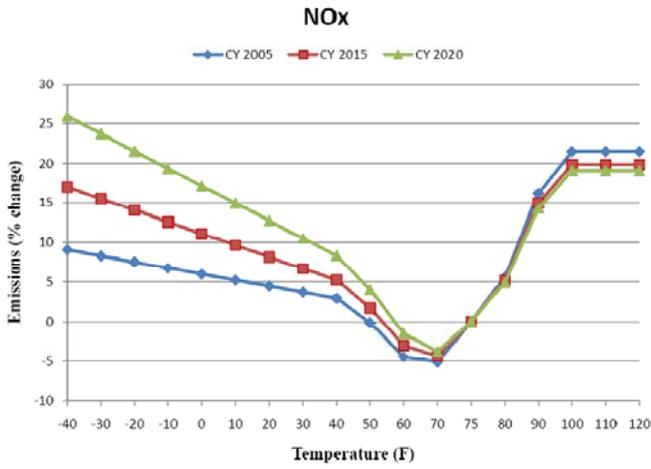
For both gasoline and diesel running HC, CO, and NOx emissions, MOVES applies temperature adjustment factors equal to 1.0, thus, no direct effect of temperature is expected. Therefore, the increase in emissions below 75 degrees is entirely due to the effect of temperature from start emissions. For temperatures above 75 degrees, the increase in emissions is due to indirect effect of temperature via air conditioning for CO and NOx, and combination of air conditioning and evaporative emissions for HC. There is no temperature effect on starts above 75 degrees for HC, CO, and NOx. The relatively large increase in overall NOx emissions at temperatures higher than 75 degrees F is caused by the influence of air conditioning on running emissions, which make up a higher share of overall emissions relative to HC and CO.

Sensitivity varies not only by pollutant, but also by calendar year. The MOVES estimates account for increased cold temperature sensitivity as the vehicle gets cleaner, (i.e., calendar year 2020 is shown as the most sensitive for CO and NOx, due to the highest fleet penetration of Tier 2 vehicles). However, for HC, calendar year 2015 is more sensitive than calendar year 2020. This apparently anomalous effect is attributable to more complete fleet penetration of vehicles complying with the Mobile Source Air Toxic (MSAT-2) rule in calendar year 2020.

Although start emissions dominate, temperature affects both hot running and cold starts for PM<sub>2.5</sub> and is modeled by multiplicative adjustment factors as illustrated by exponential increases in emissions with decreasing temperature for temperatures below 75 degrees, as shown in Figure 3. Above 75 degrees, there is no temperature effect for either running or starts. Although cold weather PM<sub>2.5</sub> is not directly regulated by MSAT-2, due to strong correlation between NMHC and PM<sub>2.5</sub>, PM<sub>2.5</sub> emissions are also reduced (3).

**Figure 3. Sensitivity to temperature for gasoline vehicles in calendar years 2005, 2015, and 2020.**



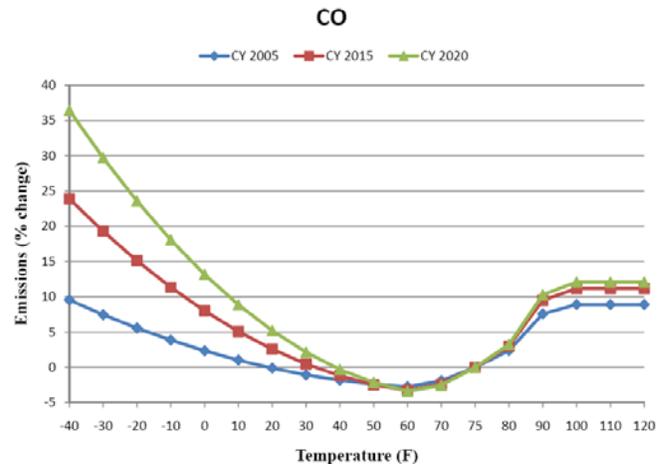
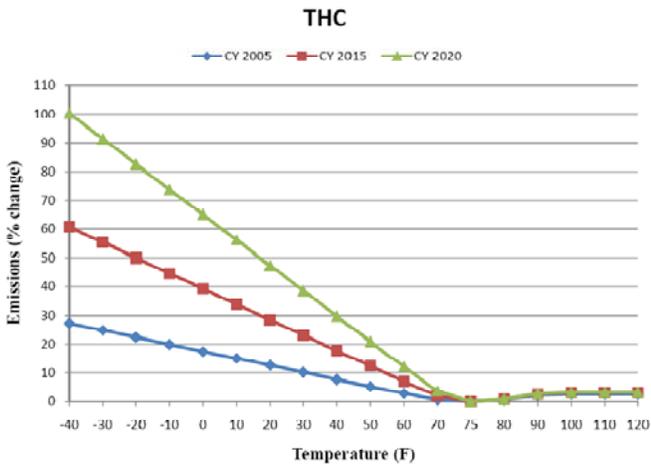


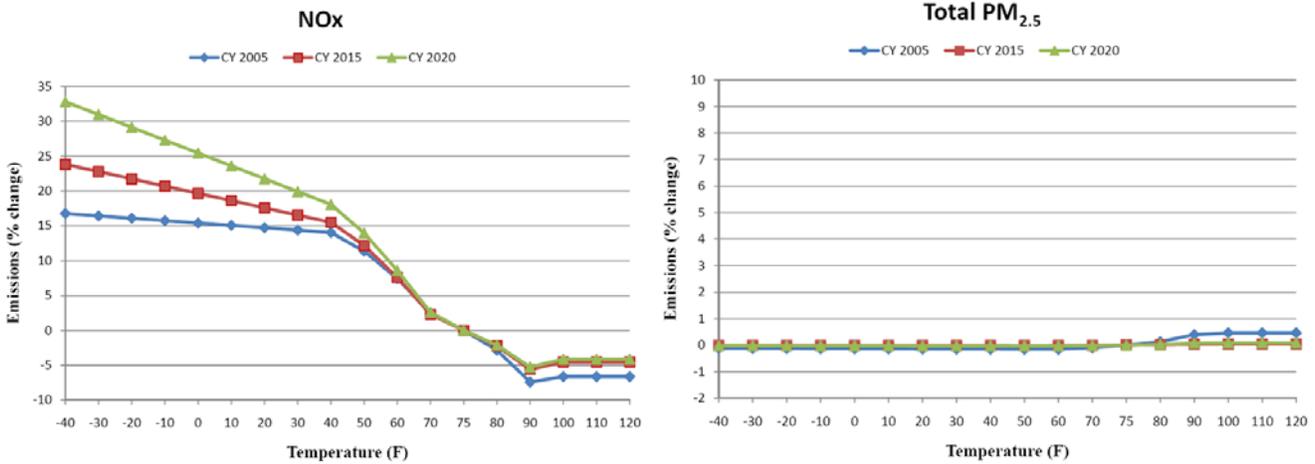
Consistent with gasoline vehicles, diesel vehicles exhibit increase in sensitivity for temperatures below 75 degrees F, predominantly due to cold starts. For temperatures above 75 degrees, the increase in emissions is due to indirect effect of temperature via air conditioning for CO and NOx, and combination of air conditioning and evaporative emissions for HC. There is no temperature effect on starts above 75 degrees for HC, CO, and NOx.

Generally, gasoline vehicles are more sensitive to temperature than diesel vehicles across pollutants. However, for NOx, diesel vehicles are slightly more sensitive than gasoline for cold temperatures, showing consistent downward trends in emission with increasing temperature, up to 90 degrees F. Total PM<sub>2.5</sub> is not affected by temperature for diesel vehicles (within 0.5 percent), simply because temperature adjustments are not applied to diesel particulate emission rates.

The relative sensitivity varies by calendar year for diesel as well, but more consistent pattern is observed; as the vehicles get cleaner for later calendar years, the sensitivity to temperature increases for HC, CO and NOx. For Total PM<sub>2.5</sub>, there are no significant differences in sensitivity among calendar years.

**Figure 4. Sensitivity to temperature for diesel vehicles in calendar years 2005, 2015, and 2020.**





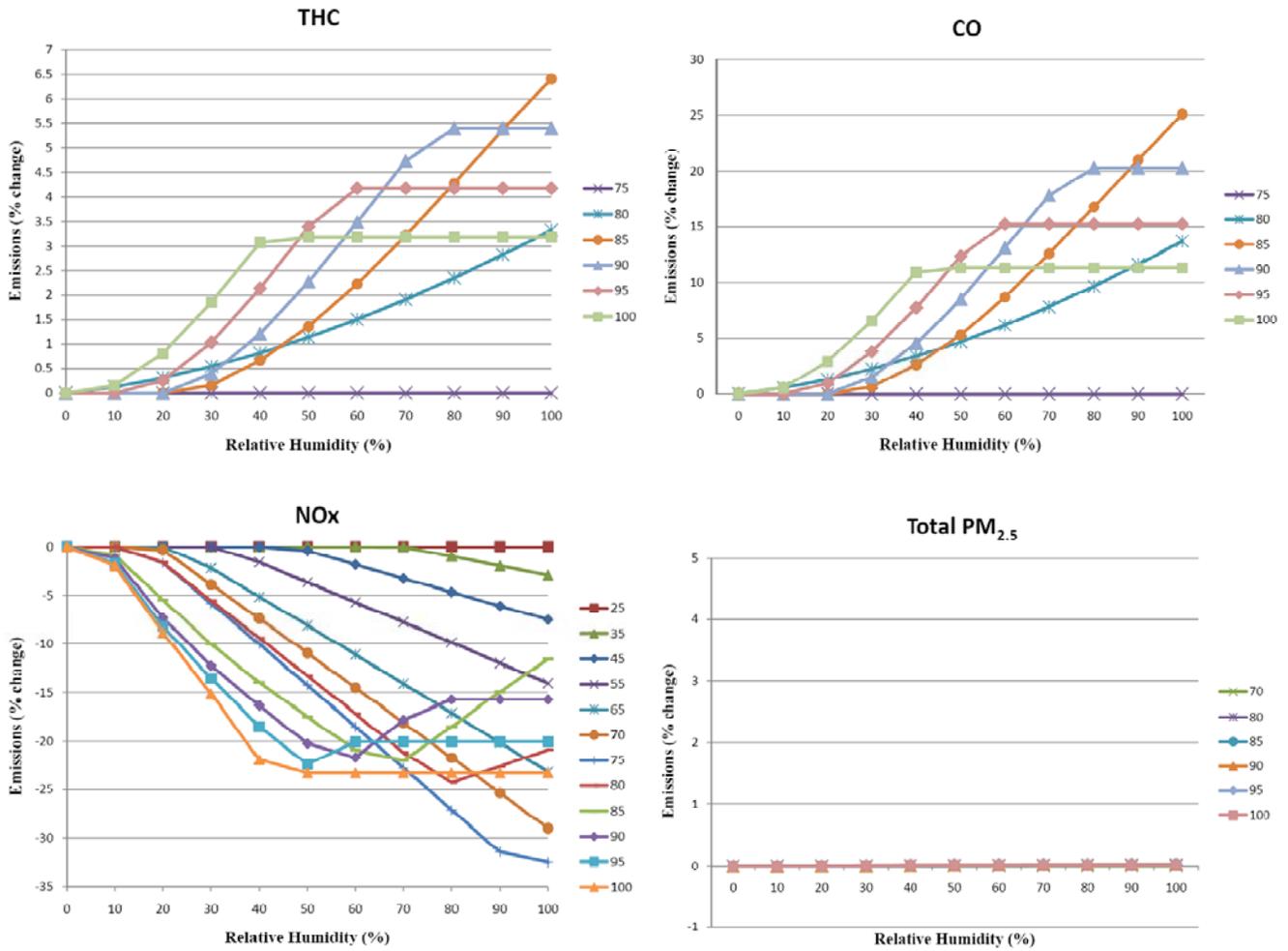
*Humidity*

In contrast to MOBILE6 which applied humidity adjustments only to gasoline vehicles, MOVES2010 adjusts both gasoline and diesel vehicle exhaust NOx emission. Figures 5 and 6 illustrate the sensitivity of humidity for gasoline and diesel vehicles, respectively. Zero percent humidity was used as the base to calculate the percent change in emissions. Because sensitivity to humidity does not vary by calendar year (within 1 percent), only the results for calendar year 2005 are shown. Analysis by emission processes indicates that humidity primarily affects running exhaust emissions; cold starts are not sensitive and evaporative emissions are sensitive only within 0.5 percent.

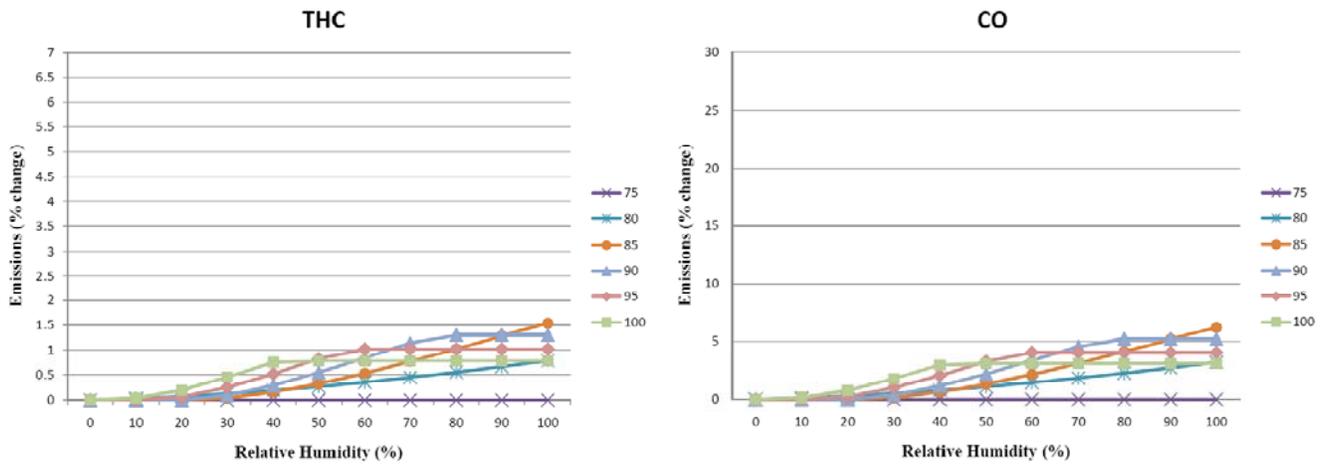
For NOx, emissions are affected by both the direct effect of humidity adjustment and the indirect effect of air conditioning adjustment. Because gasoline and diesel have different humidity correction coefficients, the sensitivities are slightly different – gasoline vehicles are more sensitive to humidity although the differences are minimal. For temperatures greater than 75 degrees, combination of humidity and air conditioning adjustments apply; for temperatures between 25 and 75 degrees, only the direct effect of humidity correction applies; for temperatures below 25, emission estimates are not sensitive to humidity.

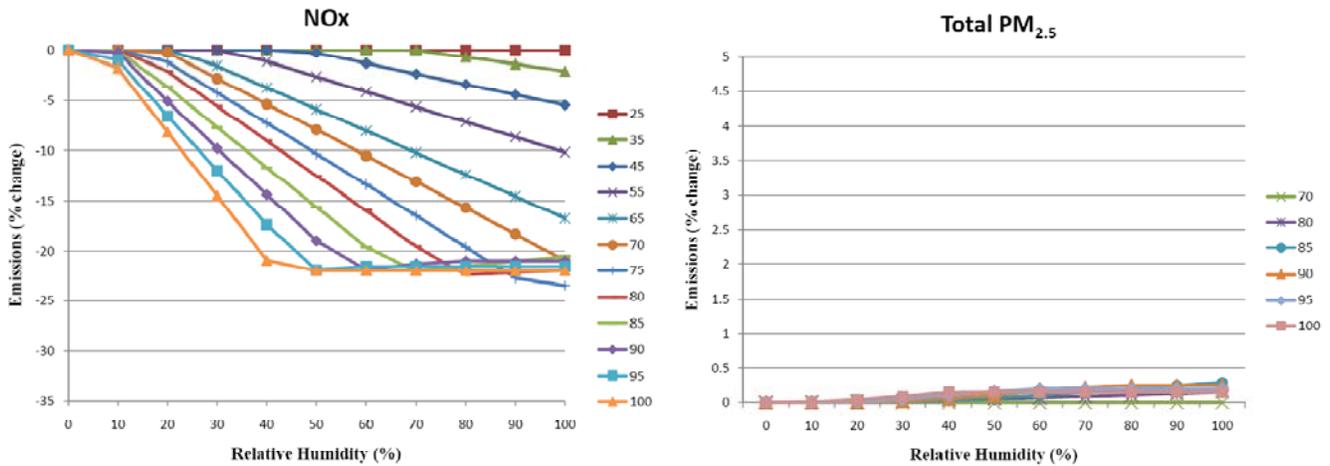
For HC and CO, for both gasoline and diesel, only the indirect effect of humidity through air conditioning adjustment applies for temperatures greater than 75 degrees; there is no humidity effect for temperatures less than or equal to 75 degrees. The “bend-over” trends seen for temperatures above 90 degrees F illustrate the effect of air conditioning; above certain humidity at a given temperature, air conditioning is on regardless of the level of humidity resulting in no change in emissions. Although gasoline vehicles are more sensitive to humidity effect through air conditioning, the overall trend is consistent across fuel types. Total PM<sub>2.5</sub> emissions are not sensitive to humidity for both gasoline and diesel vehicles (within 0.5 percent).

**Figure 5. Sensitivity to humidity for gasoline vehicles in calendar year 2005.**



**Figure 6. Sensitivity to humidity for diesel vehicles in calendar year 2005.**





## CONCLUSIONS

The relationships among selected MOVES input parameters, namely temperature and humidity, and HC, CO, NO<sub>x</sub>, and Total PM<sub>2.5</sub> emission were examined by comparing the percent change in emissions to base input values. The results demonstrate that temperature can have substantial impact on MOVES' estimates of emissions, especially for cold temperatures. The magnitude of impact is the greatest for gasoline PM<sub>2.5</sub>, while HC and CO are also highly sensitive to temperature. Although the magnitude of temperature effect is less for diesel vehicles, they are impacted by variations in temperature, nevertheless. The differences in relative sensitivity to temperature by calendar years indicate that as vehicles get cleaner, the contribution of temperature increases.

As for the sensitivity to humidity, temperatures above 75 degrees F are impacted for HC and CO; temperatures above 25 degrees F are affected for NO<sub>x</sub>, exhibiting increased sensitivity with increase in relative humidity. Gasoline vehicles are more sensitive to humidity than diesel vehicles. Finally, the results indicate that Total PM<sub>2.5</sub> is not responsive to changes in humidity for both gasoline and diesel vehicles.

In conclusion, current analysis addresses the degree to which MOVES' estimates of emission are affected by temperature and humidity, allows the potential users to be more knowledgeable about the impact of input parameters and thus, accurately estimate emissions inventories using MOVES. The results of the analysis emphasize the importance of obtaining accurate local meteorological data when using MOVES. Furthermore, the analysis provides assurance for MOVES' ability to generate reasonable estimates for temperatures and humidity beyond MOVES default ranges. Future sensitivity analysis will address the impacts of additional input parameters such as source type population, age distribution, vehicle type VMT, average speed distribution, road type distribution, ramp fraction, fuel supply, and I/M program.

## REFERENCES

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## **KEYWORDS**

MOVES, on-road mobile emissions, sensitivity analysis, temperature, humidity.

## APPENDIX

The fraction of vehicles with air conditioning turned on is calculated from AC activity terms and heat index which is populated during a MOVES run, using temperature and relative humidity from the default meteorology table.

$$\begin{aligned} \text{Heat Index} = & -42.379 + 2.04901523 \times T + 10.14333127 \times RH \\ & - 0.22475541 \times T \times RH - 6.83783 \times 0.001 \times T^2 \\ & - 5.481717 \times 0.01 \times RH^2 + 1.22874 \times 0.001 \times T^2 \times RH \\ & + 8.5282 \times 0.0001 \times T \times RH^2 - 1.99 \times 0.000001 \times T^2 \times RH^2 \end{aligned} \quad (\text{A-1})$$

Where:

T is the temperature in degrees F  
RH is the relative humidity in percent

The relative humidity in percent is converted to specific humidity in units of grains of water per pound of dry air using the equations taken from CFR section 86.344-79. Then, the relationship between temperature and specific humidity was examined.

$$\text{Specific Humidity} = 4347.8 \times \frac{P_v}{(P_b - P_v)} \quad (\text{A-2})$$

$$P_v = P_{db} \times \left( \frac{\text{RelHum}}{100} \right)$$

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

$$T_0 = 647.27 - T_k$$

$$T_k = \left( \frac{5}{9} \right) [T_F - 32] + 273$$

Where:

T<sub>F</sub> is the temperature in degrees F  
P<sub>b</sub> is the barometric pressure

Figure A.1. Sensitivity to temperature for gasoline vehicles: Running only.

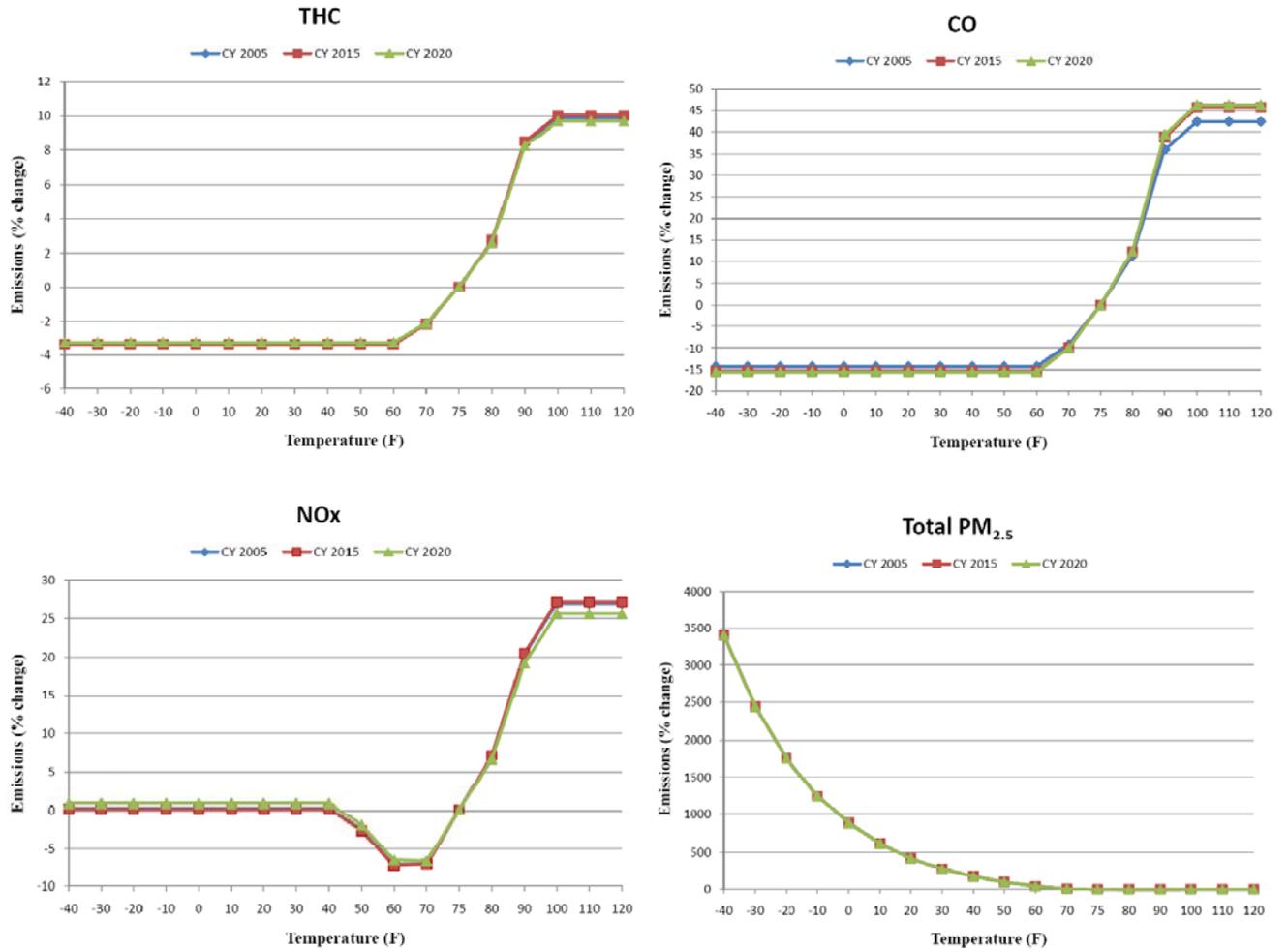
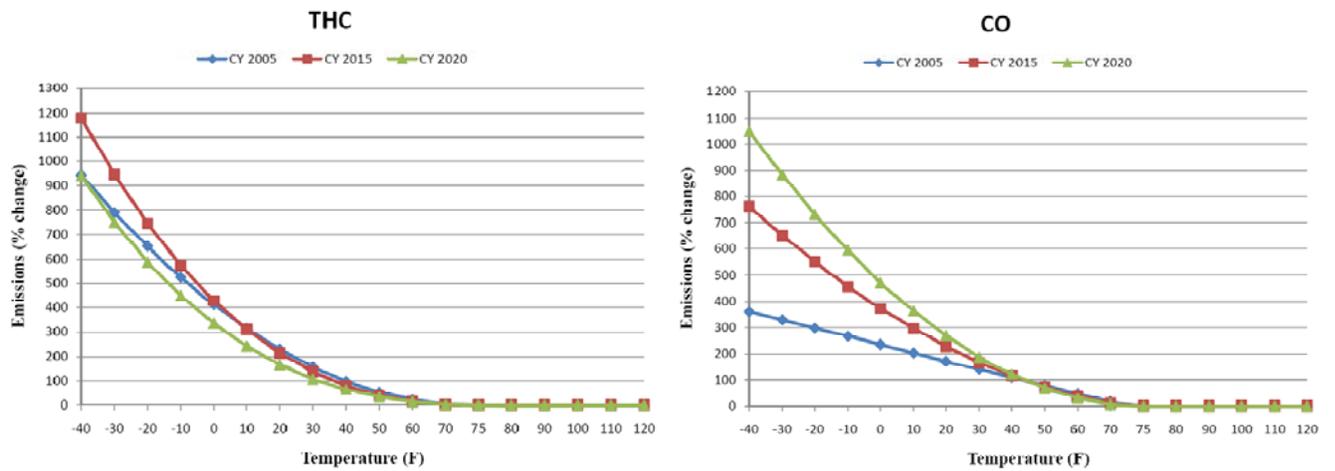


Figure A.2. Sensitivity to temperature for gasoline vehicles: Cold starts only.



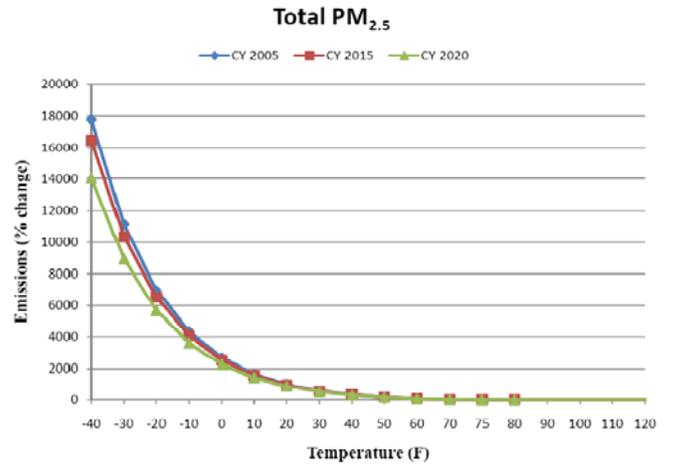
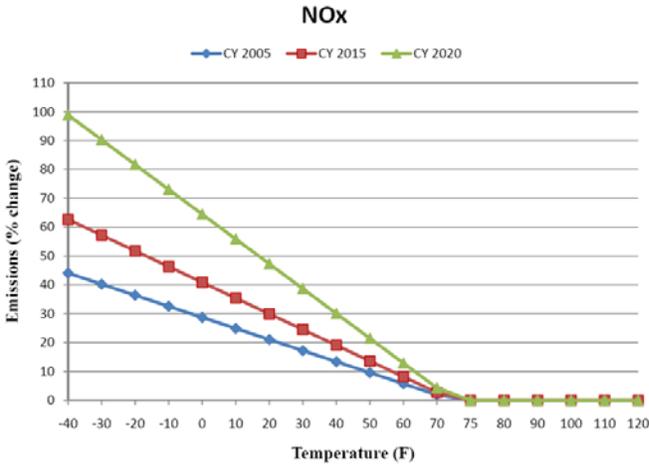


Figure A.3. Sensitivity to temperature for gasoline vehicles: Evaporative only.

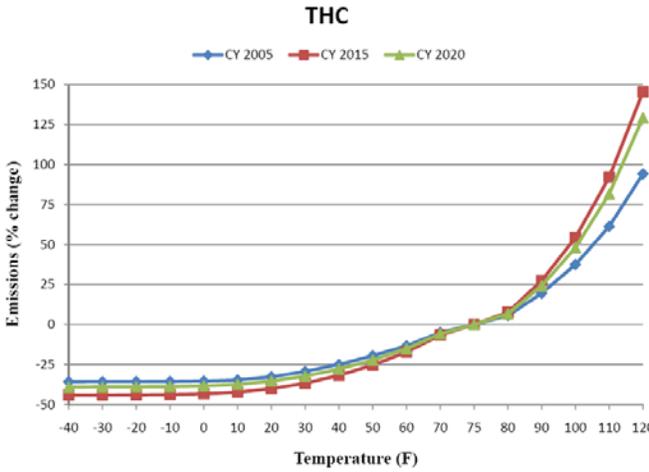
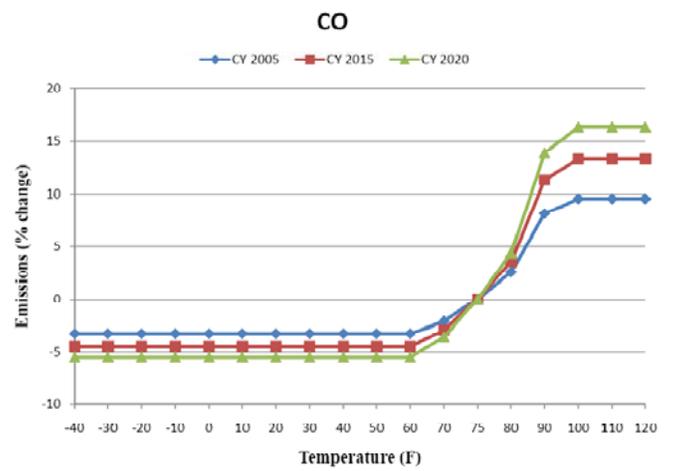
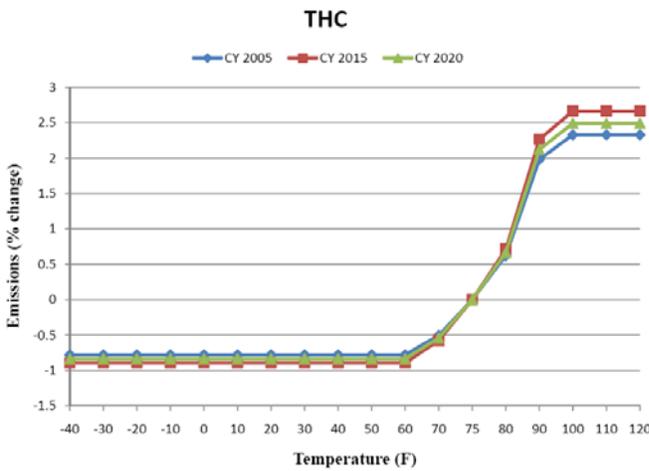


Figure A.4. Sensitivity to temperature for diesel vehicles: Running only.



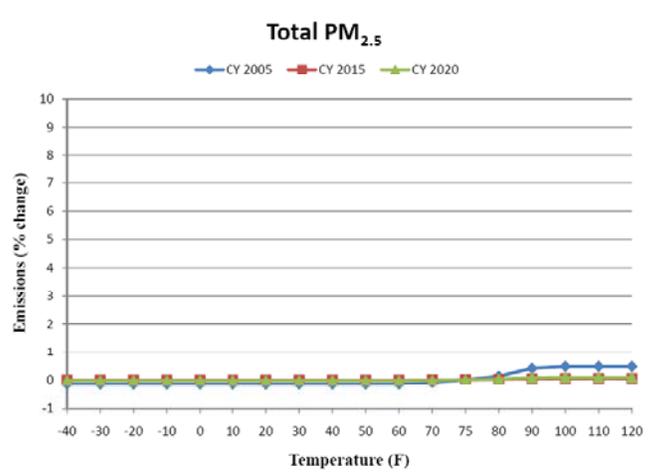
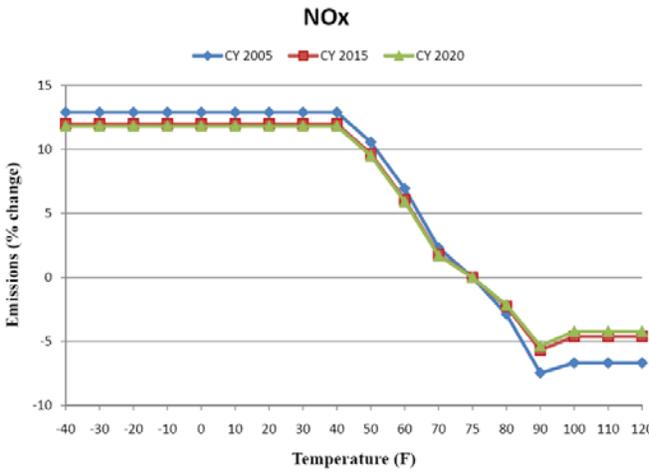


Figure A.5. Sensitivity to temperature for diesel vehicles: Cold starts only.

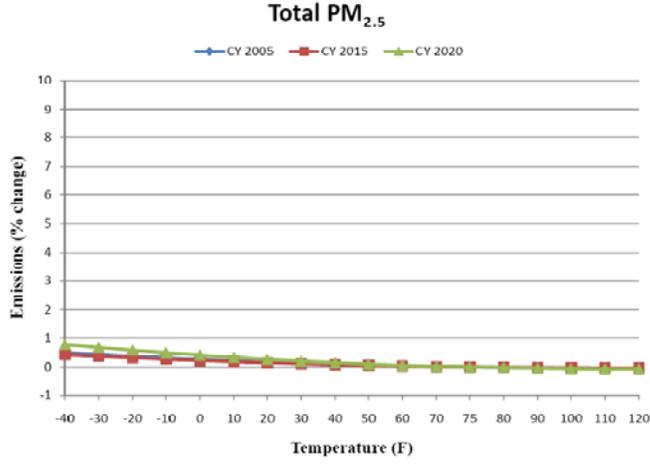
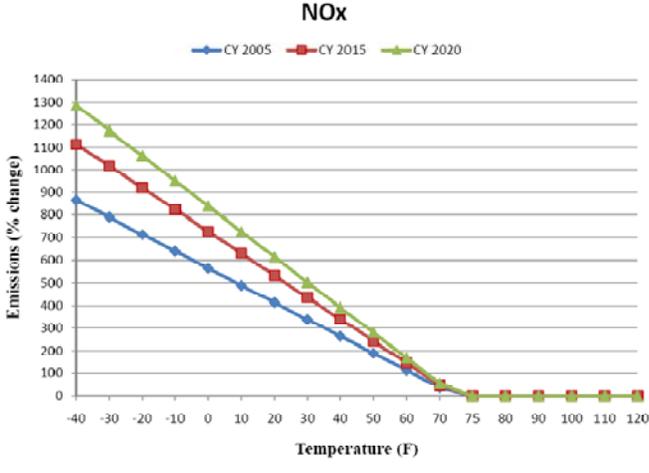
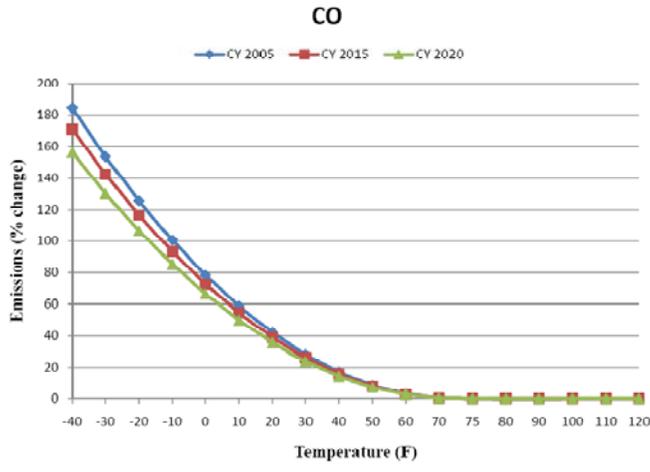
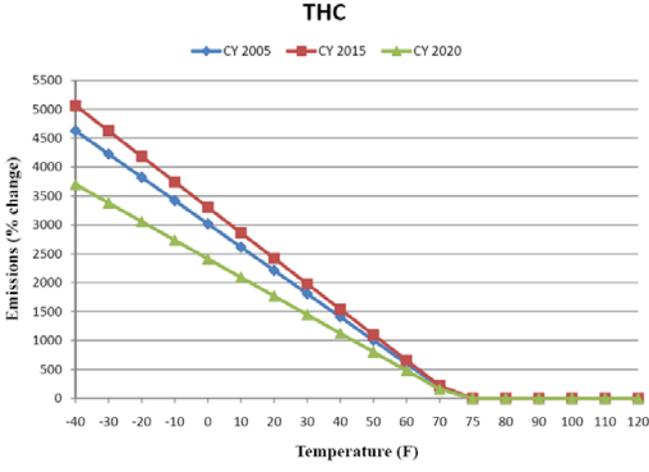


Figure A.6. Sensitivity to temperature for diesel vehicles: Evaporative only.

