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Temperature Effects on Particulate Matter Emissions from Light-Duty, Gasoline-Powered Motor Vehicles

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ABSTRACT

The Kansas City Light-Duty Vehicle Emissions Study (KCVES) measured exhaust emissions of regulated and unregulated pollutants from 496 vehicles recruited in the Kansas City metropolitan area in 2004 and 2005. Vehicle emissions testing occurred during the summer and winter, with the vehicles operated at ambient temperatures. One key component of this study was the investigation of the influence of ambient temperature on PM emissions from gasoline-powered vehicles. A subset of the recruited vehicles were tested in both the summer and winter in order to further elucidate the effects of temperature on vehicle tailpipe emissions.

The study results indicated that PM emissions increased exponentially as temperature decreased. In general, PM emissions doubled for every 20˚F drop in ambient temperature, with these increases independent of vehicle model year. The effects of temperature on vehicle emissions was most pronounced during the initial start-up of the vehicle (cold start phase) when the vehicle was still cold, leading to inefficient combustion, inefficient catalyst operation, and the potential for the vehicle to be operating under fuel-rich conditions. The large dataset available from this study also allowed for the development of a model to describe temperature effects on PM emission rates due to changing ambient conditions. This study has been used as the foundation to develop PM emissions rates, and model the impact of ambient temperature on these rates, for gasoline powered vehicles in EPA's new regulatory motor vehicle emissions model, MOVES.

Keywords

Motor vehicle emissions, particulate matter, ambient temperature, gasoline, cold start, emissions model

INTRODUCTION

Particulate matter (PM) is a dynamic pollutant that is constantly being influenced by its environment; therefore, PM formation is constantly changing both in the motor vehicle exhaust stream and in the ambient air. PM exhaust emissions from gasoline-powered motor vehicles have changed significantly over the past 25 years.[1,2] These changes have resulted from reformulation of fuels especially the removal of lead additives, the wide application of exhaust gas treatment in gasoline-powered passenger cars and trucks, and changes in engine design and operation. Particularly, as emission standards reduced exhaust hydrocarbons with the introduction of catalysts in 1975, the organic component of exhaust PM also decreased. Lead, which was the major PM component in gasoline vehicle exhaust, was virtually eliminated with the introduction of unleaded gasoline mandated in the United States for the 1975 model year vehicles and the later phase-out of lead in all motor vehicle gasoline.

The majority of exhaust PM emitted by catalyst-equipped motor vehicles is in the $PM_{2.5}$ size range (particulate matter mass with aerodynamic size of 2.5μm or less, typically collected on a filter). Gasoline and diesel fueled vehicles produce particles that are predominantly less than 2.0 μm in diameter.[3] In-use gasoline vehicles in the Denver area have been shown to emit 91% of PM in the $PM_{2.5}$ size range, which increased to 97% for “smokers” (i.e., light-duty vehicles with visible smoke emitted from their tailpipes).[1] In California, smoking vehicles emitted 92% of PM in the 2.5 μm size fraction.[3] The mass median diameter of the PM emitted by the gasoline vehicles sampled in Denver was about 0.12 μm, which increased to 0.18 μm for smoking vehicles.[1] PM measurement techniques used n these studies were similar to the laboratory grade PM sampling systems described for this study in the experimental section.[4]

At the time of this study, Kansas City was the largest metropolitan area in the United States without a vehicle inspection and maintenance program (I/M program). Since EPA’s emissions modeling method requires estimates for vehicles not influenced by I/M programs, this metropolitan area was selected. Corrections for other local factors such as I/M programs, regional fuel effects, ambient conditions, and other regional characteristics are done separately in the models. . Kansas City was also chosen for its relatively wide range of winter and summer ambient temperatures and the vehicle fleet conforms to US vehicle standards. The participants of this study were also chosen to represent the overall population demographics of the region.[4]

Previous studies have suggested that ambient temperature can influence the amount of PM emitted from light-duty vehicles, with emissions increasing at colder temperatures and during cold start conditions.[1,5,6,7,8,9,10] The U.S. Environmental Protection Agency (EPA) initiated the Kansas City Light-Duty Vehicle Emissions (KCVES) study in 2004 to identify the distribution of PM emissions in the U.S. light-duty vehicle fleet.[11] To identify the effects of ambient temperature on vehicle emissions, the study was conducted in two rounds of vehicle testing. The first round of vehicle testing occurred during the summer months of 2004 and the second occurred during the winter months of 2004-2005. Since the Kansas City metropolitan area experiences a wide range of temperature fluctuations between summer and winter months, this study design allowed for vehicle testing under a wide range of ambient temperature conditions. To evaluate PM emission trends between the summer and winter rounds, forty-two vehicles were tested during both the summer and winter rounds. This paper reports the results from this testing program that highlights the impacts of ambient temperature conditions on motor vehicle PM mass emissions.

EXPERIMENTAL SECTION

The KCVES program test facility was located at a warehouse in Kansas City, Kansas, USA. Vehicles were randomly recruited from a nine county area encompassing portions of both the states of Kansas and Missouri. Vehicle processing and testing occurred in a warehouse with two large open bay doors located at each end of the building so ambient temperatures were maintained inside the building. Details on the project facility, study design, instrumentation, and testing methods employed can be found in other documents.[1,11]

The KCVES was conducted in two distinct rounds: Round 1- summer testing and Round 2 - winter testing. Vehicles were tested on the EPA Office of Research and Development transportable Clayton Model CTE-50-0 twin-roll chassis dynamometer. A Positive Displacement Pump-Constant Volume Sampling (PDP-CVS) system was used to dilute and transport the vehicle tailpipe exhaust to analyzers during the dynamometer test. Dilution tunnel air was kept constant at 47°C ± 5°C to prevent loss of volatile PM components during all tests. Procedures for conditioning the tunnel and analytical equipment to minimize any release of volatile compounds were checked weekly during both rounds of tests.

Vehicles were operated over the LA92 Unified Driving Cycle.[1,12] The LA92 cycle consists of three operating phases. Phase 1 (also known and described in this paper as "bag 1") was a vehicle cold start and initial driving for the first 310 seconds of operation. "Cold start" represents an engine start after the vehicle has been "soaking" at a relatively constant temperature with the engine off. In the KCVES, the vehicles were soaked overnight in ambient conditions. Bag 1 (310 seconds or 1.18 miles) was followed by a stabilized Bag 2 or "hot running" (311 – 1427 seconds or 8.63 miles) operating phase. At the end of Bag 2, the engine was turned off and the vehicle was allowed to "soak" in the test facility at ambient temperatures for ten minutes. At the end of the soak period, the vehicle was started again, and driven under identical driving conditions as Bag 1. Bag 3 represents a "hot start" condition because the vehicle was started while the engine and after-treatment devices were still hot from the prior operation. Criteria pollutants were measured both in continuous and bag modes. PM was gathered for each of the three Bags of the LA92 on 47 mm Teflon filters, with filter face temperatures maintained at 47°C ± 2°C. A total of 261 vehicles were tested during the summer round, and 235 vehicles were tested during the winter round. A goal of the study was to perform a replicate test on one vehicle every week; thus, fifteen vehicles received a replicate test during the summer and eleven vehicles during the winter.

Forty-two vehicles recruited and tested during the summer round were re-recruited and tested during the winter round to estimate the effect of ambient temperature on exhaust emissions. One of these vehicles received a duplicate test during the summer. In addition, one vehicle was tested once every week as a correlation vehicle. As with all other tests, ambient temperatures were not controlled for any of the re-test vehicles or the correlation vehicle during either round of the study.

RESULTS AND DISCUSSION

The results from this study demonstrated the effects of varying ambient temperatures on motor vehicle exhaust emissions. Figure 1 shows histograms of PM mass emission rates for all vehicles tested during the summer and winter rounds, respectively. As shown in this figure, a higher frequency and proportion of elevated PM mass emission rates occurred during the winter round as opposed to the summer round.

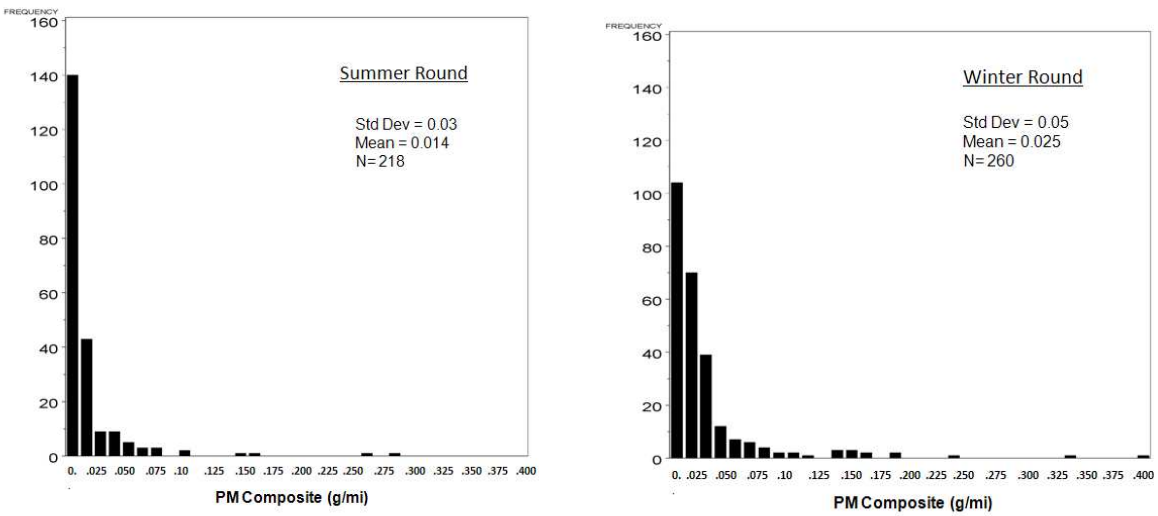


Figure 1. Histogram of PM mass emission rates for all vehicles tested during the summer (left) and winter (right) rounds, respectively. For this figure, all emission rates represent a composite of all Bags collected over the LA92 driving cycle.

An evaluation of the forty-two vehicles tested in both the summer and winter rounds provide additional information on the effects of ambient temperature on auto emissions. Figure 2 compares the summer and winter round tests for these vehicles. Each point compares individual PM measurements during the winter (Y axis) and summer (X axis) test of that vehicle. The figure shows that winter emissions exceeded summer emissions in nearly all cases. Some vehicles had more than an order of magnitude higher PM emissions in the winter compared to the summer. Because of this large variation in emission rates by round, subsequent analyses were conducted in log-space, which allows for quantification of effects across a large range of results.

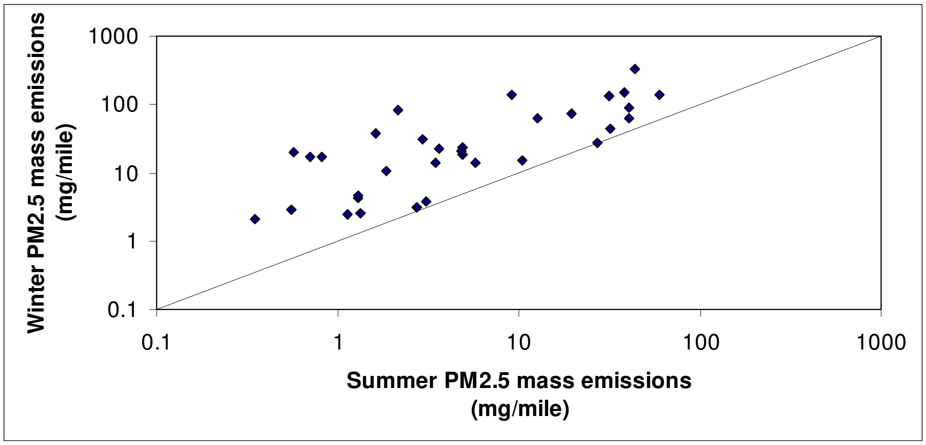


Figure 2. Scatter plot comparing winter and summer round PM mass emission rates on log scales.

An evaluation of PM trends with temperature can be determined based on all vehicles tested during the study, the re-test vehicles between the summer and winter rounds, and the correlation vehicle test results as shown in Figure 3. The open and solid circles (retested vehicles) represent PM mass emission rates for all vehicles included in the study with the exception of the correlation vehicle, with a corresponding trend line drawn through this grouping. The (log-linear) slope for all vehicles including the retested vehicles was -0.022. The solid circles represent the summer-winter paired retest results also included in Figure 2, with the solid triangles representing the correlation vehicle weekly repeat tests. The slope for the correlation vehicle was -0.042, indicating that the correlation vehicle showed more sensitivity to temperature changes than the average study vehicle.

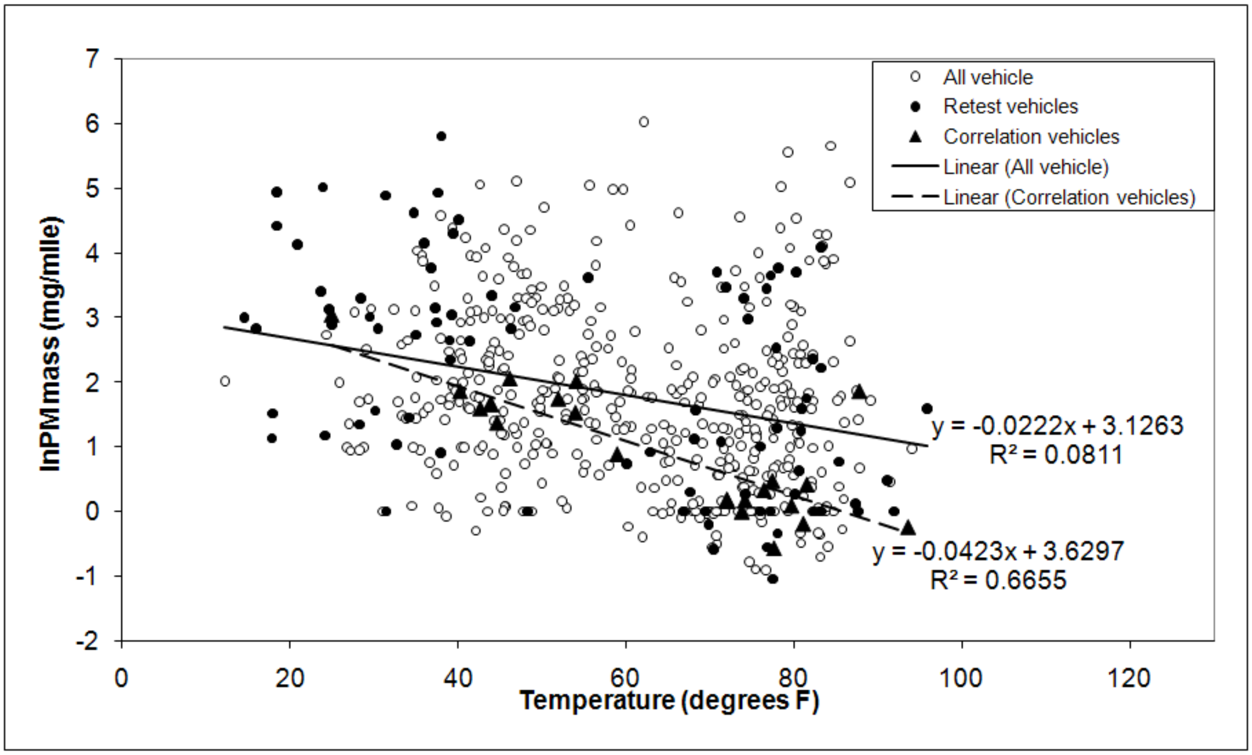


Figure 3. lnPM vs test (ambient) temperature for all vehicles, paired tests, and the correlation vehicle.

The matching paired re-test emission factors each had separate slopes, calculated using the following linear equation in log-space:

$$m = (\ln PM2 - \ln PM1)/(T2 - T1) \qquad \text{Equation 1}$$

Figure 4 shows the slopes for these matched pair emission factors plotted by model years. The results in Figure 4 do not show the matched pairs that were omitted due to missing values or if the temperature difference between the two tests was less than 10°F. For temperature differences less than 10°F, the test-to-test variability dominated any observable temperature effects, leading to ill-defined slopes. Unfortunately, these criteria eliminated 10 of the 43 paired tests (42 vehicles, with one duplicate test). The average of the slopes plotted in Figure 4 was -0.036 +/- 0.009 (95%CI). These results did not indicate an apparent model year trend for PM emissions. Model years correspond to both a change in technology and age of the vehicle tested at a particular time. These results suggested little or no vehicle technology or age influence on the resultant slope; thus, not influencing the rate of change of vehicle emissions with changing temperature. The results also did not suggest a slope dependence based on the average temperature of the repeat tests.

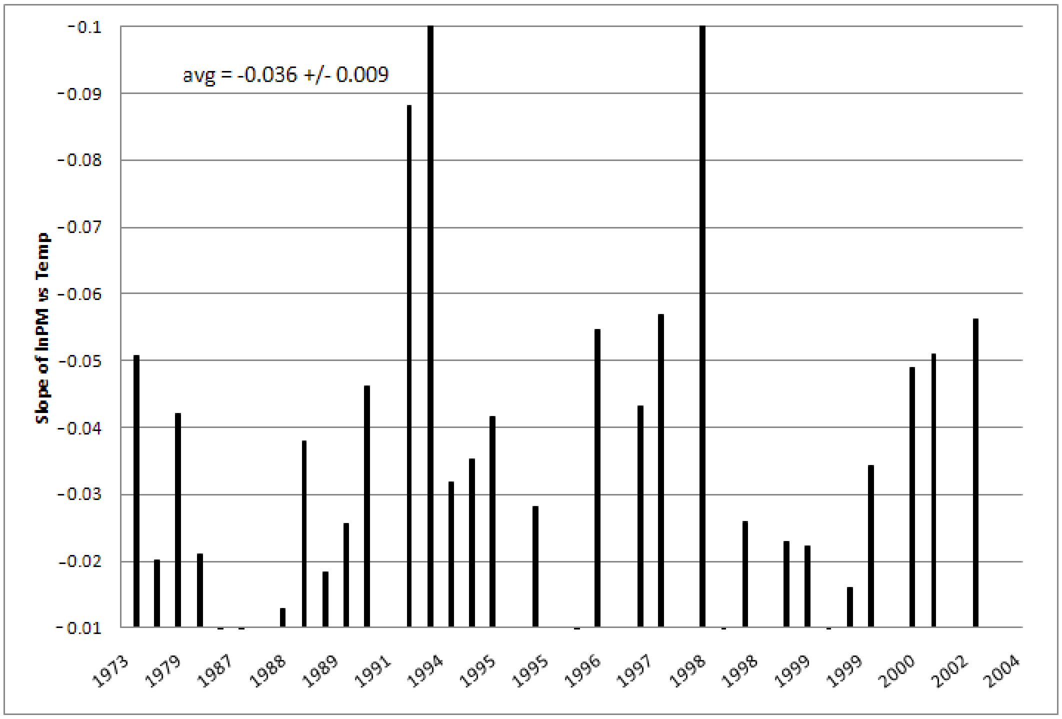


Figure 4. Temperature slope from individual matched pairs of summer and winter round retests as a function of vehicle model year.

A univariate general linear model, run on the Statistical Package for the Social Sciences (SPSS) statistical software, provided an estimate of the effect of temperature from the summer/winter matched pair vehicle tests. The "vehicle" was treated as a fixed factor (categorical variable) and the correlation vehicle was weighted by a factor of 0.09 in order to give it the same weighting as the other 33 (43 original minus10 with a temperature difference less than 10°F between tests) matched pairs. Figure 5 contains the matched vehicle slopes. Although the magnitude of the temperature effect varies for each vehicle, a statistical mean was discerned. Using Equation 1, the temperature effect on PM emissions was estimated as follows:

$$\ln PM2 = -0.03356*(72°F - T1) + \ln PM1 \qquad \text{Equation 2}$$

This approach assumed that the slope drove the temperature effect; thus, each individual test defined the offset in the slope and was ignored for the purposes of this “temperature model”. Due to the relatively short time between the summer and winter testing (less than one year), the emissions increases were not likely due to engine or emission control system deterioration, but instead these temperature effects.

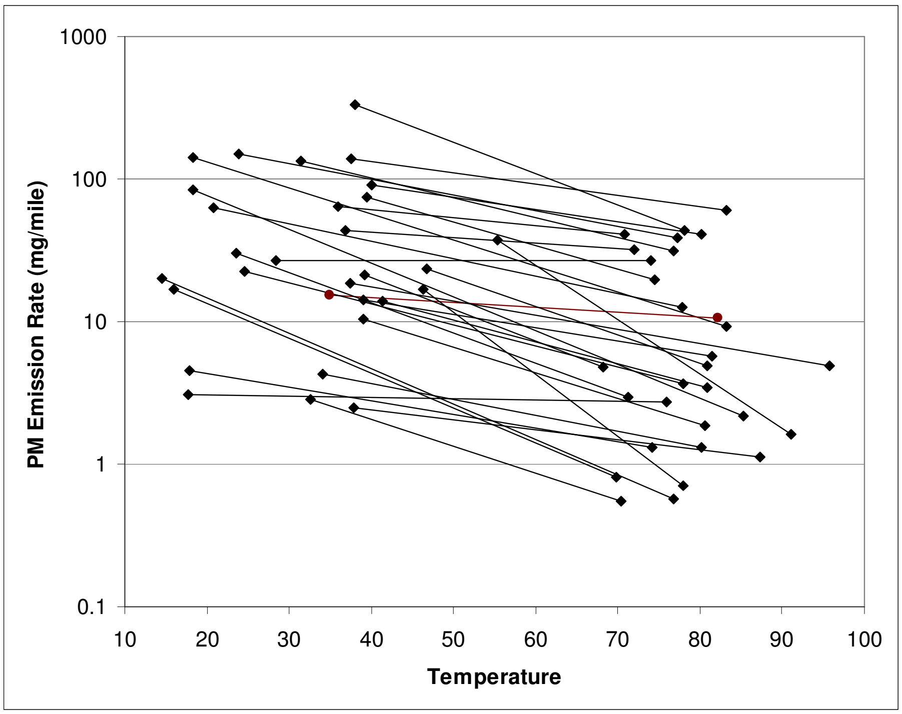


Figure 5. Matched pair vehicle winter and summer round retest emission rates as a function of temperature on log scale.

The KCVES data was compared to other recent testing programs conducted at varying temperatures ranging from -20°F to 75°F.[6,7,8] Figure 6 compares the results of these three test programs with the KCVES data. This Figure demonstrates similar trends in PM emission rates due to temperature differences among all the studies, with the KCVES data consistent with the other study data. The MSAT Test Vehicles[8] PM emission rates were offset lower since this program targeted lower emitting, Tier 2 vehicles. However, as shown in some other figures, temperature trends (slopes) seemed to be independent of vehicle technology, with consistent slopes among all of the various test programs. The historical studies were conducted on back-to-back testing in laboratory controlled conditions; however, small sample sizes limited the ability to extrapolate the temperature-PM relationship to the rest of the fleet. The KCVES temperature-PM trend compared favorably with the historical studies even considering these studies used different test facilities and different PM measurement methods. The KCVES program also added a large number of in-use vehicles to the total dataset; thus providing justification for extrapolating these results to the average fleet independent of model year and age.

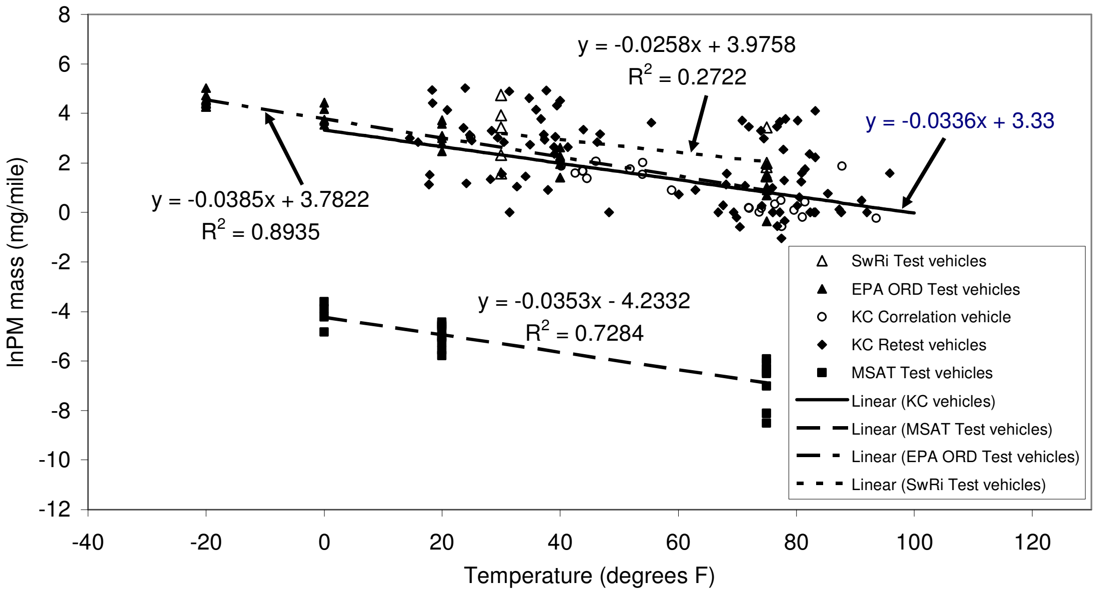


Figure 6. PM emission trends relative to ambient temperature comparing the KCVES to results from EPA ORD test vehicles with model years ranging from 1987 to 2001 tested at 75°F, 20°F, 0°F and a subset at -20°F,[6] SwRI test vehicles that included seven pre-2000 model year vehicles tested at 30°F and 75°F,[7] and MSAT test vehicles that included four Tier 2 vehicles tested at 75°F, 20°F and 0°F. Similar concentration-to-temperature slopes are evident for all datasets.

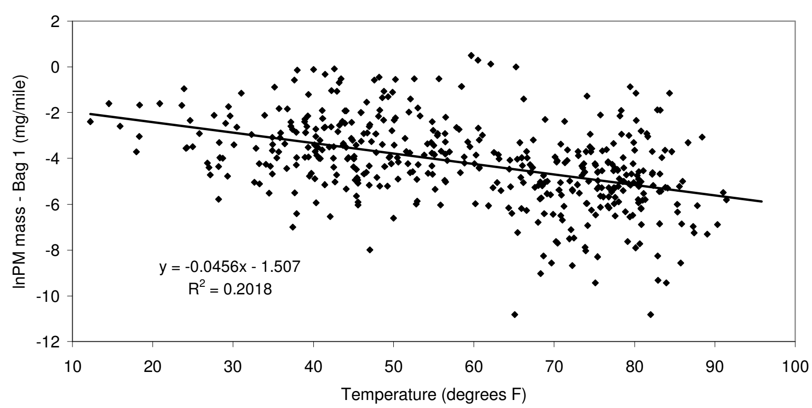
Temperature effects from other regulated pollutants measured in the KCVES were calculated in a similar manner, with results shown in Table 1. The temperature effects for PM were greater than for these other pollutants; however, all of these pollutants showed an increase in emissions with decreasing temperatures as all slopes were significantly different from zero at the 5% confidence level.

Figure 7 shows the temperature trend for cold start (Bag 1, Figure 7a) and hot running (Bag 2, Figure 7b) PM concentrations, respectively. This Figure shows that the increased PM emissions rates at decreasing temperatures mainly occurred during cold start operations. The cold start slope was more than double the effect experienced during the hot running condition. The hot running PM showed a small but discernable temperature effect. PM emissions were elevated during cold starts for three primary reasons: incomplete combustion due to low combustion cylinder temperatures, the catalyst not yet fully heated and "lit-off", and the engine often running a fuel-rich mixture in order to assist combustion during cold engine conditions. During colder ambient temperature conditions, all of these factors could be enhanced and prolonged than during higher ambient temperatures. These combinations of factors caused emissions to be an exponential function of temperature. The temperature effect seen during hot operation may be due in part from some vehicles still warming up during the beginning of phase 2 of the test.

Table 1. Exponential emissions dependence on temperature ($p<0.05$).

Pollutant	Slope (ΔT/ln conc)	Standard Error	Samples (N)
PM	-0.0336	0.0029	34
HC	-0.0124	0.0012	44
CO	-0.0145	0.0014	44
NOx	-0.00234	0.00082	43
CO2	-0.00077	0.00014	44

a) Cold start (Bag 1)



b) Hot running (Bag 2)

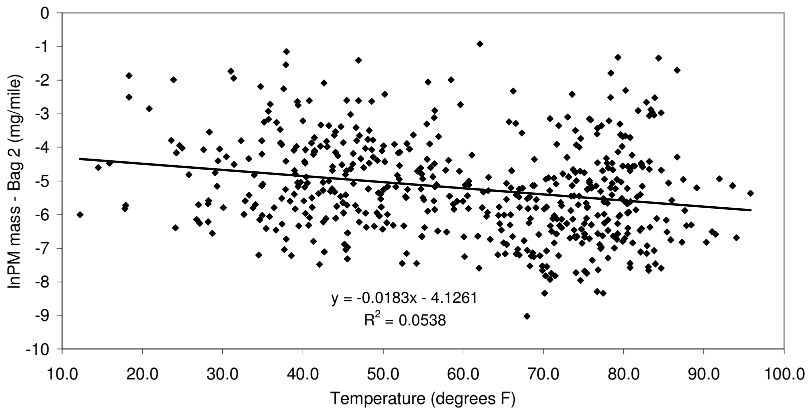


Figure 7. Comparison of PM emission rates with changing ambient temperatures during cold start (Bag 1, Figure 7a) and hot running (Bag 2, Figure 7b) vehicle operating modes.

Results from the KCVES demonstrated the relationship of PM emission rates from light-duty, gasoline-powered motor vehicles on ambient temperatures, with emission rates increasing exponentially with decreasing temperature. This exponential relationship has also been identified in other independent studies investigating ambient temperature effects on PM emission rates. In general, PM emissions doubled for every 20˚F drop in ambient temperature and were independent of vehicle model year. The effects of temperature on vehicle emissions was most pronounced during the initial start-up of the vehicle (cold start phase) when the vehicle was still cold, leading to operation under fuel-rich conditions, inefficient combustion and inefficient catalyst operation. The large dataset available from this study allowed, for the first time, the development of a model to describe temperature effects on PM emission rates due to changing ambient conditions. This study and the relationships shown have been used to develop PM emissions rates for EPA's new regulatory emissions model, MOVES.[12] While the test program measured vehicle emissions in an area not subject to an I/M program, the consistency of temperature dependence with other studies suggested these trends were independent of vehicle technology, age and model year.

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BRIEF

This research describes and models the increase in particulate matter emissions from light-duty, gasoline powered vehicles during decreases in ambient temperature.

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