DRAFT

Characterizing Vehicular Contributions to $PM_{2.5}$ in Fairbanks, Alaska

Volume 1: Dynamometer-Based Emissions Measurements, Vehicle Keep-Warm Activities and MOVES Analysis

prepared for:

Alaska Department of Environmental Conservation

July 2011

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the authors

Testing team members (left to right): Nadine Carroll, Charlisa Attla, Alberta John, Nadine Winters, Kelly Shaw, Rodney Evans, Dan Govoni, Paul Simpson, Karen Remick, Ron Lovell, Sung Hoon Yoon (not pictured: Dennis McClement, Missy Jensen, Joan Hardesty, Steve Gano, Todd Thompson and Adelia Falk; photo by Frank Di Genova)

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Table of Contents

Page

Additional volumes:

Volume 2. Dynamometer Pilot Study in 2009-10

Volume 3. Description of Test Vehicles

Volume 4. On-road Emission Testing

List of Figures

List of Tables

1. EXECUTIVE SUMMARY

1.1 Purpose

The main purposes of this study were as follows:

1. To determine the extent to which motor vehicles contribute to the existing $PM_{2.5}$[*] problem in Fairbanks, Alaska;

2. To determine, for a representative sample of Fairbanks vehicles, the effects of low temperatures and plug-ins upon $PM_{2.5}$ emissions;

3. To determine on-road $PM_{2.5}$ emissions through a plume-following study;

4. To determine the typical state of warm-up at engine start for on-road vehicles; and

5. To determine whether the U.S. Environmental Protection Agency's (EPA's) MOVES emissions model will work properly under winter time conditions in Fairbanks, or whether it may need "adjustments."

The study consisted of four main elements: repeated chassis dynamometer testing of more than 30 vehicles, on-road sampling of more than 1,000 vehicle plumes using an instrumented vehicle, sampling and recording of in-use engine coolant temperatures to document the state of engine warm-up, and an examination of MOVES in consideration of the possible need for low-temperature adjustments. A brief overview of the study's activities and main findings is provided below; details are provided in the subsequent sections and separate volumes of this report.

1.2 Dynamometer Testing

Chassis dynamometer-based exhaust emission measurements of $PM_{2.5}$ and criteria pollutant gases were conducted in the winter of 2011 to determine the effect of ambient temperature and block heater plug-in upon exhaust emissions. Using a chassis dynamometer, dilution tunnel and upgraded constant volume sampling (CVS) system, both integrated filter measurements and second-by-second continuous analyzer-based

[*] "$PM_{2.5}$" refers to fine particles having an aerodynamic diameter smaller than 2.5 microns.

measurements were made of $PM_{2.5}$. Pollutant gases carbon monoxide (CO), total hydrocarbon (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2) were also measured. The equipment and procedures generally complied with those specified in the Federal Code of Regulations with adaptations for low temperatures.

A stratified random sample of 32 Fairbanks light-duty gasoline vehicles was tested. Following overnight soaks, more than 100 cold start tests were successfully completed. Each vehicle nominally received three tests: one test with block heater plug-in, and two non-plug-in tests targeted for different ambient temperatures. Each test included two phases—referred to herein as a "Cold ADC" (Alaska Drive Cycle) and "Hot ADC"—separated by a 10-minute soak (engine off). The Cold ADC drive was preceded by a 5-minute warm-up idle, which is common for vehicle operation in Fairbanks. The Alaska Drive Cycle is a time/speed driving pattern designed to represent on-ride driving in Alaska in winter. It is 816 seconds in duration, 4.7 miles long, and has generally milder accelerations and speeds (consistent with icy road conditions) than exist in the test cycle used in the Federal Test Procedure. The testing was conducted at the Fairbanks Cold Temperature Test Facility between January 12 and March 26, 2011, over a range of ambient temperatures from -30° F to 44°F (avg. 2°F).

Findings from the dynamometer-based testing are summarized below.

1. Use of block heaters ("plug-in"), heated garages, and extended warm-up idle for light duty vehicles are all normal activities and/or practical necessities in Fairbanks in winter that can significantly affect $PM_{2.5}$ emissions. However, examination of these effects, which are critical in Fairbanks but less important in locations in the lower 48 states, was beyond the scope of EPA's Kansas City PM Emissions Characterization Study[1] and of current EPA guidance[2*] for using MOVES.[†] In addition, the PM emission factors in MOVES, including the temperature corrections of those emission factors, are derived from measurements made in Kansas City, where the minimum temperature for the testing was +12°F.[‡] That Kansas City minimum temperature exceeds the long-term average monthly temperature in Fairbanks for the months of November through March[3] and is well

[*] On p. 43, EPA states "The temperature adjustments in MOVES are intended to represent the effects on vehicle emissions when the ambient temperature to which the vehicle is subjected is known. There may be factors that cause difficulty in determining the appropriate temperature to apply to the fleet, such as the variation of ambient temperature over the area you wish to model. However, these are issues for guidance on how best to use the model for specific scenarios." This guidance was provided in response to the following comment: "Part of the difficulty with adjusting for Tamb (i.e. ambient temperature effects) in the general fleet may be due to the many vehicle parking options: outdoors, unheated indoors, heated indoors or with plugged in block heater. If a vehicle is parked outdoors, the wind chill factor might also influence cold-start emissions. The test data do not seem to account for all of these factors." What the reviewer suggested as "options" are not, however, optional at Fairbanks winter temperatures, but instead are required for reliable daily vehicle starts.

[†] Sierra believes that both MOVES and the Kansas City Study are ambitious, pioneering efforts that have substantially advanced the art of emission measurement and engineering; neither, however, was designed to apply to Fairbanks-like winter conditions, and therefore they don't apply well without further adjustment.

[‡] At this and higher temperatures, block heater plug-in is not typically required for gasoline-powered vehicles, and it was not used in the Kansas City Study.

above the -12°F average daily temperature for $PM_{2.5}$ design day episodes in Fairbanks.[4] Other "low temperature" vehicle PM emission studies used to support or help corroborate MOVES had only a limited number of vehicles and tests; conducted testing down to only about -20 or 0°F; and did not include analysis of plug-in, heated garaging, or warm-up idle. As a result of the above limitations, any modeling of Fairbanks PM emissions using MOVES must necessarily rely upon extrapolations of effects measured at higher temperatures, neglect the effects of plug-in and extended idle, and/or neglect other real effects that significantly influence emissions. The results from emission testing in Fairbanks in the winter of 2011 (summarized below) confirm that such extrapolation and assumptions are not technically supportable and could result in overestimating the $PM_{2.5}$ emissions from light-duty gasoline vehicles by up to 680%.

2. $PM_{2.5}$ emissions from a "Cold ADC" test, representing a morning cold start, warm-up idle, and drive ("Cold ADC") had an average baseline value of 27.5 mg/mi at an ambient temperature of 20°F. These emissions (assuming no vehicle garaging or plug-in) increased exponentially by 26.2% for each 10°F drop in ambient temperature below 20°F (temperature coefficient of 0.0233). By contrast, the EPA-sponsored Kansas City Study reported a $PM_{2.5}$ emissions increase of 58% (more than twice as much) for the same temperature drop (temperature coefficient of -0.0456).

3. For the warm ("hot start") phase of testing, Fairbanks (and Kansas City) vehicles showed, as expected, much lower base $PM_{2.5}$ emissions than the cold start phase. However, the testing of Fairbanks vehicles showed no residual influence of ambient temperature in the hot phase, whereas Kansas City (KC) testing showed a temperature sensitivity coefficient of -0.0318±0.0028, which predicts an increase of 37% in "stabilized, hot running" emissions for every 10°F decrease in temperature (assuming that the KC temperature coefficient is extrapolated to the colder range of Alaska winters). While the reasons for the difference are not all known, it is noted that the Fairbanks testing had a much longer first phase (300 seconds warm-up idle plus 816 second ADC = 1,116 seconds) compared to 310 seconds for the first phase of the LA92 cycle used in Kansas City, and the Fairbanks cold starts began with a 5-minute warm-up idle; both of these factors are expected to reduce temperature influence. In addition, all of the Fairbanks 32-vehicle testing was completed within 2½ months, whereas the KC testing was conducted in a summer phase and a later winter phase, between which different fuels could have been used and other changes may have occurred.

4. The EPA-sponsored Kansas City study collected data under different conditions and for an older fleet (with smaller fraction of low-temperature certified vehicles) than the Fairbanks study. For example, the Kansas City data were collected in the temperature range from +90°F to +12°F. Thus, application of the Kansas City data to Fairbanks winter temperatures requires extrapolation of temperature effects outside the range in which the data were collected. It is unclear whether

the KC fleet $PM_{2.5}$ measurements at temperatures as high as +90°F have the same reliability as emissions measurements collected in Fairbanks at typical Alaskan winter temperatures.

5. Based on Fairbanks winter test results, block heater plug-in during overnight soak and 5-minute warm-up idle after engine start (which together are the common practice for vehicles parked out of doors overnight or for extended periods in Fairbanks in winter[*5]) reduced cold start $PM_{2.5}$ emissions by 74%. Neither plug-in nor warm-up idle of light duty gas vehicles is considered in MOVES, despite the fact that at temperatures below about -20°F, most gasoline vehicles will not start reliably without starting assist, and such starting is not routinely attempted in normal winter operation in Fairbanks.

6. Based on filter-calibrated continuous analyzer measurements from non-plug-in cold ADC dynamometer (dyno) drives, most of the $PM_{2.5}$ was emitted within the first two minutes after engine start, i.e., probably before the catalyst "lit off" and the vehicle's emission control system entered close loop operation. In addition to startup, $PM_{2.5}$ emissions tended to "spike" during high power accelerations. Compared to the foregoing two types of events, $PM_{2.5}$ emissions at almost all other times were low for most vehicles, regardless of temperature (this may not be true for "high emitting vehicles").

7. As a secondary objective of the dynamometer study, gaseous criteria pollutants were also measured and results are presented for the temperature dependencies of those emissions.

1.3 State of Engine Warm-up in Fairbanks

Based upon a review of earlier telephone survey data, both old and new electronically logged vehicle activity data (including soak times and engine coolant temperature data), ambient temperature measurements at several locations, and coolant and other engine temperature data collected during dyno testing, several observations were made about the state of engine warm-up in Fairbanks winters. The key finding is that, at typical $PM_{2.5}$ design day temperatures, vehicle operators use a variety of "keep warm" activities to avoid most engine starts where the engine is near ambient temperature. By comparison, MOVES assumes that such cold engine starts (which would have the highest "start increments" of emissions) occur regardless of how low ambient temperature drops. This assumption in MOVES conflicts with the evidence of "keep warm" activity in Fairbanks, as outlined below.

1. Plug-in engine block heaters are ubiquitous in the Fairbanks winter vehicle population, and they are widely used when vehicles are parked outside for more than a few hours. This is documented by phone survey data showing that for

[*] Five- to 15-minute warm-up idles are common in Fairbanks, as is the use of radio-based remote start devices, referred to locally as "autostarts."

overnight parking at home, heated garaging is the most common vehicle "keep warm" strategy (used by 57% of phone survey respondents) and plug-in is the next most common (37%). For vehicles parked at work, plug-in (66%) is the most common keep-warm activity.

2. For overnight outdoor soaks (of dyno test vehicles), the average difference between starting engine (or coolant) temperature and ambient temperature was less than 5°F. That is, non-plugged-in vehicles do tend to equilibrate overnight to nearly ambient temperature. In contrast, plugged-in vehicles had engine temperatures that were, on average, 56°F higher than ambient temperature (similar, we expect, to heated garage temperatures).

3. Based on instrumented vehicle data, vehicles in Fairbanks typically exhibit markedly elevated coolant temperatures at engine start after extended soaks compared to what would be expected based on ambient temperature cool-down. For soak times longer than six hours, and for the three ambient temperatures ranges of below -20°F, -20°F to 0°F, and 0°F to +20°F, the average startup coolant temperatures of in-use vehicles ranged from 39°F to 55°F and closely matched that of plugged-in vehicles. (For shorter soak times, the corresponding average coolant temperatures at start ranged from 119°F to 135°F, indicating partially warmed up engines.) These elevated coolant temperatures are almost certainly due to "keep warm" efforts by operators.

4. Instrumented vehicle data suggest that, except for very short soak periods (less than 2 hours), plug-in is used almost universally for engine starts at ambient temperatures below -20°F. While it is possible to start some newer gasoline-powered vehicles at ambient temperatures below -20°F, this is neither recommended nor normal practice in Fairbanks.

5. Limited instrumented vehicle data indicate that plug-in is not used at ambient temperatures above 20°F. In this temperature range, starting coolant temperatures for all soak durations better matched a cool-down model than a plug-in model. However, this temperature range is above that for most tentatively identified Fairbanks $PM_{2.5}$ "Design Day" conditions.

1.4 Plume Following

In the winter of 2009-2010, a Borough sport utility vehicle (SUV) was equipped with bumper- and roof-mounted cyclones to sample on-road plumes from followed vehicles. Real-time analyzers were used to measure $PM_{2.5}$ and CO_2 concentrations; a GPS system provided location; a computer displayed data in real time; and supplemental manual, audio and video data were logged. The vehicle was operated for on-road "plume following" over a period of 15 days in February and March of 2010. Based upon on-road measurements of $PM_{2.5}/CO_2$ ratios in the exhaust plumes of six vehicles previously tested on a dynamometer and upon a sampling of more than 1,000 plumes from pseudo-randomly selected on-road target vehicles of various types in Fairbanks, the following conclusions were reached:

1. An on-road measured plume ratio* of 0.215 ug/m^3 $PM_{2.5}$ per ppm of CO_2 during accelerations could be used to distinguish two "high emitters" from four "normal emitters" in a dynamometer pilot study sample of light-duty gasoline-powered vehicles. Thus, it could serve as a threshold to distinguish normal from high emitters. Based on this threshold ratio and the results from sampling acceleration plumes from a pseudo-randomly selected sample of 630† on-road vehicle plumes, 7.5% of the on-road fleet in Fairbanks would be classified as high emitters.

2. Additional information from license plate lookups of 549 vehicles from the on-road sample of plume ratios revealed the following rank order, beginning with the highest average emission emissions ratio: heavy-duty Diesel trucks (ratio 0.408) > heavy-duty gasoline trucks (0.326) > Diesel-powered vehicles (0.245) > light-duty Diesel trucks (0.202) > light-duty gasoline trucks (0.071).

The equipment and methods used in the on-road, plume-following emission study are contained in Volume 4 of this report, along with more detailed results.

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* Five-second ratio of vehicle-emitted $PM_{2.5}$ and CO_2 concentrations after subtracting estimated background contributions.

† This represents the subsample whose license plates could be read, thereby permitting exclusion of duplicate counts of the same vehicle.

2. INTRODUCTION AND BACKGROUND: $PM_{2.5}$ IN FAIRBANKS AND THE UNCERTAIN ROLE OF MOTOR VEHICLE EMISSIONS

Fairbanks has been collecting ambient measurements of $PM_{2.5}$ at the State Office Building in the downtown area for over a decade. Those measurements show a distinct seasonal pattern of elevated concentrations during both summer and winter months. Large uncontrolled wildfires are the principal cause of the elevated summer values. The causes of the elevated winter values are more complex and include severe meteorology (i.e., low wind speed, low mixing depth heights, and arctic winter temperatures), which limits dispersion potential; the combustion of large volumes of fuel for space heating (primarily high sulfur distillate fuel oil, wood, and relatively low sulfur, low BTU sub-bituminous coal); and poorly understood atmospheric chemistry that promotes secondary particulate formation. Collectively, these factors have caused the Borough to routinely exceed the more stringent 35 $\mu g/m^3$ National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ that EPA established in 2006, and resulted in Fairbanks being proposed as a $PM_{2.5}$ nonattainment area in December 2008.

In late 2009, the nonattainment designation was formalized in a Federal Register notice, establishing a time frame of three years for Fairbanks to develop a State Implementation Plan (SIP) that documents the control strategies that will be implemented to demonstrate attainment of the $PM_{2.5}$ standard. The first step in developing a SIP is to determine the relative contribution of the emission sources to the elevated concentrations. In recent years, the Borough and the State have undertaken several efforts to gain insight into the source mix impacting the nonattainment area. Presented below is very brief summary of the results, which provided impetus for the current study.

- Receptor models—PMF (Positive Matrix Factorization), UNMIX[6], and more recently CMB (Chemical Mass Balance)[7]—have been used to analyze the speciation data collected at the downtown site since March 2005. While final CMB results are not yet available, the results of PMF and UNMIX indicate that motor vehicles are responsible for less than 5% of the mass recorded on high concentration days. The results of these models, however, are poorly correlated (R^2=0.049), which suggests that motor vehicle contributions are not well resolved by the models.

- An instrumented vehicle was used to collect instantaneous second-by-second measurements of $PM_{2.5}$ concentrations on roads throughout the nonattainment area during the winters of 2007-08 and 2008-09. The results showed[8,9,10] that the highest concentrations occurred in densely populated areas. They also showed that daytime concentrations along Airport Way (a major arterial) were relatively high, but the source contribution was unclear, underscoring the need to better understand the motor vehicle contribution.

- Analyses of the correlation between vehicle traffic on roads adjacent to selected monitors conducted by Drs. Ron Johnson and Tom Marsik at the University of Alaska at Fairbanks (UAF)[11,12] concluded that motor vehicles are responsible for 25% to 35 % of $PM_{2.5}$ emissions.

Collectively, these and earlier studies[13] provided a conflicting picture of the motor vehicle contribution to elevated $PM_{2.5}$ concentrations and indicated that additional information was needed to resolve this issue.

Another approach that could be used to assess the relative contribution of motor vehicles to the level of directly emitted and related precursor emissions of $PM_{2.5}$ would be to construct an overall emissions inventory for Fairbanks. An examination of the available motor vehicle emission factor models, however, showed that they do not well represent winter conditions in Fairbanks. MOBILE6.2, the predecessor motor vehicle emission factor model to MOVES, did not include temperature correction factors for $PM_{2.5}$. This conflicts with results of testing programs conducted in Fairbanks in the mid-1990s[14] and more recently by EPA in Kansas City,[15] which showed that directly emitted $PM_{2.5}$ emissions increased exponentially as temperatures decreased (i.e., PM doubles for every 20°F drop in temperature.) Therefore, MOBILE6.2, as it is currently configured, cannot be used to accurately quantify wintertime $PM_{2.5}$ levels in Fairbanks.

While this problem has been addressed in EPA's latest emission factor model MOVES (EPA's Motor Vehicle Emission Simulator), there is an additional concern that the logarithmic $PM_{2.5}$ temperature correction factor applied to gasoline vehicle $PM_{2.5}$ emissions overstates the impact because it does not account for the impacts of block heaters, which are universally employed in Fairbanks at temperatures below -20ºF. Since block heaters impact several of the factors identified in the Kansas City study that influence the rate of $PM_{2.5}$ formation in gasoline vehicles (e.g., enrichment during cold start, time to catalyst light-off, etc.), it is expected that use of block heaters will diminish the impact of temperature on directly emitted $PM_{2.5}$ levels. Discussions between Sierra and EPA staff in Ann Arbor, Michigan responsible for the development of MOVES confirmed this concern. It was acknowledged that the creation of AKMOBILE6[16] established a precedent for addressing the impacts of Fairbanks-specific vehicle operating conditions (i.e., use of block heaters, extended cold start idle, and moderate winter driving) and that these also need to be addressed in MOVES.

Previous emission testing programs conducted in Fairbanks collected data quantifying the impact of block heater operation, extended idle, and diminished winter acceleration rates on HC, CO, and NOx emissions. An analysis[17] of those data showed that block heaters reduced overall trip CO by 43.8%. It also showed the HC levels were reduced by 44.4% and NOx levels by 6.4%.

Recognizing that winter operating conditions in Fairbanks impact $PM_{2.5}$ emissions, the Alaska DEC engaged Sierra Research to quantify those effects for a range of vehicle types from the Fairbanks in-use fleet. This study used the following range of approaches to better characterize vehicle emissions:

- Chassis dynamometer-based dilution tunnel sampling of exhaust emissions measurements[*] for light-duty gasoline-powered vehicles;

- Collection and analysis of electronic data logging of vehicle soak times, coolant temperatures, and other data from in-use vehicles to evaluate vehicle "keep-warm" activity;

- A MOVES modeling analysis, to help integrate the measurement studies and compare the results with what was available from EPA's default version of MOVES; and

- "Plume following" for the measurement of on-road emissions from all types of on-road vehicles, including emissions from medium- to heavy-duty trucks and Diesel-powered vehicles that are not amenable to testing at the Fairbanks Cold Temperature Test Facility.

The results from the current study are presented in four volumes. The next three sections of this volume discuss, respectively, the dynamometer-based emissions measurements, the keep-warm activity study, and the MOVES analysis. Section 6 then provides a comprehensive summary of findings and recommendations. References cited throughout the report are provided in Section 7.

Separate from this volume, Volume 2 discusses the dynamometer pilot study in 2009-2010, Volume 3 provides details about the dynamometer test vehicles, and Volume 4 describes the plume-following study.

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[*] Knowledgeable EPA staff reviewed and provided helpful comments on the conceptual design of the dilution tunnel, aspects of the dynamometer testing facility, and study plans (personal communications with EPA staff including Mssrs. Don Paulsell, John Menter, and Carl Fulper, October and November 2009).

3. DYNAMOMETER TESTING

In the fall of 2009, DEC engaged Sierra Research to perform several tasks related to better characterizing vehicular emissions in Fairbanks, including adding a dilution tunnel and other equipment to the facility to permit the measurement of $PM_{2.5}$ emissions and conducting testing (referred to here as the "pilot study") to measure emissions from a limited sample of vehicles. This section documents the upgrades and modernization of the facility, the procedures used for the dynamometer testing and data collection, quality assurance, data analysis, and test results.

3.1 The Fairbanks Cold Temperature $PM_{2.5}$ Test Facility

In 1998, under DEC sponsorship, Sierra Research designed and configured a mobile testing van to measure CO mass emissions from idling vehicles; and in the winter of 1998-1999 Sierra operated the van in Anchorage and Fairbanks at ambient temperatures approaching -50°F. In 2000, Sierra modified the van, adding a critical flow venturi (which was part of the original Horiba IMVETS), drivers aid, and other equipment and software, and integrated it with a Real Time* split, twin-roll, electric chassis dynamometer that Sierra installed at the Fairbanks North Star Borough Transportation Department, 3175 Peger Road, in Fairbanks. The facility, which has since been turned over to the Fairbanks North Star Borough, was used over the ensuing decade to test hundreds of locally recruited vehicles under Fairbanks winter conditions, with varying factors: with and without plug-in and with various lengths of warm-up idle, using a variety of fuels (high and low sulfur), measuring before and after oxygen sensor change-out, with and without the use of remote starters, and so on. Additional details about the facility and these studies are contained in a series of reports prepared by Sierra.[5,17, 18, 19, 20, 21, 22, 23] Until recently, however, there was no capability to measure exhaust PM emissions from vehicles. This project established and utilized that capability.

The system redesign in 2009 was substantial. An existing Horiba Constant Volume Sampler (CVS) transient exhaust emissions test cell for light-duty cars and trucks was modified to include particulate emissions measurement with filtration and with two continuous real-time PM analyzers. The filter-based methodology parallels that used by the U.S. EPA and vehicle manufacturers for the certification of new vehicles. The continuous analyzer measurements were included for two reasons. First, the MOVES emission modeling approach currently specified by EPA for conformity analysis is based

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* Real Time Instruments, Laguna Hills, CA.

on continuous modal emission results, which a filter-based measurement alone cannot provide. Second, it was desired to use the filter and continuous results obtained on a dynamometer to help estimate mass emissions observed during selected on-road operations (see Volume 4 of this report).

The existing CVS system control hardware and software was updated during the conversion. The control computer and system interface in the existing system were replaced with a similar system* with significantly expanded capabilities. The new system software† was further modified to include user-defined driving cycles, multiple phases per test, added inputs for the two continuous PM analyzers, and control signals for the particulate filter sampling system (provision of CVS pressure and temperature sensor measurements for flow computation and digital control lines for filter selection under software control).

A particulate dilution tunnel, custom mixing T, dilution air HEPA filter, and measurement filter system were added to the existing CVS sampler. Warm indoor air was drawn through the HEPA filter and ducted to a mixing chamber located near the vehicle exhaust outlet. Exhaust from the vehicle was transported to the mixing point through a short flexible exhaust tube (which was heated prior to the start of each test) and, as needed, a thermostatically heated stainless steel exhaust pipe. The vehicle exhaust was mixed with the dilution air and fed into the dilution tunnel. Samples for particulate measurement were drawn from the end of the dilution tunnel and directed to two continuous samplers and a CFR compliant filter sampling system.

A temperature- and humidity-controlled glove box enclosure was used to condition and weigh filters before and after testing. A pedestal to provide a stable base for a sub-microgram balance was enclosed in the glove box. Filters were stabilized in the glove box before and after each weighing. All weight measurements were performed on the day each filter was used for test.

The equipment and procedures used during testing generally comply with those specified in the Federal Code of Regulations (CFR), Title 40, Part 86. Subpart B describes the overall test procedure and equipment required to measure exhaust gases, while Subpart N describes the additional equipment and procedures used to measure particulate emissions. The regulations were adapted to the low-temperature testing environment and modified exhaust emission measurement equipment available.

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* Originally, the Horiba hardware consisted of a IMVETS (Inspection and Maintenance Vehicle Emission Test System) that was incapable of running drive cycles other than the IM240. That system was modified by Sierra to use custom hardware and software, which allowed different driving cycles, most particularly the Alaska Driving Cycle (ADC) developed by Sierra. In 2009, the IMVETS computer and J-box (junction box) were replaced with those from a Horiba IM240 System, restoring the system closer to an original Horiba configuration but still permitting essentially any drive cycle to be used.

† The software developed under this contract was adapted from software previously developed by Sierra for another government client. Additional upgrades to the earlier version provided for a pause switch (to accommodate engine stalls that are not uncommon in Fairbanks in winter) and the use of a critical flow venturi.

The vehicle dynamometer is located in a bay with an overhead door that, on testing days, was kept fully and continuously open to the outdoor environment. The dynamometer rolls are positioned such that the front end of a rear wheel drive vehicle is outside of the building during testing. Front wheel drive vehicles are positioned such that the front radiator would be within five feet of the exterior opening when mounted on the dynamometer. A fixed speed Hartzell[*] fan meeting CFR cooling specifications is positioned outside of the building, directing ambient air at the vehicle engine compartment during test.

The dynamometer cell is isolated from the remainder of the building by permanent walls. During testing, the dynamometer, test vehicle, mixing chamber, and dilution tunnel are on the "cold side" of the wall, while the measurement equipment is on the "warm side." The dilution tunnel is connected to the outlet of a mixing chamber, and serves to mix the vehicle exhaust with the warm dilution air and then return the dilute mixture back through the wall. An opening, approximately 1 foot square, provides pass-through for the continuous dilute mixture from the tunnel and for three (internal) PM sample lines which draw sample from a point in the tunnel that is ten tunnel diameters downstream of the mixing point. Other openings are used to duct HEPA-filtered dilution air from the warm side of the wall to a mixing point near the vehicle and to permit high voltage power lines and other control and sensor lines to pass between the warm-side power controller to the cold-side electric dynamometer. In Figure 3-1, dilution air passes through a port at left (not visible) and is transported through an insulated duct to the black flexible tubing, which connects to the insulated mixing chamber in the foreground. The transfer tube for vehicle exhaust consists of a short flexible tube (which is heated prior to the start of each test) and also, if needed,[†] a longer stainless steel pipe that is thermostatically heated to prevent condensation (the pipe is insulated and contained within the orange silicon rubber tube shown in the figure).

The mixing chamber[‡] is constructed of stainless steel. The dilution air enters perpendicular to the exhaust flow. Vehicle exhaust enters through a 3" stainless steel pipe, which ends flush with an annular ring on the 8" outside diameter of the mixing chamber. The dilution air and exhaust mixture is drawn down an 80" stainless steel dilution tunnel in turbulent flow (see Figure 3-2).

Stainless steel probes are used to collect particulate sample. The probes face upstream, directly into the dilute exhaust stream originating at the opposite end of the tunnel. The bulk sample stream is turned after passing through the wall, while the particulate probes pass directly out of the end of the duct. The larger (½") probe passes sample into a 10' heated line leading to a cyclonic separator and filter collection apparatus. The sample in this line is thermostatically controlled[§] to 117°F. The remaining two (¼") sample probes are connected by (¼") stainless steel lines and short sections of conductive tubing to the

[*] Hartzell Fan, Inc., Piqua, OH.
[†] The straight pipe extension was not needed for testing of front wheel drive vehicles with right-hand side exhaust.
[‡] Fabricated by Van Dyke Fabrication, Rocklin, California.
[§] Unique Heated Products, Clinton Township, MI.

Figure 3-1
Mixing Chamber, Dilution Tunnel, and Heated Transfer Tube

Note: The mixing chamber has blue insulation; the dilution tunnel has silver insulation, (at right); and the heated transfer tube is the orange tube, which covers a heated, insulated steel pipe.

Figure 3-2
Mixing Chamber Outlet Separated from Tunnel to Show Detail

continuous DustTrak Model II and DataRam4000 PM analyzers through their respective $PM_{2.5}$ impactors. Figure 3-3 shows the particulate sample lines exiting the dilute exhaust duct after passing through the wall. The heated sample line is covered with a black flexible sheathing.

Figure 3-3
Sampling Lines for PM

A cyclonic separator and three filter holders[*] are mounted in a cabinet maintained at 117°F (Figure 3-4). The heated line from the end of the dilution tunnel passes through the side of enclosure into the cyclone. Flow passes from the top of the separator into one of three filter holders, as selected by solenoids outside of the cabinet. The three filters could be used to sequentially sample multiple phases of interest for each test.

For the 2010-11 testing program, two testing phases were used. The first phase consisted of a cold start, five minute idle warm-up, and then a drive of the 816 second Alaska Drive Cycle (“Cold ADC”).[†] After a ten-minute key-off soak, the second phase consisted of a warm start and repeat of the ADC (“Hot ADC”). Sampling was not conducted between the two test phases. The test facility permits filter sampling and idle periods to be specified by the test operator at any desired times in the driving schedule.

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[*] URG Corp., Chapel Hill, N.C.

[†] The ADC was developed by Sierra to represent Alaska winter driving and was specified by DEC for this project. For more information about the ADC, see Reference 17.

Figure 3-4
Temperature Controlled Filter Sampling Cabinet

Sample from the outlet of the three external solenoids was passed through a Sierra Instruments* Flow Controller. The mass flow controller was set to the design flow rate for all tests in the initial program, but could be set to higher levels to provide increased filter loading rates for very clean vehicles. The controller output was monitored to determine total filter flow during each test phase (it varied by no more than 2%).

The CVS and analyzer system used was based on the Horiba† IM-240 System manufactured for use in state Inspection/Maintenance lanes.‡ The system includes a critical flow venturi (CFV) and blower, with HC, CO, CO_2, and NOx analyzers. A dedicated microcomputer and data acquisition system manages the sampling system under the control of a remote Microsoft Windows based host computer. The I/M system differs from the CFR standard CVS exhaust measurement system in that dilute sample is

* Sierra Instruments, Monterey, CA.
† Horiba Instruments, Inc., Ann Arbor, Michigan.
‡ One adaptation to the CVS system by Sierra to accommodate cold start testing of vehicles at Alaska conditions was the addition of two isolation amplifiers ("DC Input Field Configurable Isolator," Model DRG-SC-DC, from Omega Engineering, Stamford, CT) between the IM240 "mother board" and the HC and CO analyzers. This was designed to prevent saturation of the analog to digital conversion board (which occasionally happened in the pilot study, but not in the main study) when high concentrations briefly pegged those two analyzers.

monitored continuously and integrated in software for test phase totals. In addition, background concentrations were measured immediately prior to the start of the test and assumed to remain constant throughout the test. With a standard system for gaseous pollutants, Tedlar bags were used to collect an integrated sample during each test phase for post test analysis.

The electric dynamometer is controlled by a Real Time Instruments ARCTIC-2 dynamometer control system. A Sierra Research vehicle parameter look-up table was used for this project with the Horiba host computer software system as a part of the software modification and update. The equipment operator used the Horiba host program to specify the vehicle undergoing test. The host program used the lookup table to determine the appropriate dynamometer loading parameters, and communicated those values to the Real Time dynamometer control program.

The Horiba CVS blower and IM240-VETS system are installed in a commercial "step van," which is parked parallel to the test vehicle on the warm side of the wall enclosing the dynamometer. The inside of the van is divided into two compartments. The CVS blower and motor are mounted in a small rear compartment. A 25" X 36" cabinet containing the CFV, the exhaust gas analyzers, and the system control computer is mounted at the rear of the main compartment. The remainder of the front compartment is occupied by a control console for the equipment operator and the computers used to control the system. Gas cylinders and the standard vehicle driver's seat occupy the remaining space.

Dilute exhaust sample is drawn from the end of the dilution tunnel, through the CFV, and into the blower. Vehicle gaseous emissions are sampled at the inlet of the CFV. Total hydrocarbon (THC) and NOx are measured using a Horiba FCA-240 bench containing an FID-based analyzer for THC and a chemiluminescent analyzer for NOx. A Horiba AIA-240 bench is used to measure CO and CO_2 using a non-dispersive infrared (NDIR) analyzer.

The bench is calibrated (11-point calibration) using 1% standard calibration gases within one-month before to the start of testing, and a zero-span calibration is performed once near the start of each test day (after about one hour of instrument startup) and, typically, a second time at midday (and at any other times deemed necessary by the system operator).

The measurement system monitors ambient pressure and temperature at the CFV inlet. These values are used to calculate the instantaneous flow rate through the CFV. The analyzer concentrations and CVS flow permit calculation of the exhaust gas mass each second. The IM-240 system transmits the second-by-second data to the remote Host computer. The host logs the second-by-second results to disk, and integrates the results to provide an immediate summary of results at the end of each test.

Second-by-second mass emissions are computed using CFR procedures, assuming concentration is specified in parts per million (§40 CFR 86.144):

$$\text{Mass} = \text{Volume X Density X Concentration} / 1000000$$

In the CVS method, dilution air is added to vehicle exhaust up to the total volume passing through the CFV. A correction to the measured mixture concentration is made to account for the pollutants that exist in the dilution air. The correction uses an estimate of the relative amount of exhaust and dilution air. The dilution factor (DF) uses the measured levels of THC, CO, and CO_2 in the dilute exhaust stream, assuming complete combustion of the liquid fuel (where CO_2 is reported in percent, HC and CO as ppm):

$$DF = 13.4 / (CO_2 + (HC + CO) \text{ X } 10^{-4})$$

The measured dilute concentrations are corrected by subtracting the background levels measured at the start of the test using the DF as follows:

Corrected concentration = -dilute concentration - (1-1/DF)*background concentration

The magnitude of the dilution factor depends on the venturi flow. In the IM-240 system, the nominal CFV flow is 700 CFM. Typical dilution factors are 20-40, so the dilute exhaust concentration is corrected by subtracting 0.95 to 0.975 of the measured dilution air background concentrations.

A similar dilution correction is required for the particulate filter measurements. Even with a 99.99% efficient HEPA filter in the inlet air stream, there can be a low background level of particulate (generally 0-2 ug/m^3) that is not produced by the vehicle undergoing test. Two one-hour filter measurements of background particulate were collected. The average of the two samples was used to arrive at an average background PM accumulation rate. During each test, exhaust emission measurements were collected to permit calculation of the DF for the filter readings for that test.

A final adjustment affecting emission calculations in non-arctic conditions is the NOx humidity correction factor. The level of NOx emissions generated during operation at a given temperature (for example, 75°F) is indirectly proportional to the humidity of the engine combustion air. Actual testing results were used to generate a correction factor to allow comparison of results obtained at different humidity levels. The range of temperature and humidity included in the correction factor algorithm does not apply to the extremely low absolute humidity and temperatures encountered in Fairbanks. Therefore, no NOx correction factors were applied to the results reported for this program.

3.1.1 Changes to the Test Facility Following the Pilot Study

A number of problems were encountered and limitations existed in 2009-2010 pilot study that led to changes in either hardware, software, or procedures for the current study. A list of these changes (several of which have already been mentioned) is provided below.

- Replaced clogged capillary in HC analyzer allowing calibration to specification
- Replaced underperforming blower
- Increased vehicle sample from 6 targeted vehicles to 30 randomly selected by telephone survey, eliminated replicate testing, and conducted 2-phase rather than 3-phase testing
- Replaced custom transfer tubes with system parts having interchangeable pieces, and replaced stock heating blankets with dedicated heaters for interchangeable pieces
- Installed isolation amplifiers in Horiba system for HC and CO
- Shortened and straightened dilution air CVS flow
- Used digital rather than analog communication between PM analyzers and Horiba computer (final modifications to the computer program were made early in 2011)
- Stopped using driver pendant (it failed early in 2011)
- Used wireless ambient temperature probe for daily review and planning
- Systematically measured engine temperature if coolant temperature was not available via OBDII data logger
- Used only one driver
- Adopted more comprehensive anti-static measures for the weighing of filters
- Scrubbed tires with Scotch-Brite prior to testing
- Replaced all silicon rubber sampling 'boots'

Additional details about the pilot study may be found in Volume 2.

3.2 Procedures Used for Dynamometer Testing

3.2.1 Testing Plan

To address the project goals of evaluating the effects of temperature and plug-in upon vehicular $PM_{2.5}$ emissions for a representative sample of Fairbanks vehicles, a test plan was developed that called for sampling the exhaust of at least 30 vehicles over three tests of each vehicle: "cold day plug-in," "cold day non-plug-in" and "warmer day non-plug-in" (at least 15°F warmer, if possible).

To provide the most realistic simulation of operations in Fairbanks, the plug-in tests were planned only at temperatures below 0°F.* Non-plug-in tests were to be in the range from about 0°F to -20°F†. The low end of this range was selected to provide reasonable assurance that the vehicle could still be started without plug-in, and the top of this range was selected so that the third test ("warmer day non-plug-in") would be significantly warmer (ideally, at least 15°F) than the cold day non-plug-in. Additional testing included make-up tests for most missed or invalid tests, one test with unheated dilution air, one engine start test of a light-duty Diesel truck (not discussed further here), and several tests that were conducted as repeats or back-up tests.

The testing was scheduled and conducted in two campaigns, from January 12-26 and March 19-26, 2010. In the much colder January testing, almost all test vehicles received one cold-day plug-in test; in addition, roughly 60% of the vehicles also received one cold-day non-plug-in test. During the March testing, essentially all vehicles received their planned warmer day test and their remaining colder day test. In all, 129 cold-start tests were attempted and 103 tests were successfully completed with at least one test phase (compared to the goal of 90 tests, i.e., 3 tests for each of 30 vehicles).

3.2.2 Vehicles Selected for Dynamometer Testing

Consistent with the goals, budget, and timing of the project, a completed sample size of at least 30 vehicles‡ was sought for testing (more were recruited to allow for participant dropout, vehicle problems, and other attrition). Ultimately, 36 vehicles were recruited and accepted for testing and all but 3 successfully completed one or more full tests.§

Test vehicles were recruited primarily through phone surveys. All accepted test vehicles were Alaska-licensed, street legal, in-use vehicles that are used in the winter. Table 3-1 summarizes information about the targeted and actual vehicle samples.

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* Because the facility has no effective temperature control, "choosing temperature ranges" means choosing the time of year, weather pattern, and time of day for testing in order to best meet temperature targets.

† These targets for the test program could not always be achieved due to inaccurate weather forecasts, limited availability of test vehicles, and/or for other reasons.

‡ This was the maximum practical number of full cold-start test cycles and corresponding filter analyses (two to three filters per test, each weighed before and after) that could be performed by the test team each day.

§ Vehicle #15 was aborted from testing because it illuminated CEL on the first hill; vehicle #26 was aborted after it couldn't be put into gear; and vehicle #27 was aborted on the first drive because 4WD could not be disabled. Several other vehicles also had unexpected problems but were nevertheless able to complete one or more tests successfully (although not always on the original schedule). One additional vehicle (#1) was a practice vehicle (rental car).

Table 3-1 Targeted and Actual Vehicle Samples for Dyno Testing		
Vehicle Category	**Targeted sample (n>=30)**	**Actual Sample (n=33)**
Trucks	60%	22(67%)
Passenger Cars	40%	11(33%)
MY ≥ 2004	33%	10(30%)
1987-2003	33%	17(52%)
MY ≤ 1986	33%	4(12%)

Vehicles were first recruited by random telephone survey. This produced very close to the final "actual sample" shown in Table 3-1[*] and had a notable shortage of older vehicles compared to targets.[†] A second phone survey was then conducted that attempted to target college students, as this was expected to capture a larger fraction of older vehicles; this attempt was unsuccessful, however, and resulted in no additional vehicles. A few final adjustments to the test sample were made by having the vehicle recruitment manager make persistent calls to wavering or previously unwilling respondents and persuading them to participate. In addition, when several older vehicles encountered testing problems and dropped out, one older vehicle (number 36) was added in March (and was able to conduct all three tests).

Before being accepted for testing, prospective test vehicles were screened[‡] for safe testability (no significant exhaust leaks or liquid leaks, no bald or studded tires,[§] etc.) and suitability (no fault codes set, meeting targets for the sample, etc.) All vehicle owners were required to sign a participation agreement, promising that their vehicles could be used in both of the planned test campaigns (no one refused). A consideration was also paid to vehicle owners and to volunteers who brought vehicles for screening in good faith, even if those vehicles ultimately were not needed or could not be tested.

A brief description of each of the test vehicles is contained in Table 3-2. More detailed information about the test vehicles is contained in Volume 3.

[*] As discussed later in the report, regression analyses of the test results were weighted appropriately according to their use, either to match the Kansas vehicle sample or to match the Fairbanks fleet.
[†] This is a common recruitment problem, and one which was also experienced by the EPA in its Kansas City PM study, despite intensive recruitment efforts.
[‡] Vehicle screening was performed by FNSB staff .
[§] Studded tires are widely used in Fairbanks in winter, and otherwise conforming vehicles were admitted into the program if their owners brought unstudded summer tires (on rims) for the dyno testing (most were willing and able to do so). The tire swaps were performed by project staff with no charge to the owners.

Table 3-2
Summary Information about Test Vehicles
(n=33, which excludes 3 disqualified vehicles)

Vehicle Number[a]	Model Year	Make	Model	Odometer as Received[b]	Engine Size (liters)	Transmission A or M
1	2010	Chevy	Impala	14,626	3.5	A
2	1983	Jeep	CJ7(carb)	89,577	2.58	M
3	1991	Nissan	Sentra	138,560	1.6	A
4	1993	Honda	Accord	98,940	2.2	M
5	1988	Plymouth	Reliant	59,138	2.5	A
6	2010	Ford	E350	9,276	6.8	A
7	2002	Ford	Windstar	102,758	3.8	A
8	1995	Mazda	Protégé	81,039	1.5	A
9	1993	Ford	Explorer	82,284	4	M
10	2006	Ford	Expedition	34,732	5.4	A
11	2000	Toyota	Tacoma	87,063	2.7	M
12	1996	Toyota	Tacoma	146,940	2.7	M
13	1996	Chevy	K1500	102,165	5	A
14	2004	Nissan	Frontier	84,695	3.3	A
16	1997	Toyota	Paseo	134,532	1.5	M
17	1984	Toyota	pickup(carb)	165,192	2.4	M
18	1994	Toyota	4-Runner	78,240	3	M
19	2007	Chevy	Silverado	26,294	4.8	A
20	1993	Toyota	pickup	160,899	2.4	M
21	2003	Mitsubishi	Eclipse	78,707	3	A
22	2006	Toyota	Tundra	87,156	4.7	A
23	1986	Ford	F150	93,124	5	M
24	2009	Ford	Focus	23,932	2	M
25	1995	Isuzu	Rodeo	145,481	3.2	A
28	2007	Toyota	FJ Cruiser	32,993	4	M
29	2004	Ford	Focus	63,361	2	A
30	2001	Honda	Civic EX	124,992	1.7	M
31	1985	Toyota	pickup(carb)	188,532	2.4	M
32	1990	Ford	Tbird	91,416	3.8	A
33	1988	Dodge	Dakota	216,649	3.9	M
34	2005	Ford	F250	60,390	5.4	M
35	2001	Chevy	Silverado	159,420	6	A
36	1997	Jeep	Cherokee	187,281	4	M

[a] Vehicles numbered 15, 26, and 27 (not shown) did not complete any tests and were removed from the test program.
[b] The 5-digit odometers of several of the older vehicles had likely rolled over. The values shown are raw odometer readings (no attempt to correct). Three of the older vehicles were carbureted ("carb" is listed under "Model").

3.2.3 Test Procedures

After prescreening and acceptance into the test program, vehicles were driven to the test site with at least half a tank of gas, parked outside, plugged in (as appropriate), and soaked (usually 1-2 nights). Vehicle conditioning consisted of one of the following:

- The prior day's testing (or two days, in the case of Monday testing, as testing was conducted 6 days per week),
- The drive to the test site (if more than 5 miles), or
- Driving over a prescribed 5.2 mile on-road loop (this was generally performed only for those vehicles that had been standing by for testing more than 48 hours).

Typical Daily Operations for the Test Van (Instrument) Operator – Cold start testing was conducted after an overnight (or 8+ hour) soak outdoors (except for a small number tests with shorter soaks that were excluded from the data analysis as appropriate). All vehicles used "as-received" commercial fuel.

To prepare for each day's testing, the van operator performed the tasks listed below.

- Powered ON all PCs and instruments not powered overnight.

- Opened the rollup door to the test cell and turned ON sample line and equipment heaters.

- Started low-speed dyno warm-up and, just before the first test, ran the automated RealTime "Dyno Warmup." This initiated a series of automated timed coastdowns and checked whether imputed parasitic losses match stored values, offering an option to rerun parasitic loss measurements if required (which was rare).

- Zeroed the DataRAM and DustTrak (these were left on overnight), cleaned and oiled the DustTrak Impactor, and began sampling with both instruments.

- Finalized the test schedule for the day.

- Configured the dynamometer for the test vehicle using the integrated Sierra lookup table and placed the RealTime dynamometer program in "remote mode" (to be controlled by the Horiba program).*

- At start of day when instruments were fully warm (and again at midday and whenever deemed necessary), zeroed and spanned all gas analyzers.

* To minimize tire/roll slip and help avoid overheated brakes, particularly on older pickups with light rear ends and rear drum brakes, the "auto braking assist" option was generally invoked for such vehicles (see RealTime Dynamometer Manual).

- Commanded the Horiba to commence the initial test sequence and reviewed the resulting background concentration measurements,* repeating if necessary.

- Directed the test crew and driver in making final preparations for the test and, when ready, cleared the driver to start the engine.

- Upon receiving the drivers notification of engine start, commenced the test.

Typical Daily Operations for the Test Cell Crew – Outlined below are the typical daily activities of the test cell crew.

- Shortly before a test, the test crew unplugged each vehicle (where applicable) and pushed it in reverse onto the dyno (typically using a pusher vehicle), assisted with vehicle alignment, and secured the vehicle longitudinally and laterally against excessive movement.

- Checked and adjusted tire pressure as appropriate; scrubbed tire friction surfaces to remove ice and snow.†

- Attached heated (custom) flexible transfer tube from the mixing chamber inlet to the exhaust pipe via a silicon rubber boot,‡ and if needed (as it is for all RWD vehicles), attached an additional custom thermostatically heated, insulated stainless steel extension pipe (the flexible tube heater was unplugged when the test started).

- Positioned (but did not yet turn on) the cooling fan and unlatched (but did not yet open) the hood.

- Plugged a CarChip into the vehicle (where approppropriate), or measured the starting engine temperature with IR temperature gun.

- Assisted the driver in positioning the drivers aid cart (with monitor).

- When the Cold ADC drive began (after 5-minute warm-up idle), a crew member opened the hood and turned on the cooling fan; this process was reversed during the 10-minute soak and then repeated for the Hot ADC drive.

Once the test begins, a scrolling representation of the desired speed (or, for test phase 1, commencement of a 5-minute warm-up idle) is graphically displayed on the driver's

* A level of 0-2 ug/m^3 was considered acceptable and was typically measured on the first background sampling attempt.
† This quick step was found in the pilot program to reduce tire-roll slip and increase the accuracy of driving to the target trace.
‡ Bel Air Composites, Spokane, WA.

monitor. The driver operates the throttle and brakes as required to maintain the indicated speed at each second of the test. The host program records the schedule time, the actual and desired vehicle speed, a tally of any speed deviations (as defined in the CFR), the CVS flow, and the analyzer concentrations for each second of a test. The modified program also contemporaneously records results from the continuous PM analyzers and provides control signals to the PM filter sampling bench. In synchronization with the driving schedule, the PM sampling computer software activates solenoid valves that draw sample through the appropriate filter, transmits a set point signal to the flow controller, records the achieved sample flow, and controls and records temperature in the heated filter enclosure.

Six cold start test attempts were made on most days.

Filter Measurements – Particulate measurements on a filter require that an unloaded filter be stabilized in a temperature- and humidity-controlled environment prior to initial weighing, be stored in an environment with very low ambient PM levels before and after use, and be stabilized and reweighed after the filter is exposed during testing. The extremely low levels of filter loading that occur with a modern gasoline-powered vehicle additionally call for an ultra-microgram balance with a resolution of 0.1 microgram. A Sartorius[*] model SE2-F ultra- microgram balance meeting all CFR requirements was used. An AD-1683 static eliminator was used to neutralize static charge prior to weighing. The balance was installed in a custom fabricated glove box enclosure equipped with a HEPA filter and humidifier (see Figures 3-5 and 3-6). A weighted pedestal in the glove box provided a stable base for the balance. Humidity and temperature were continuously monitored during filter stabilization. A humidifier was used to maintain humidity. The balance was connected to a personal computer outside of the glove box enclosure. The balance operator recorded current weighing results and transmitted them to the computer, by a keypress, through the use of custom-programmed software (Winwedge[†]), storing the result in an Excel spreadsheet.

Pall[‡] PTFE Teflon 47 mm filters with a PMP support ring were used for all PM measurements in this program. Using CFR procedures (§ 86.1312–2007), the bottom half of a filter cassette was placed in a Petri dish, a new filter was placed on the cassette, and the Petri cover was used to partially cover the filter as it stabilized inside the glove box environment. Reference filters remained continuously in the glove box, and were measured periodically to monitor gross contamination in the glove box. Observed changes in the reference filters greater than ±0.010 mg would have been cause for rejection of all in process filters, but no such changes were observed over the course of the program. Filters were handled with tweezers grounded to the balance. Filters were allowed to stabilize a minimum of 30 minutes prior to weighing. Filters received a

[*] Sartorius, Goettingen, Germany.
[†] Winwedge, by TAL Technologies, Philadelphia, PA.
[‡] Pall Corp., Ann Arbor, Michigan.

Figure 3-5
Glove Box before Final Assembly

Figure 3-6
Final Glove Box

minimum of three weighings at each point. Additional weighings were performed if the range in weights observed was greater than 0.002–0.003 mg. Outlier readings typically exceeded the remaining readings by 0.010 mg or more, but repeated readings would stabilize to the 0.002–0.003 mg range with added exposure of the filters to the antistatic device.

Following weighing, filters were assembled in cassettes and stored in covered Petri dishes, normally within 0 to 2 hours of use in testing. Shortly prior to testing, the Petri dishes containing the filters were removed from the glove box environment and transported to the test area. The cassettes were installed in the filter holders and the filter cabinet was closed and allowed to return to a stabilized temperature of 117°F before starting the next test. During this process, filters from the previous test were normally replaced into their Petri dishes and returned to the glove box to be allowed to stabilize at least 30 minutes before reweighing.

The Petri dishes were numbered. On the evening before testing, fresh filters were distributed to the available Petri dishes to allow overnight stabilization. At the beginning of the test day, the test schedule and vehicle order would be reviewed. Filter Petri dish numbers were then assigned to the tests for the day. Tests required two filters per test: one for the cold start ADC, and a second for the hot start ADC. The Petri dish numbers for the subsequent tests would be assigned through the end of the test day. The first filter set would be weighed and transported to the test area just before the start of the first test. Weighing would continue during testing, but with careful coordination between the test area and the weighing operation (which was in a part of the same building but far from the test cell). When a test was complete, the filter set would be placed into the weighing schedule, insuring that at a minimum 30 minutes of stabilization would pass before the post-test filter weights were measured. Filter weighings would continue throughout the test day, alternating between pre-test and post-test weighings.

Filter results were transmitted to an Excel spreadsheet. At the start of the day, spaces were pre-assigned on a spreadsheet for each of the Petri dishes. The expected dynamometer test number associated with the individual filters was entered. Slots were then inserted at appropriate times through the day for the post-test weights. As the day progressed, the spreadsheet was rearranged to accommodate changes in the test schedule and served as the primary scheduling tool for the balance operator. As results from the scale include a date/time stamp, all filter soak time intervals were documented. The electronic communication between the scale and the spreadsheet prevented transcription errors. Typical filter weights were around 175 mg, so a single weighing to 0.1 μg would include seven digits, e.g., 175.1234 mg.

Buoyancy corrections of filter weights were performed using CFR methods (40 CFR 86.1312-2007(c)(3)). The corrections considered the barometric pressure, the temperature, and the dew point humidity in the glove box at the time the filter was weighed. The CFR values for PTFE filter density were used, assuming a filter density of 2,300 kg/m^3 and a support ring density of 850 kg/m^3, and an average of 920 kg/m^3 for the filter assembly. The CFR assumed density of 8,000 kg/m^3 for stainless steel calibration weights was applied.

PM mass was computed in accordance with the CFR procedure, as follows:

$$P_{mass} = (V_{mix} + V_{sf})x\left[\frac{P_f}{V_{sf}} - \left(\frac{P_{bf}}{V_{bf}} x\left[1 - (1/DF)\right]\right)\right]$$

where

P_{mass}	Corrected PM mass per test phase
V_{mix}	Volume of dilute exhaust drawn through CFV
V_{sf}	Volume of dilute exhaust removed from bulk stream before CFV that was passed through the sample filter
P_f	Net mass of particulate collected on the sample filter, corrected for buoyancy
P_{bf}	Net mass of particulate collected on the background filter, corrected for buoyancy
V_{bf}	Volume of gas drawn through the background filter
DF	Dilution factor computed from exhaust gas emission results

The first sum is total flow, while the second factor is average particulate per unit flow, corrected for dilution.

The 1 – 1/DF factor corresponds to the use for exhaust gases: 95 to 98% of the total flow is dilution air while the remaining is exhaust gas. The P_{bf}/V_{bf} is the rate of background mass collection per volume of background filter flow. In this application, representative background samples were collected separately from the exhaust gas samples collected during testing.

$PM_{2.5}$ tunnel concentration measurements from the DustTrak were aligned with the second-by-second Horiba data and together used to estimate mass emissions. In cases where DustTrak data were not available, DataRAM measurements were used. The resulting concentrations were averaged over each test phase to compare with filter measurements to derive a scaling factor, which was then applied to the analyzer measurements.

3.2.4 Data Collection

Data collected throughout the test program were logged for later analysis. The automatically logged second-by-second data values included the following:

- CVS flow rate;

- Vehicle (rear roll) speed and cumulative distance;

- Mass emissions and continuous dilute concentrations of total HC, NOx, CO_2, and CO; and

- Concentrations of $PM_{2.5}$ from the two analyzers (contemporaneously logged values used factory calibration; these were subsequently calibrated to filter readings so that the sum of the second by second data equaled the filter mass).

The results provide the ability, for example, to perform binning by VSP power bins for MOVES modeling (described later in this report). Analysis of the effects of vehicle dynamics and graphical representation of second-by-second results require this type of data.

The filter cabinet control software was used to control filter cabinet temperature and the filter flow set-point. The total flow observed through a filter during a particular test phase is required to calculate total mass emissions. The cabinet temperature results are required to document system performance.

A similar program was used to control and monitor the ambient humidity and temperature in the filter weight measurement glove box. These values are required to perform buoyancy corrections of filter weights. The control program ran continuously, with separate files for each day (24-hour period).

An electronic connection was established between the ultra-microgram balance in the temperature- and humidity-controlled glove box and the external PC used to control and monitor temperature and humidity. When the operator pressed the print button on the scale, the current date, time, and weight were transmitted to an Excel spreadsheet. The spreadsheet was used by the operator throughout the day to coordinate filter measurement activities with test cell operations. Filter weight differences were monitored to provide early detection of problems.

To characterize vehicle soaks and testing, ambient temperature measurements were retrieved from the FNSB's records for the Peger Road air quality monitor, which was located approximately 400 feet from the outdoor vehicle soak location. The Borough's air monitor is a Beta Attenuation particulate Monitor (BAM). The BAM is equipped with a Met-One BX-596 AT/BP sensor (-40° to +131°F). The temperature sensor uses a non-aspirated solar shield. To estimate temperatures below the range of the Met-One, measurable Met One temperatures were correlated with those from Fairbanks International Airport, and the Airport temperatures, calibrated to the Met-One, were substituted for the below-range values.

The van equipment operator recorded the following information:

- Test numbers, dates, and times;
- Vehicle numbers and odometers at each test start;
- Background concentrations for all gaseous pollutants and tunnel background $PM_{2.5}$ from both PM analyzers (as backup, since this was recorded automatically prior to each test); and
- Local temperatures, including engine temperature (if coolant temperature was not available by CarChip, e.g., for 1995 and earlier model year vehicles).

3.2.5 CarChip Data

For OBDII-compatible vehicles, CarChip data were collected during the dyno tests. Examination of these data revealed two issues. First, it was noted that in logging second-by-second data, the CarChip occasionally missed a second.[*] This minor problem is very apparent from close inspection of the resulting output files. Second, when CarChip data were compared to dyno test data, the clocks in the two systems were not always consistent. Further investigation showed that while the difference was negligible in the vast majority of cases, and the clock rate *between* trips did not appear to be a problem, the CarChip clock rate *during* a dyno "trip" could vary by as much 1% (worst case) from a valid clock.[†] This is completely separate from the problem of the missing seconds, which, if corrected, could still leave a clock rate discrepancy. Neither of these issues was serious for the purposes of the current study, because they were both minor and were corrected, as described below.

Because it was desired to merge the CarChip coolant temperature measurements (collected every ten seconds) with the other second-by-second dyno test data, it was necessary to develop and apply a procedure to properly adjust and align the CarChip data. This was done using the procedure outlined below (using the example of test number 78).

1. Identify the starting point of the test (Cold ADC or Hot ADC) in CarChip data and Horiba data, and then align CarChip data with Horiba data from the starting point. At the starting point, there is no time misalignment.
2. Identify how many seconds are off when the test is done. This could be positive or negative—if positive, it means the CarChip time scale is longer than Horiba time scale; if negative, the CarChip time scale is shorter than the Horiba's. For example, in the case of test number 78, the CarChip data are off by 5 seconds.

[*] Sierra has discussed this problem with Davis Instruments, who indicated that it is aware of the problem and is working on a solution, possibly by the end of 2011 (personal communication, May 2011).
[†] The Carchip clock also differed from independent clocks in the DataRAM and DustTrak.

3. Calculate the offset ratio by dividing testing time by off time. This ratio indicates the amount of time "slip" occurring each second. For example, the offset ratio is 5 sec/1091 sec = 0.0046

4. Calculate cumulative offsets as test time elapses. For example, the offset at the starting point is zero; the offset after one second is 0.0046; after two seconds, 0.0092; …and 1091 seconds after the starting point, the offset is 5 seconds.

5. Calculate a corrected CarChip time by subtracting cumulative offset values from corresponding Horiba seconds. For example, the corrected CarChip time at Horiba time 30 is 30 – (4*0.0046) = 29.98.

6. Round corrected CarChip time to the seconds digits (e.g., round 29.98 to 30).

7. Delete duplicates or fill in missing seconds: rounding the corrected CarChip time generates duplicate seconds (when the offset has a positive value or CarChip time scale is longer than Horiba time scale) or missing seconds (when the offset has a negative value) periodically, depending on the amount of the offset. When there are duplicates, delete one of the duplicates and replace the remaining value with the average of the values. When there is missing second, fill the data with the average of the preceding and following seconds.

Following the adjustment described above, the CarChip data, including engine coolant temperature (the primary parameter of interest from the OBD port), were merged with Horiba second by second data.

3.3 Tests Completed, Data Collected, and Quality Assurance

3.3.1 Tests Completed

The completed PM test matrix is shown in Table 3-3. All of the listed tests included a soak of at least 8 hours (generally overnight), cold start, 5-minute warm-up idle, Cold ADC, 10-minute soak, and restart with ADC. Each vehicle was tested at least one test with plug-in and twice without, except as noted. As also noted, there were some cases in which additional, unplanned, tests were performed, sometimes because a vehicle was not delivered as expected so duplicate tests were run to avoid wasting already prepared test resources.

Not included in the PM test matrix are those tests that lacked PM data, e.g., due to filter and sample handing problems, but that were otherwise successfully performed and resulted in valid gaseous pollutant data. Also not listed is vehicle 15, which received only one successful hot-start plug-in test.

3.3.2 Data Collected

For each test, ideal data collection included filter weights; second-by-second DataRAM and DustTrak measurements; Horiba-based gaseous pollutant measurements and other related measurements and calculated test results; RealTime Dynamometer test results; the operator's test log; and other secondary information, such as CarChip data (second-by-second data, organized by run—i.e., from key on to key off). However, not all of these data were available for all tests, for reasons that include those listed below.

- Equipment problems related to cold temperature failures and programming problems that were discovered and rectified early in the test program (this resulted in the need for manual alignment of PM analyzer data, and in a few cases, loss of second-by-second PM test results for the first several days of the test program; filter data were unaffected). Other low temperature problems included freezing of the sample pump outlet (a one-time problem) and intermittent failure of the drivers pendant (which resulted in several test aborts or the loss of one test phase before the problem was diagnosed and rectified).

- Driver and equipment operator errors, including filter mishandling accidents (the latter were rare and in all cases resulted in invalidated PM test results).

- Some data being either flagged as qualified or invalidated as a result of quality assurance checks (discussed in the following section).

Table 3-3 Summary of PM Tests Completed				
Vehicle No.	**Plug-in**	**Non-Plug-In***		**Comment**
		Colder	**Warmer**	
1	X	-	-	practice vehicle
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	-	vehicle problems prevented Hot ADC
6	X	X	X	2 plug-in; 2 non-plug-ins at nearly same temp.
7	X	X	-	vehicle not available for final non-plug-in test
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	2 plug-ins at nearly same temperature
12	X	X	X	
13	X	X	X	
14	X	X	X	
16	X	X	X	
17	X	X	X	2 non-plug-ins 9° F apart
18	X	X	X	3 non-plug-ins
19	X	X	X	2 non-plug-ins 5°F apart
20	X	X	X	2 non-plug-ins 7° F apart
21	X	X	X	
22	X	X	X	3 non-plug-ins
23	X	X	X	2 plug-ins 7° F apart
24	X	X	X	
25	X	X	X	
28	X	X	X	
29	X	X	X	
30	X	X	X	
31	X	X	X	
32	X	X	X	
33	X	X	X	
34	X	X	X	
35	X	X	X	
36	X	X	X	

Note: "X" indicates the planned test sequence was completed; "-" indicates it was not, for the reason(s) noted.

* Except as noted, non-plug-in tests were at least 10° F apart in ambient temperature. EPA[15] has determined, from PM testing in Kansas City, that "If the temperature difference is less than 10°F, the test-to-test variability dominates over any temperature effects and the slopes become ill-defined."

3.3.3 Quality Assurance

Particular attention in the study was devoted to data quality assurance prior to, during, and after the dyno testing. Prior to the 2011 main study, both temperature sensors in the Horiba CVS system (for CVS temperature and propane flow) were calibrated to ice water and boiling water. Pressure sensors were calibrated using internal shunt calibrations and were spot-checked against reported airport pressures (adjusted to airport elevation).

Dynamometer roll speed was checked using an Extech* Stroboscope/Tachometer, and found to agree within Strobotach measurement accuracy. Daily dyno warm-ups and (automated) coast-down checks were performed prior to testing. "Warm-ups" were also performed, at the discretion of the system operator, if there were excessive delays between tests.

Before and after each testing campaign in the main study, propane injection tests were performed in triplicate, back-to-back, and yielded recovery errors that averaged 1.6% (range: -2.9 to 5.3%).

All drives were reviewed for accuracy in following the trace (any violations were normally discussed with the driver immediately after the drive): 73% of drives were perfect (no violations), and 90% of drives had 5 seconds or fewer of violations (usually occurring contiguously for one acceleration early in the drive). Typically, if violations occurred they were the result of not being able to manually shift gears timely due to a clutch or manual gear shifting problem, or due to a stall† (typically a vehicle malfunction). The test driver was a very experienced Fairbanks winter driver and dyno driver, and he was knowledgeable about starting and operating Fairbanks vehicles.‡ Nevertheless, driver unfamiliarity with the test vehicle may have been a contributor in some of these cases. Tire/roll slip, which has been an intermittent problem in several previous test programs at low temperature, was substantially absent from this program, which is attributed to scrubbing ice and snow from the tire surfaces prior to each test.

All of the second-by-second PM and gaseous measurements were plotted and inspected manually. This labor-intensive activity was considered necessary both to support the integrated test phase data and to produce sufficiently reliable second-by-second data for subsequent MOVES modal analysis. The data inspection revealed a number of problems with the second-by-second data, some of which required adjustments, realignment, flagging or, in a few cases, invalidation of some of or all of the second-by-second data from a test.

* Extech, Waltham, MA.

† The system and procedures provided for pausing the trace for an engine stall, restarting the engine, bringing the vehicle up to speed, and restarting the trace, and this occurred in a small number of tests.

‡ The test driver was Kelly Shaw, a FNSB employee who was formerly the referee for the Borough's I/M program.

One problem seen with the DataRAM measurements was an occasional one-second data drop during periods when the concentration was high and increasing rapidly. This occurred most often during non-plug-in cold starts of higher-emitting vehicles or during the first big “hill” of the ADC. Interpolated one-second values were substituted for the missing DataRAM measurements. DataRAM, DustTrak, and (to a lesser extent) HC instruments were occasionally “pegged” during these same periods of high concentration. Usually, the period of pegged measurements was less than 15 seconds. The measurements for these seconds could not be removed without introducing further bias. Instead, the pegged data were retained and “flagged” as indicating only a lower bound for the emissions for those seconds and the corresponding test phase.

A number of the test drives included logging of on-board OBDII data—for all of these tests, the OBD-logged data indicated missing seconds or apparent timing errors with the the onboard datalogger. Both were found to be correctable problems for the intended purposes of these data in the current study, as discussed earlier.

3.4 Results – $PM_{2.5}$ and Gaseous Pollutant Emissions from Test Vehicles

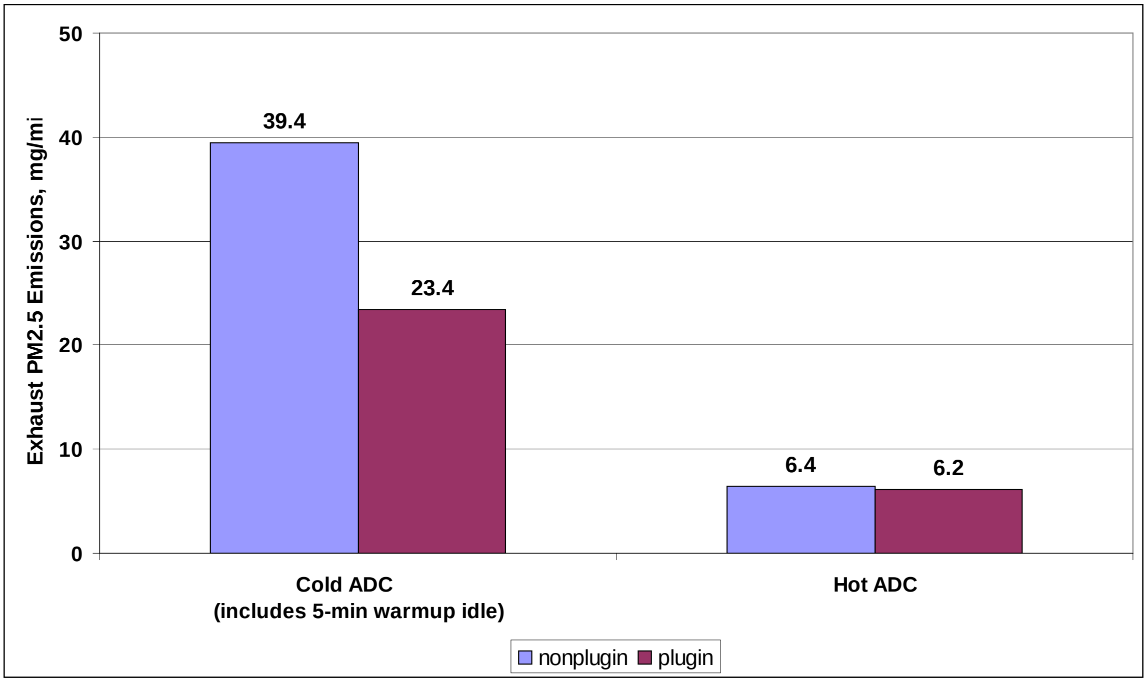
This section presents emissions data from the dyno testing with a primary focus on the $PM_{2.5}$. It begins with an overview of the test results, then describes weightings to correct for vehicle sample imbalance (compared to Kansas City), and then provides a summary of the statistical analyses for PM and gaseous pollutant emissions.

3.4.1 Overview of Vehicle Testing PM Data

Graphical presentations of the vehicle testing data were prepared to understand and display the basic trends in emissions for the Cold and Hot ADC cycles. Figure 3-7 compares the raw* averages of all valid tests (excluding several with soaks less than 8 hrs). In the figure, “Cold ADC” means a cold start, plus 5-minute warm-up idle, plus 816-second Alaska Drive Cycle; and “Hot ADC” means a warm start (after ten minutes of engine off “soak”) plus an ADC (with no idle). The Cold ADC is intended to represent a typical Alaskan cold start, which may have a warm-up idle anywhere from about 2 minutes to 15 minutes) followed by a typical 4.7 mile drive. The Hot ADC generally corresponds to the return trip, or one of many short errand trips that occur throughout the day, with the vehicle starting almost fully warmed up and no need by the driver for warm-up idle.

* Temperature adjustments and sample weightings, which are necessary to compute valid percentage changes for specific cases, are discussed later in this section.

Figure 3-7
$PM_{2.5}$ Emissions for Cold and Hot Alaska Drive Cycles



Note: Raw average for test sample, unweighted and not temperature-corrected.

If this same average vehicle were parked outside overnight in Fairbanks in winter, it may or may not be plugged in, primarily depending upon the ambient temperature (as discussed in the next chapter). Briefly, if the temperature is above about +20°F, plug-in is unlikely, but below about -20°F, plug-in is almost certain (otherwise starting cannot reasonably be assured). At the average daily temperature of -12°F for tentatively selected $PM_{2.5}$ design days for Fairbanks, plug-in is very likely for extended outdoor soaks.

$PM_{2.5}$ emissions from the Cold ADC test fleet are shown (in logarithmic form) in Figures 3-8 and 3-9, without and with plug-in, respectively. Results are unweighted and there is no age-adjustment. Without plug-in, the measurements are reasonably represented by an exponential regression with a temperature coefficient of -0.0244 (r^2=0.1948). The test results with plug-in (which tend, by design, to be at lower ambient temperatures) show no consistent temperature dependence. As discussed later in this section, care should be used in comparing these and other temperature trends with those found in other studies, as a number of factors—such as state of engine warm-up, drive cycle, and range of ambient temperature of the test—may affect the comparisons.

While there was no standard or “typical” vehicle, one vehicle has been selected from the test sample to display a number of common features of the test measurements, including second by second data. Vehicle number 28 is a 2007 Toyota FJ Cruiser, with a 4-liter engine. This vehicle was tested with and without plug-in at ambient temperatures close to the average daily episodic temperature of -12°F, and its emissions are not far from the test sample averages shown earlier. Because it is an OBDII vehicle, coolant temperatures were also logged throughout each test. Table 3-4 summarizes the conditions and results of the three standard tests performed on this vehicle.

All of the modes of operation of Vehicle 28 represented by the test types and ambient temperatures shown in Table 3-4 appear to be plausible when this vehicle is in normal customer service, although at -13°F, as noted earlier, plug-in is more likely than non-plug-in. As shown in the table, emissions with plug-in are significantly lower than without, and the difference is greatest for the lower non-plug-in temperature. Also as expected, $PM_{2.5}$ emissions from the Hot ADC are significantly lower than for the Cold ADC. Plug-in raised the coolant temperature at test start 44°F above ambient temperature (slightly below the average of about 50°F temperature rise, as discussed later in this report). In short, none of these aspects of Vehicle 28 are remarkable, which is the point we wish to make before presenting the second-by-second $PM_{2.5}$ emissions data for the same three tests, which are shown in Figures 3-10 through 3-12, respectively. For ease of comparison, the figures are plotted using the same scale.

Table 3-4 Emission Test PM Summary for Vehicle 28, 2007 Toyota FJ Cruiser				
Test Type	**Ambient Temp. (°F)**	**Starting Coolant Temp. (°F)**	**Cold ADC $PM_{2.5}$ (mg/mi)**	**Hot ADC $PM_{2.5}$ (mg/mi)**
Plug-in	-1	43	13	3
Non-plug-in (cold)	-13	-9	52	7
Non-plug-in(warm)	12	14	22	9

Figure 3-8
$PM_{2.5}$ Emissions vs. Ambient Temperature,Tests Without Plug-in (n=62)
Cold Start + 5-min Warm-Up Idle + ADC (unweighted) with Exponential Trendline

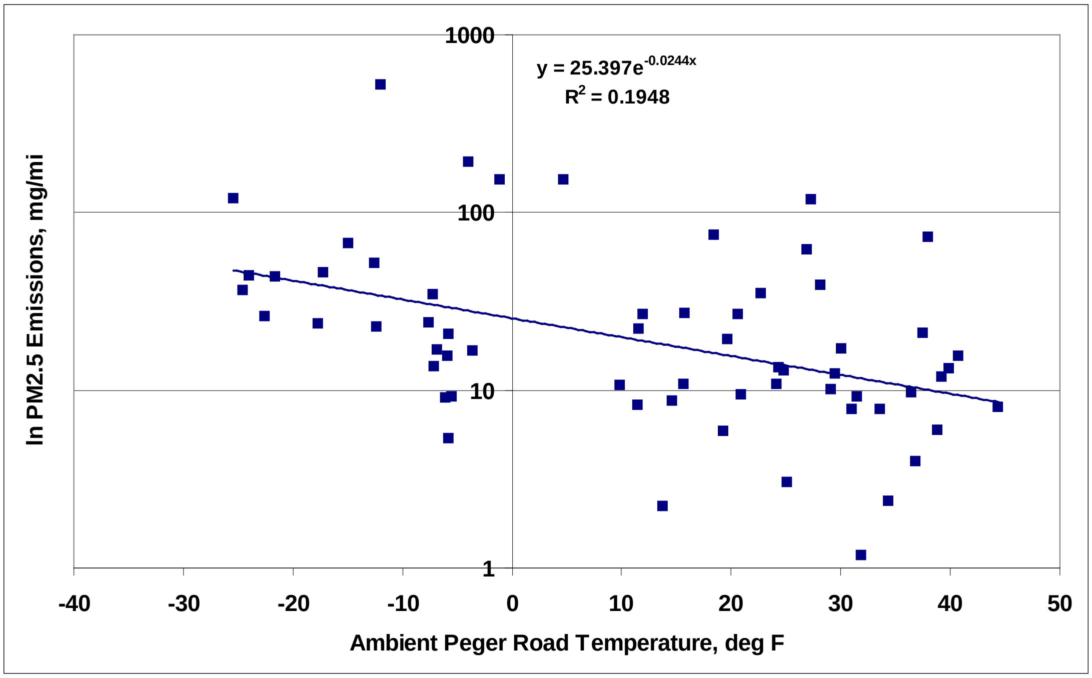
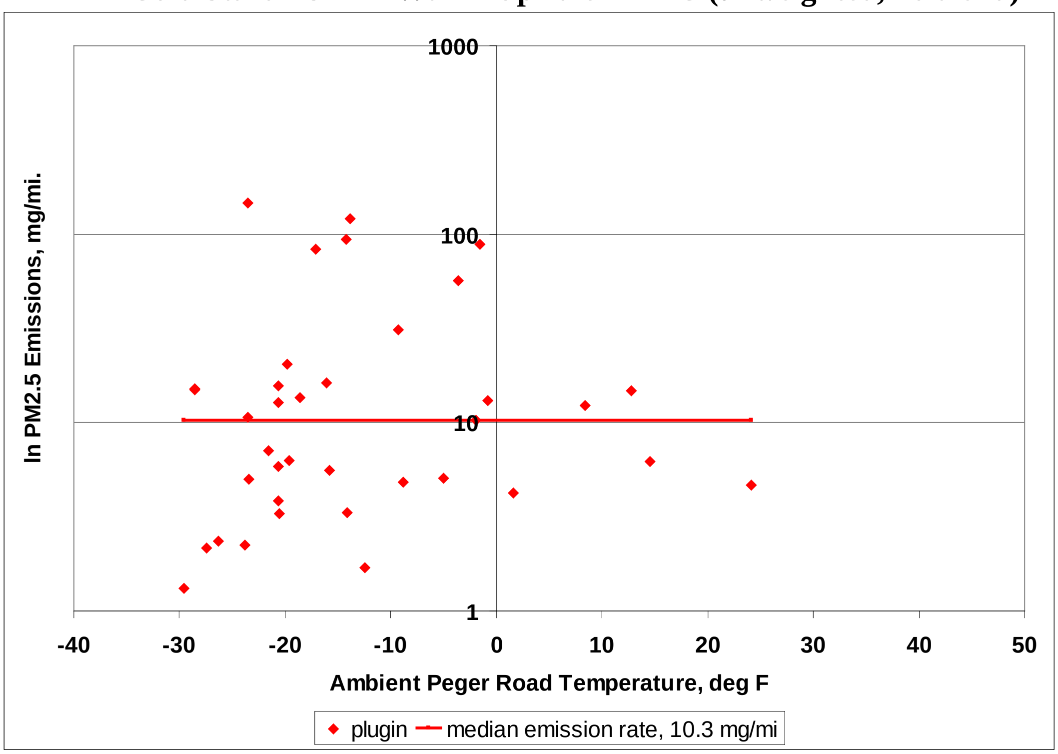


Figure 3-9
$PM_{2.5}$ Emissions vs. Ambient Temperature for Tests with Plug-in (n=37)
Cold Start + 5-min Warm-Up Idle + ADC (unweighted, no trend)



Notable features of the second-by-second $PM_{2.5}$ emissions measurements (for this vehicle and for other vehicles whose test results have been spot-checked) are outlined below.

- For non-plug-in Cold ADC tests, most of the $PM_{2.5}$ emissions occur in the first two minutes, presumably prior to catalyst light-off (note the steep early rise in the green line, representing cumulative $PM_{2.5}$ emissions); cold engine starts with plug-in and warm engine starts for the Hot ADC have much lower emissions than cold engine starts without plug-in.

- Emissions are characterized by spikes that tend to occur during the highest power accelerations (usually accelerations to high speed), although the example shows at least one instance of an unexplained spike (end of test 65).

- Compared to the above two types of events, emissions at most other times are much less for most vehicles, regardless of temperature.

- The rate of coolant warm-up is high immediately after the start, declines during the 5-minute idle, and increases again when driving commences. The coolant temperature stabilizes about 10 minutes after the start of test and decreases only slightly during the 10-minute soak.

Figure 3-10
Test No. 56, Toyota FJ Cruiser (4l.), Plug-in, Ambient Temperature -1°F
Cold ADC 13 mg/mi., Hot ADC 3 mg/mi.

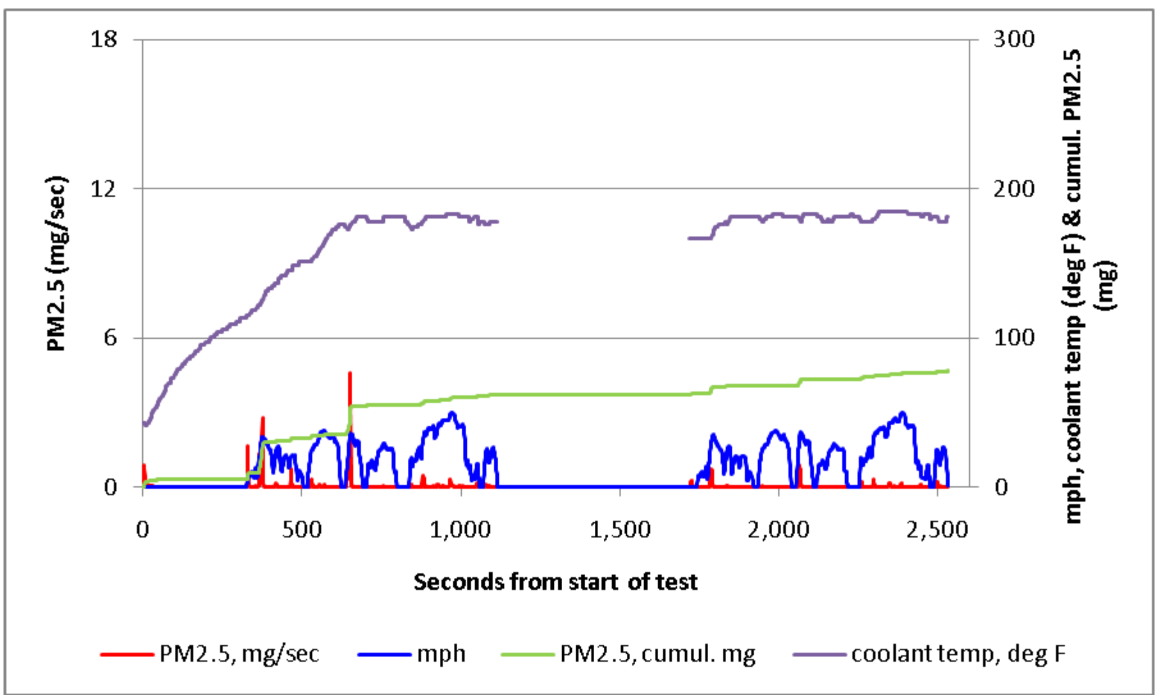


Figure 3-11
Test No. 65, Toyota FJ Cruiser (4 l.) Non-Plug-in, Ambient Temperature -13°F, Cold ADC 52 mg/mi., Hot ADC 7 mg/mi.

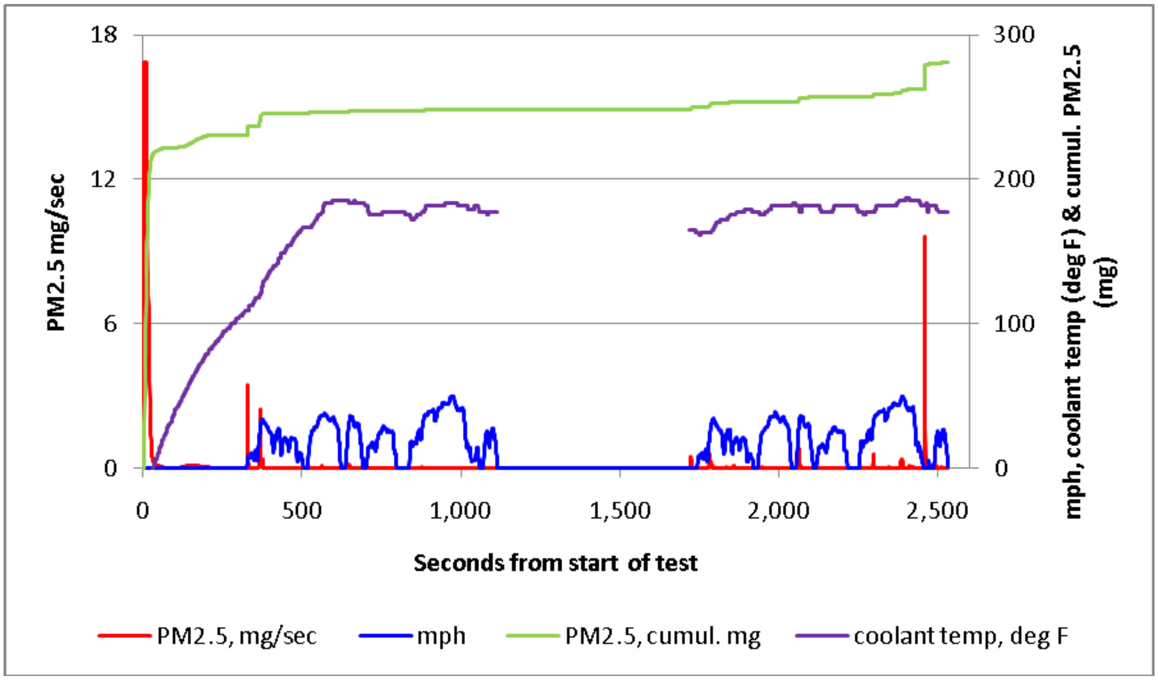
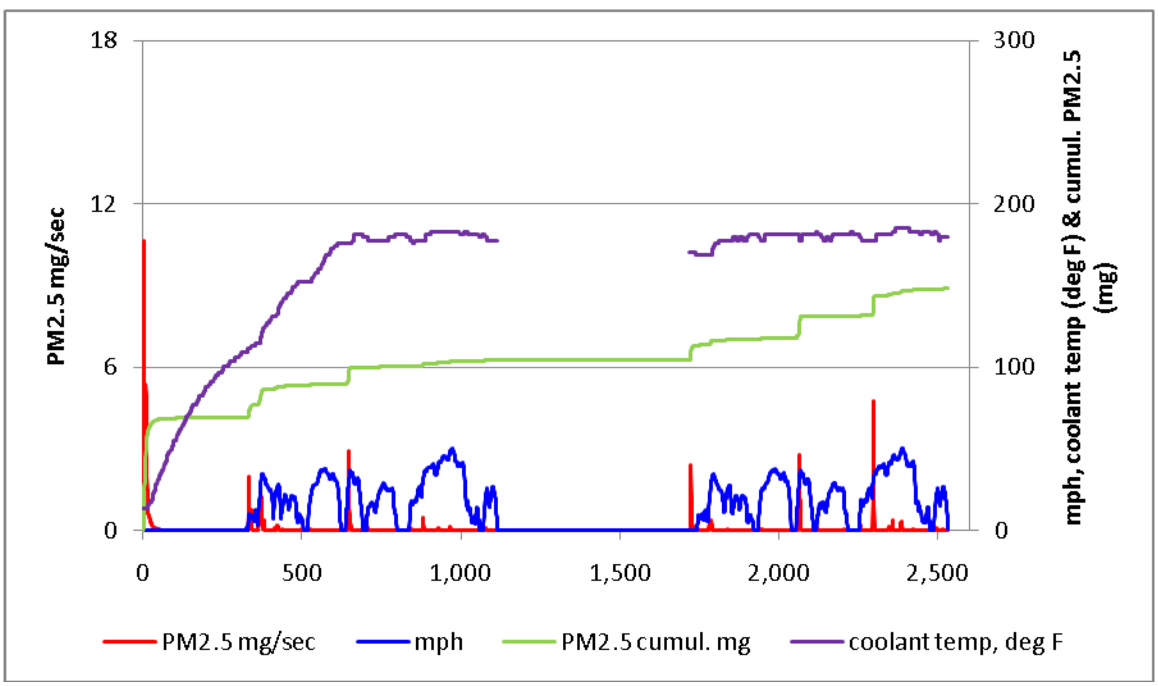


Figure 3-12
Test No. 72, Toyota FJ Cruiser (4 l.), Non-Plug-in, Ambient Temperature 12°F, Cold ADC 22 mg/mi., Hot ADC 9 mg/mi.



Data of this type are available for most of the tests, although not always including coolant temperatures (OBDII-based) and not necessarily showing the same features in every case.

3.4.2 Weighting Factors

The next step was to conduct a statistical analysis of the data by test phase by first developing weighting factors to account for the limitations of the vehicle sample and then applying them in weighted regression analyses. Vehicles were recruited to the DEC testing program to give a representative sample of the Fairbanks fleet that, except for the unavoidable under- and over-sampling of some groups, would be proportionate to the vehicle types (passenger car and light truck) and model years (age) on the road. The Fairbanks fleet is known to differ from the fleet tested in the Kansas City study in the following ways:[*]

- It has a larger proportion of light trucks in comparison to passenger cars; and
- It will have a generally newer mix of model years in the test fleet due to the lapse of time since the Kansas City study was conducted.

To facilitate direct comparisons between the results seen in the Fairbanks testing and those of the Kansas City study, the Fairbanks data have been weighted to better match the vehicle type and model year distributions of vehicles tested in the Kansas City study. As shown in Table 3-5, vehicles were organized into cells based on vehicle type and the model year groups used in the MOVES model for emission factor characterization. The same weighting factors were used for both the Cold and Hot ADC tests because the two samples contained equal numbers of tests. As seen in the table, the weighting factors control primarily for differences in the vehicle type distribution between the studies, with the cars tested in the Fairbanks program being weighted by a factor of 2.0 and the trucks weighted by a factor of 0.5 to match the Kansas City vehicle type distribution. The weighting factors by model year group are nearly unity.

Use of these weighting factors in analyzing the Fairbanks test data will reduce biases that could be introduced by the differing distributions of test vehicles in the two studies. Note, however, that the weightings are imperfect—the Fairbanks vehicle sample did not contain pre-1981 vehicles, which constituted 10% of the Kansas city sample, and the Fairbanks sample for the MY 1996 and later group contains late model year vehicles that were not on the road at the time of the Kansas City study.[†] These differences

[*] It is also possible there is a residual effect of the Inspection and Maintenance (I/M) program in Fairbanks, which was an idle-only testing program for CO that was terminated in December 2009. Kansas City has no I/M program. CO is known to correlate with PM, and it is possible that CO emission control measures from the defunct I/M program would residually benefit PM reduction as well; however, no attempt was made to estimate or adjust for such an effect.

[†] Federal low temperature CO emission standards were phased in between model years 1994-1996. Thus, Fairbanks testing likely contained more low temperature certified vehicles than Kansas City. The effect of

notwithstanding, the empirical effect of different weightings is relatively small (about 15% difference in emissions sensitivity to temperature when comparing results weighted to the Kansas City and Fairbanks fleets), so that imperfections in the weighting should not undermine the comparison of the Fairbanks test results to those from the Kansas City study.

Table 3-5
Weighting of the Fairbanks Sample to Better Match the Kansas City Sample

MOVES MY Groups	Kansas City Sample[a]			Cold and Hot ADC					
				Fairbanks Vehicle Tests			Weighting Factors		
	PCs	Trucks	Total	PCs	Trucks	Total	PCs	Trucks	Total
pre-1981	3	1	4	0	0	0	—	—	—
1981-1990	4	4	8	5	16	21	1.9	0.6	0.9
1991-1995	7	2	9	9	12	21	1.9	0.4	1.0
1996+	12	9	21	17	42	59	1.7	0.5	0.9
Fleet	26	16	42	31	70	101	2.0	0.5	1.0

[a] These represent only the KC vehicles that were sampled in summer and winter and used by EPA to derive estimate temperature slopes.

3.4.3 Statistical Analysis of Cold and Hot ADC $PM_{2.5}$ Emissions

The Cold and Hot ADC test cycles represent complete trips of 4.74 miles in length beginning from a cold start (after overnight soak) and from a hot start (after a 10-minute hot soak). The driving traces are identical, but the cold start cycle begins with a 5-minute warm-up idle before the vehicle begins to follow the trace. The driving cycle represents distinctive features of winter-time trips in Fairbanks compared to the Lower 48 states, including less-aggressive accelerations on frozen roads and shorter average trip lengths.

The testing was designed to evaluate the effect on emissions of $PM_{2.5}$ and gaseous pollutants of ambient temperatures below +20°F and the effect of using supplemental engine block heaters during cold soaks ("plug-in"). The use of engine block heaters in the testing represents one of a variety of strategies employed in the Fairbanks vehicle fleet to facilitate cold-temperature operation. Other measures include heated garages, unheated garages, and use of extended idle with or without auto-start devices. Use of supplemental heaters also varies by temperature, with survey results suggesting that

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this emission standard change upon PM or other pollutant emissions is unknown and beyond the scope of the current study.

supplemental heating becomes increasingly common at temperatures below +20°F and becomes widespread at temperatures below -20°F (see Section 4 for additional details). In the 2011 test program, most of the plug-in testing of vehicles was conducted in the January testing period and most of the non-plug-in testing was conducted in March, when temperatures tended to be much warmer.

The emissions data used in the analysis had been pre-screened for deviations from the test protocol and tests deemed to be invalid were removed from the dataset. Tests were excluded when the cold soak before the Cold ADC cycle was less than eight hours. Formal tests were also conducted after the statistical analysis to identify the presence of outliers (i.e., valid tests that deviate implausibly from the other data), although in the end no outliers were identified.

The emissions data collected in the Fairbanks test program contains four primary sources of variation, as summarized below.

- Each vehicle will have its own, individual level of $PM_{2.5}$ emissions as determined by its type, design, condition, and age.* Emissions can differ significantly across vehicles (all other factors held constant) and this factor is the largest single source of emissions variation in the data.

- $PM_{2.5}$ emissions are expected to vary systematically in response to ambient temperature, particularly following an overnight soak, with emissions increasing on average as the soak temperature falls.

- $PM_{2.5}$ emissions are expected to vary systematically in response to plug-in, particularly following an overnight soak, with emissions decreasing on average when plug-in is used.

- Various sources of non-systematic error will affect the measured emissions values, also known as measurement variability.

Other forms of systematic variability could be present in the data (such as variation in the temperature sensitivity between cars and light trucks) and were tested for in the analysis.

A multiple linear regression model was structured as follows to represent the known sources of emissions variability:

$$\mathrm{Ln}(\ E_{i,j}\ ) = A_i + B * \mathrm{AmbTemp}_j + C * \mathrm{dPlug\text{-}In}_j \qquad \text{(Eq. 1)}$$

where:

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* As-received odometer values were recorded, but because of uncertainty about possible odometer rollover for older vehicles and the limited scope of the current study, there was no attempt to evaluate emissions based on odometer readings.

$E_{i,j}$ = emissions of vehicle i on its j^th test
A_i = an intercept term for the i^th vehicle representing its individual emission level
B = the temperature slope of emissions with respect to ambient temperature; (this temperature was measured as the ambient air temperature at the test facility immediately preceding the start of the Cold ADC test)
C = the emissions effect associated with use of engine block heaters during the cold-soak preceding the test.

This model form assumes that the temperature slope B can be represented in the form of a constant percent change per degree F temperature change and the emissions effect of plug-in can be represented as a constant percent change independent of ambient temperature. These assumptions were tested and validated during the analysis. This model can be implemented in multilinear regression using N-1 dummy variables to represent the intercept terms for the test vehicles. Here, the models were estimated using the SAS GLM procedure, using an option in which vehicle-specific differences are "absorbed" so that the analysis is not influenced by the differing overall emission levels of the vehicles. Use of the ABSORB option is equivalent to estimating separate intercepts for each vehicle, but only terms for the coefficients B and C need be coded. When absorption is used, the R^2 statistic for the regression includes the sum-of-square reduction from removing vehicle-specific effects in addition to the contributions from the temperature and plug-in terms. Weighted linear regression was performed using SAS Proc GLM and the weighting factors developed above to re-weight the sample to the vehicle distribution in the Kansas City sample.

Intercept terms are not calculated by the regression, but can be recovered by using the estimated regression model to adjust each data point to a standardized temperature (+20°F in this case*) and test state without plug-in. The fleet-wide intercept is computed as the (weighted) average emissions value at +20°F without plug-in. Intercepts by model year group can be similarly defined. The weighting factors developed above to reweight to the Kansas City sample were used in the univariate statistics as well.

Table 3-6 summarizes the results of the weighted multilinear regression analysis for the Cold and Hot ADC cycles. For the Cold ADC, $PM_{2.5}$ emissions are estimated to increase by 26.2% for every 10°F drop in ambient temperature below +20°F. The use of engine block heaters is estimated to decrease $PM_{2.5}$ emissions by a constant 70% independent of ambient temperature. These results are remarkable close to the estimates developed from pilot testing of 4 vehicles during the winter 2009-10 pilot study, which estimated an emissions increase of 30% for every 10°F drop in ambient temperature and an emissions reduction of 74% from plug-in (see Volume 2).

* This reference temperature was chosen for several reasons. It is close to the lower limit of KC testing and the upper limit for Fairbanks testing. It is also, as described in Section 4, the temperature above which there is almost no plugin and below which plugin use begins to phase in. Finally, it is close to the upper limit of temperatures for all Fairbanks design day episodes.

The Hot ADC cycle is run after conclusion of the Cold ADC cycle, following a 10-minute hot soak interval. $PM_{2.5}$ emissions on the Hot ADC cycle were found to not be sensitive to the ambient temperature preceding the Cold ADC test or to the use of plug-in during the preceding cold soak. The coefficients B and C as estimated by the regression failed to approach any acceptable level of statistical significance and are reported as zero in the table. This finding strongly suggests that the vehicle is fully warmed at the conclusion of the Cold ADC cycle,* so that emissions during the subsequent Hot ADC cycle would be affected by temperature only to the minor extent associated with the temperature of the intake air charge. This effect cannot be detected in the test sample.

A variety of alternative model formulations were tested and rejected during the analysis, as described below.

- Tests were made to determine if the temperature sensitivity or the plug-in effect varied by between cars and light trucks. Such differences were small and not statistically significant on either the Cold or Hot ADC cycles.

- Tests were made of the hypothesis that the temperature slope was not constant, but varied with ambient temperature (over the range sampled). No evidence for such differences was found.

- Tests were made of the hypothesis that the plug-in effect was not constant, but varied with ambient temperature. A statistically significant model was developed in which the percentage change in emissions due to plug-in increases at colder ambient temperatures. This model, however, changes the basic temperature slope of emissions to a value that is inconsistent with that seen in the subset of tests that did not use plug-in, and was therefore rejected.

* This is consistent with the sample coolant temperature data shown previously for the 4 liter engine Ford FJ, which showed coolant temperature stabilization about ten minutes after engine start.

Table 3-6 PM2.5 Emission Factors for Cold and Hot ADC Tests $\ln(E_{i,j}) = A_i + B * AmbTemp_j + C * dPlug\text{-}In_j$			
Regression Statistics (Cold ADC Cycle) N = 100 R^2 = 0.76 (0.61 due to vehicle-specific emissions differences) Weighted to Kansas City vehicle distributions			
Cold ADC Emissions	**Units**	**Coefficient (Std Error)**	**Computation of Percentage Emissions Effect dE**
Base Emissions at +20°F	mg/mi	27.5 (4.0)	
Temperature Coefficient B	decimal	-0.0233 (0.0047)	dE = exp(-0.0233 · AmbTemp) - 1
Plug-In Coefficient C	decimal	-1.23 (0.12)	dE = exp(-1.23 · dPlug-In) - 1
Regression Statistics (Hot ADC Cycle) N = 100 R^2 = 0.63 (0.63 due to vehicle-specific emissions differences) Weighted to Kansas City vehicle distributions			
Hot ADC Emissions			
Base Emissions at +20°F	mg/mi	8.0 (1.1)	
Temperature Coefficient B	decimal	Zero	None
Plug-In Coefficient C	decimal	Zero	None

The last of these findings suggests that additional understanding of the emissions effect of plug-in could be obtained through further analysis of the ADC data. Supplemental engine block heaters do not all work in the same manner: some will raise the engine coolant temperature to a greater extent than others, and some are thermostatically controlled to provide supplemental heat only below a threshold temperature. Plug-in is not a discrete state, but one better measured by the actual rise in engine coolant temperature above ambient. If warranted by future needs, the emission factor analysis presented here could be made more sophisticated by basing the emission factor model on the engine coolant temperature (not the ambient temperature) and conducting an analysis of the extent to which engine coolant temperatures are raised above ambient in the Fairbanks fleet due to the various forms of supplemental engine heating. Such a model would not require explicit information about plug-in vs. non-plug-in (which is reflected implicitly in coolant temperature measurements) and could potentially be used with coolant temperature data, available from relatively inexpensive data logger surveys, to quantitatively estimate emissions potential for in-use vehicle. This idea is explored conceptually in Section 4.

3.4.4 Comparison of PM Emission Measurements from Fairbanks and Kansas City

Table 3-7 compares the current study results to those from EPA's 2004-2005 study of PM emissions from light-duty gasoline vehicles in Kansas City, which was used to develop PM emission factors for MOVES, including the form and slope for PM emission temperature dependency. Since the ADC was not bagged, i.e., not broken out into separate phases like the LA92 cycle in Kansas City, the latter bag data are used to construct cold- and hot-start ADC "trips."

Comparing the Fairbanks test results for temperature coefficient on the right side of Table 3-7 (-0.0233 and 0.0000, respectively, for cold and hot start ADCs) with the corresponding values constructed using the Kansas City data on the left side, there appears to be much less temperature sensitivity in the Fairbanks data. But this is due to the fact that the definition of Bag 1 for the Kansas City Study (first 310 seconds of the LA92 drive cycle) did not in every case[24] include sufficient time or activity to fully warm up the vehicle—as a result, vehicle warm-up and temperature sensitivity carried over into the second bag, which is described in various EPA reports as a "stabilized" or "hot running" Phase 2.

A recent CRC study[25] pointed out that FTP Bag 2 (which follows a 505-second long bag 1) does not appear to be temperature sensitive (MSAT data). It is recommended that EPA examine the modal data to take the temperature-sensitive start emissions out of KC Bag 2 and put them into KC Bag 1 for purposes of PM temperature correction factors.[*]

[*] The same CRC Study concluded (p. 155) that "For some vehicles, high PM during the cold start appeared to extend into bag 2. At the time of this report, this PM was being counted as part of the hot running PM emissions, although including it in the cold start portion of the PM was being considered." It went on to note (p. 163) that "It is likely that the reason for the Bag 2 temperature effects in Kansas City are due to the shorter Bag 1 of the LA-92 used in Kansas City combined with the fact that the LA92 Bag 1 driving cycle isles aggressive than that of the FTP. Thus the LA-92 Bag 1 test could have resulted in some start effects carrying over into running operation."

Table 3-7
Comparing the Fairbanks Dyno Test Results to Kansas City

	Kansas City Testing (2004-05)			Fairbanks Testing (2011)		
	Drive Cycle	**Engine Temperature**	**Temperature Coefficient**	**Drive Cycle**	**Engine Temperature**	**Temperature Coefficient[a]**
Cold Start Trip						
Bag 1	LA92 Bag 1 (1.18 mi)	Fully cold at start Partially warm at end	-0.0456 (Fig 28, actually Bag 1-3)	Cold ADC (4.74 mi)	Fully cold at start Fully warm at end	-0.0233
Bag 2	LA92 Bag 2 (8.63 mi)	Partially warm at start Fully warm at end	-0.0183 (Fig 29)			
Total Trip	9.81 mi	See text for calculation	-0.038 (constructed)			
	4.74 mi	See text for calculation	-0.042 (constructed)			
Hot Start Trip						
Bag 3	LA92 Bag 1 (1.18 mi)	Fully warm at start Fully warm at end	None (assumed; no analysis reported)	Hot ADC (4.74 mi)	Fully warm at start Fully warm at end	-0.0000 (none)
Bag 4[b]	LA92 Bag 2 (8.63 mi)	Fully warm at start Fully warm at end	None (assumed)			
Total Trip	9.81 mi		None (assumed)			
	4.74 mi		None (assumed)			

[a] Test fleet weighted to match model year distribution in Kansas City study. Pre-1981 vehicles were not testing in Fairbanks program. The 1996 and later model year group in the Fairbanks program contains late model year vehicles (through 2010) that were not on the road at the time of the Kansas City Study.
[b] Hypothetical test phase used to complete the comparison of the Kansas City testing to the Hot ADC cycle.

The temperature correction factors for $PM_{2.5}$ currently in MOVES are shown in Table 3-8, which is adapted from the EPA's Kansas City PM report.[15] The Cold Start slope (-0.0463) shown in Table 3-8 is very close to the value (-0.0456) for Kansas City Bag 1-3 shown in the same report (Figure 28, p. 43). However, the Running emissions value (-0.0318) is much larger than the -0.0183 value that the Kansas City study showed for LA92 UC Bag 2 (Figure 29, p. 44). This value would logically be zero if it applied to hot, i.e., already warmed-up, running emissions.

Table 3-8
"Cold Start and Hot Running Slopes with Temperature" for PM

Process	Slope*	N
Cold Start	-0.0463	32
Hot Running	-0.0318	41

Note: Adapted from Table 12 in Nam et al, p. 46.[15]

It is difficult to predict what the slope for cold-start emissions would be if EPA were to re-bag the KC data to put all of the temperature-sensitive start emissions into Bag 1—it would account for more grams of incremental emissions, but over a longer mileage, and the coefficient might not be much different than what is there.

How to Construct the Kansas City Temperature Sensitivity for the Cold Start Trip – This computation uses the regression lines shown in Figures 28 and 29 of the Kansas City PM report to construct a Cold Start trip that can be compared to the Fairbanks Cold ADC testing (where a complete drive of 4.74 miles is tested in one bag). The calculation is a weighting of a cold start increment (from Fig 28, Bag 1-3) and a (partially warm) running emissions value (from Fig 29, Bag 2). However, both figures must be interpreted as showing the logarithm of PM emissions in grams/mi (not milligrams) in order for the reported regression lines to give PM emissions on a scale that is plausible and consistent with other information in the report (10s to 100s of mg/mi). When temperature sensitivity is calculated by fitting a curve to the predicted emissions at the various temperatures, the Kansas City study shows a temperature sensitivity of -0.038 for a cold-start trip of 9.81 mi (the LA92 drive) and -0.042 for a cold-start trip of 4.74 mi (the ADC drive). Both values exceed the temperature sensitivity (-0.0233) determined for the Cold ADC cycle (Fairbanks test data are weighted to the Kansas City fleet). (Because the Kansas City report does not present any information on the sensitivity of the Bag 3 data to temperature, it is assumed the study did not see such an effect.)

When making this comparison, it is worth recalling that the ADC and LA92 cycles are different—the ADC is more moderate and has a lower top speed, and the Cold ADC is preceded by a typical 5-

* In each case, the intercept corresponding to the slope is 1.

minute warm-up idle. Regarding the PM emissions effect of such extended initial idle or more moderate driving, Mulawa[14] noted the following:

> *…if most drivers extend the initial idle time or operate at low load initially under cold weather conditions…such modified operation would produce a less severe temperature effect. The trend in NOx emission rates…is not as consistent.*

We concur with Mulawa's assessment, but have not attempted to evaluate for the difference explicitly.

Temperature Sensitivity of Composite PM Emissions – Figures 12 and 13 in the Kansas City report (pg 32) plot "composite" emissions versus temperature. Although not specified in the report, it is assumed that the calculation uses the usual 43/57 split of cold- and hot-starts and then weights the bags according to mileage.* Bag 2 is double-weighted under the assumption it measures hot running emissions equally well for the cold- and hot-start trips. This is not true, however, since Bag 4 (running emissions for a hot-start trip) would be expected to have no temperature sensitivity at all. Given the weighting, 43% of the composite value is treated—for reasons that are not clear—as having the temperature sensitivity observed in the Bag 2 data from the Kansas City study. This assumption and its consequences have carried over from the analysis of Kansas City data into MOVES.

Weighted average emissions were computed by taking the 43/57 weight of predicted trip emissions, then determining what the aggregate temperature sensitivity should be. Table 3-9 shows that the weighting of composite emissions for Kansas City test results in Figures 12-13 of EPA's Kansas City report increases the apparent temperature sensitivity of a composite trip. However, PM emissions from the cold trip dominate composite emissions, so the differences are not as large as they might be. The proper comparison is a Kansas City 4.74 mi trip to ADC 4.74 mi trip on any consistent basis (Cold, Hot, or composite). The ADC data show lower temperature sensitivity below +20°F by a factor of nearly two.

Table 3-9
Estimates of Temperature Sensitivity Coefficients

	Cold Start Trip	Hot Start Trip	Composite Trip
KC Figs 12-13, 9.81 mi Trip	n/a	n/a	-0.0385
KC Data 9.81 mi Trip	-0.038	0.000	-0.033
KC Data 4.74 mi Trip	-0.042	0.000	-0.038
ADC Data 4.74 mi Trip	-0.0233	0.000	-0.026

* It is perhaps also worth noting that the ORD study results shown in both figures are not "composite" FTP results in the usual sense of weighted bags. Rather, these tests were done by exposing a single filter for all three test phases, i.e., each test results in one integrated filter sample, which is sometimes referred to as a "composite filter."

It is instructive to include MOVES results in this comparison. To do this, emission factors were extracted for the average trip mix simulated in a series of discrete temperature runs for Fairbanks in January 2008, and these were used to determine the implied temperature sensitivity below +20°F. That value is -0.040, which is higher than the above-described composite value that was reported for Kansas City testing in Figures 12-13 of the Kansas City report. More information on this diagnostic MOVES run for Fairbanks and implications for the Fairbanks emissions inventory are presented in Section 5.

<u>Reasons for the Differing Temperature Sensitivity of PM Emissions in Fairbanks and Kansas City Studies</u> – Although the cause of the differing temperature sensitivity of the two studies is unknown, there are several possible causal or contributing factors. Some of these were noted above; others are discussed below.

1. Mulawa et al[14] have suggested that "new vehicles built to comply with the low-temperature CO standards may produce less PM emissions." It is possible that technological improvements have made $PM_{2.5}$ emissions from newer vehicles not only lower, but also less sensitive to temperature. This could occur both as a result of more stringent emission standards in general and the cold-temp/high-altitude certification standards in particular. Close-coupled rapid light-off catalysts, heated oxygen sensors, and other newer technologies[*] that have been developed to comply with lower emission limits may have the side benefit of greater PM control and less temperature sensitivity as a result of more rapid onset of both catalyst light-off and closed loop fuel control. Although the Fairbanks data were weighted to be comparable to Kansas City, it is still true that the Fairbanks sample is newer than the Kansas City sample, and more of the Fairbanks vehicles were subject to the cold-temperature CO emission standard.

2. It is possible that the formative process of PM or the destructive process of catalytic PM removal reaches a saturation point at a cold enough temperature. A simple conceptual view would be that ambient temperature controls the fraction X of the fuel charge that is vaporized during the initial moments of the cold start and it also controls the length of time L until the engine is fully warm, stabilized, and no longer sensitive to temperature. The observed emissions change is a composite of how temperature affects X and L. At some cold-enough temperature, X will be zero (or some small limiting value) and any additional drop in temperature will not decrease X further. At that point, the temperature sensitivity that will remain is determined only by L. A lower total temperature sensitivity will be seen because the formative process has hit a saturation point.

3. Contributing to this is the possibility, noted earlier, that the less-aggressive ADC cycle with its initial 5-minute idle results in reduced vehicle sensitivity to ambient temperature.

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[*] The primary statistical approach used herein relied upon SAS "absorption" of individual vehicle effects. However, alternative statistical models of PM emissions that treated model year (or age based on model year) as an independent variable typically showed it to be a significant factor in explaining Cold ADC PM emissions. One such four-parameter model used model, plug-in status, ambient temperature, and vehicle type (car vs. truck), and produced an r^2 value of 0.51, with all estimated coefficients significantly different from zero and MY slope of -0.101, which roughly matched the MY slope of the aforementioned Fairbanks MOVES output.

3.4.5 Analysis of Gaseous Pollutant Emissions and Comparison with Kansas City

The Fairbanks dynamometer testing results for HC, CO, NOx, and CO_2* showed no significant temperature effects for running emissions, but did show temperature-dependent emissions increases for "start increment" emissions. Presented below are a series of figures depicting the temperature dependency of Fairbanks "start increment" and "running" emissions as compared with the several corresponding figures reported by EPA from its Kansas City study. Emissions are in mg/mi and shown on a logarithm scale with no adjustment for age or model year and no weighting of the included temperature trend lines. These are then followed by a more detailed statistical analysis and comparison.

Figure 3-13 shows start increment HC emissions from Fairbanks, calculated as bag 1 (Cold ADC) minus bag 2 (Hot ADC adjusted), where bag 2 has been adjusted by the addition of emissions from 300 seconds of warmed idle† for each vehicle (to provide a comparable cycle to the Cold ADC cycle, which has 300 seconds of warm-up idle). Only non-plug-in tests are shown. Figure 3-14 shows the roughly corresponding Bag 1 – Bag 3 from Kansas City. Although the temperature scales and many other factors differ, a similar temperature slope is observed for the HC start increment.

Figure 3-15 shows Hot ADC HC emissions from Fairbanks (not adjusted by idle), followed by the roughly corresponding bag 2 running HC emissions from Kansas City in Figure 3-16. Both trends are flat. Figures 3-17 and 3-18, respectively, show start increment and flat running CO emissions for Fairbanks for the same tests. NOx emissions are also available but not shown here.

* Dyno testing results and statistical analysis for CO_2 are shown here only for completeness. They are not discussed further in this report.

† The addition, as expected, is very small for warmed up idling. It was on the order of 1% for PM.

Figure 3-13
Fairbanks Ln HC Start Increment vs. Ambient Temperature
(unweighted; no age-adjustment; n=60)

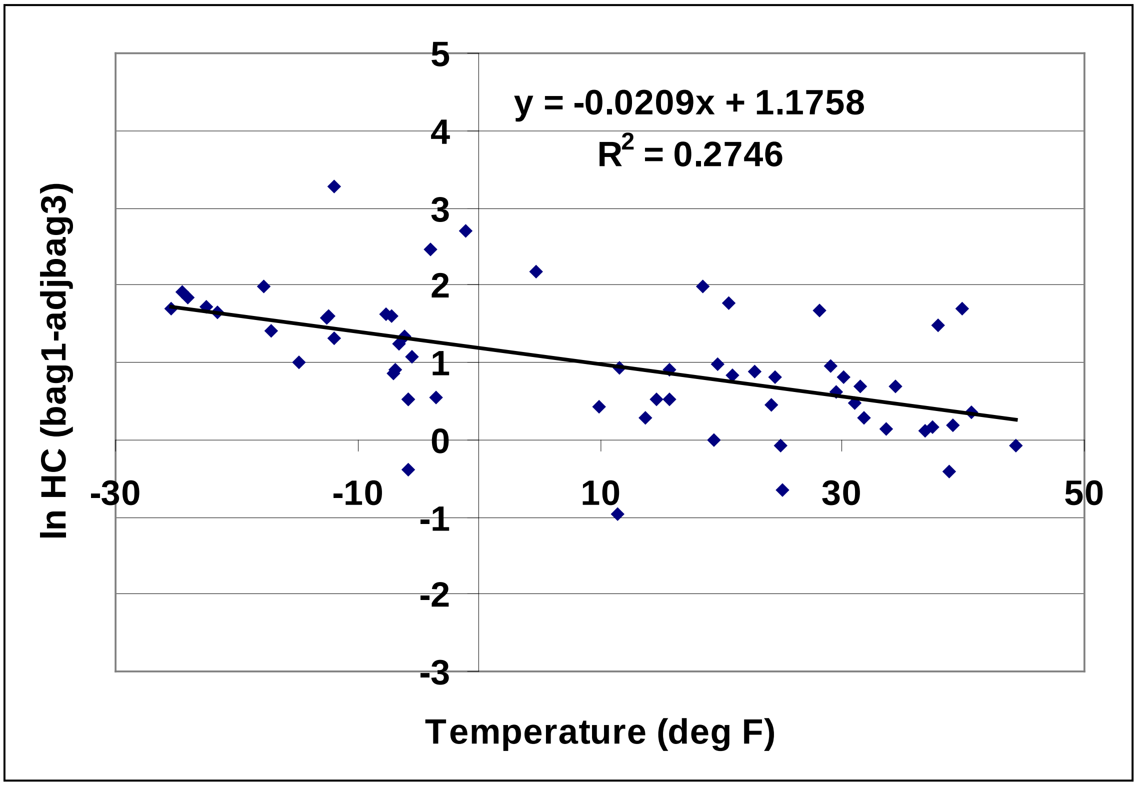


Figure 3-14 (EPA KC PM report Fig 30)
Cold Start HC Emissions as a Function of Temperature

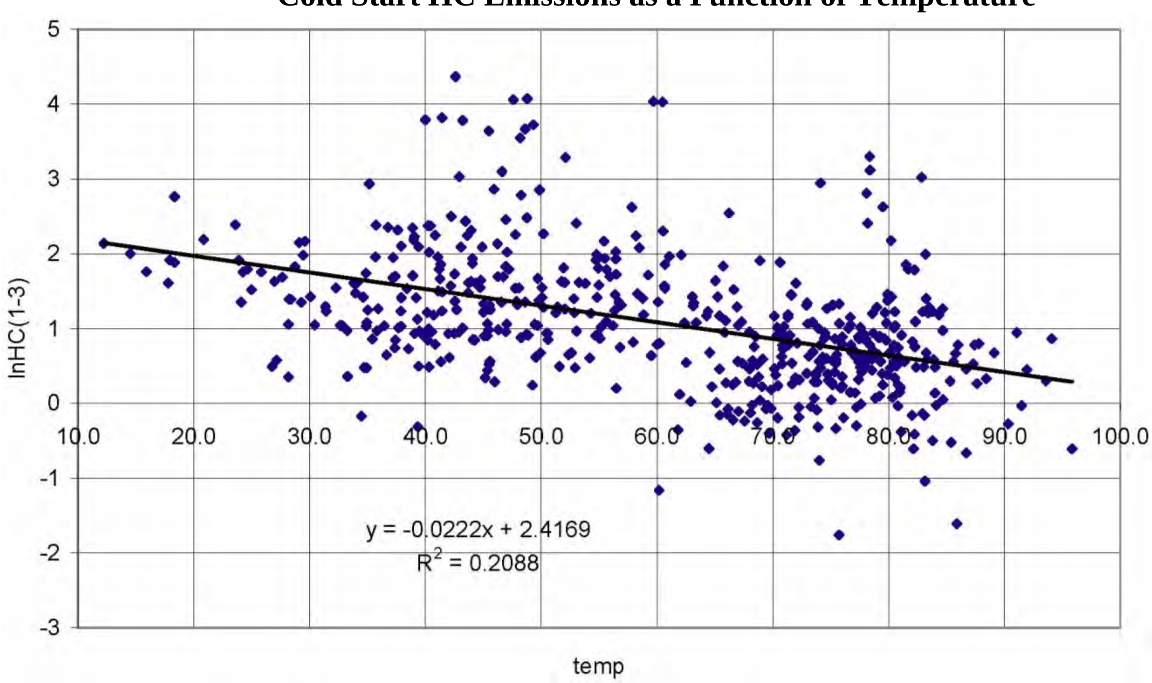


Figure 3-15
Fairbanks Hot ADC HC Emissions vs. Temperature
(unweighted, no age-adjustment; n=64; no trend, median value: -2.16)

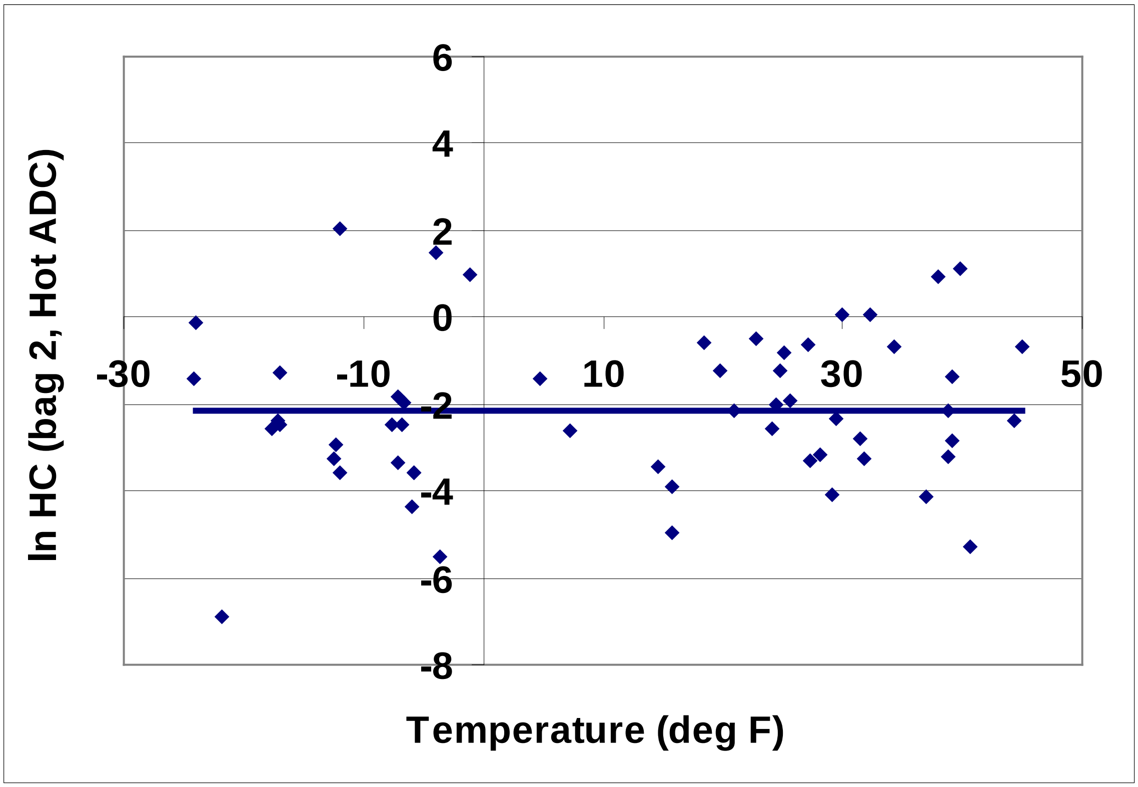


Figure 3-16 (EPA KC PM report Fig 31)
Bag 2 HC Emissions as a Function of Temperature

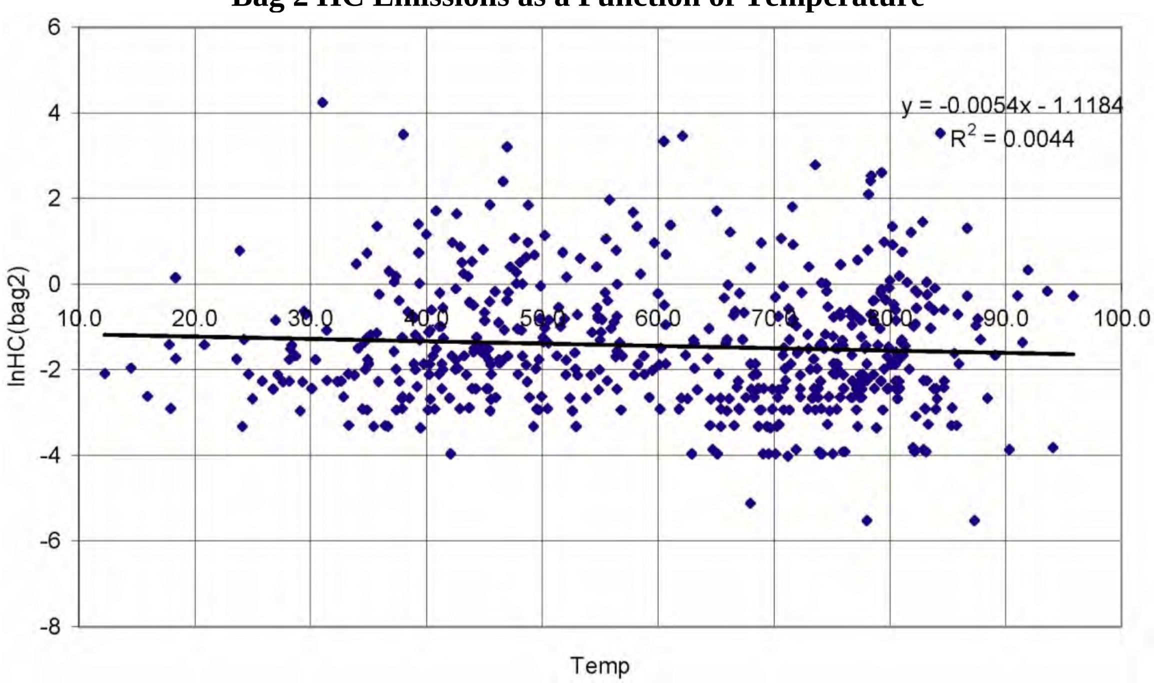


Figure 3-17
Fairbanks Ln CO Start Increment vs. Ambient Temperature
(unweighted: no age adjustment; n=60)

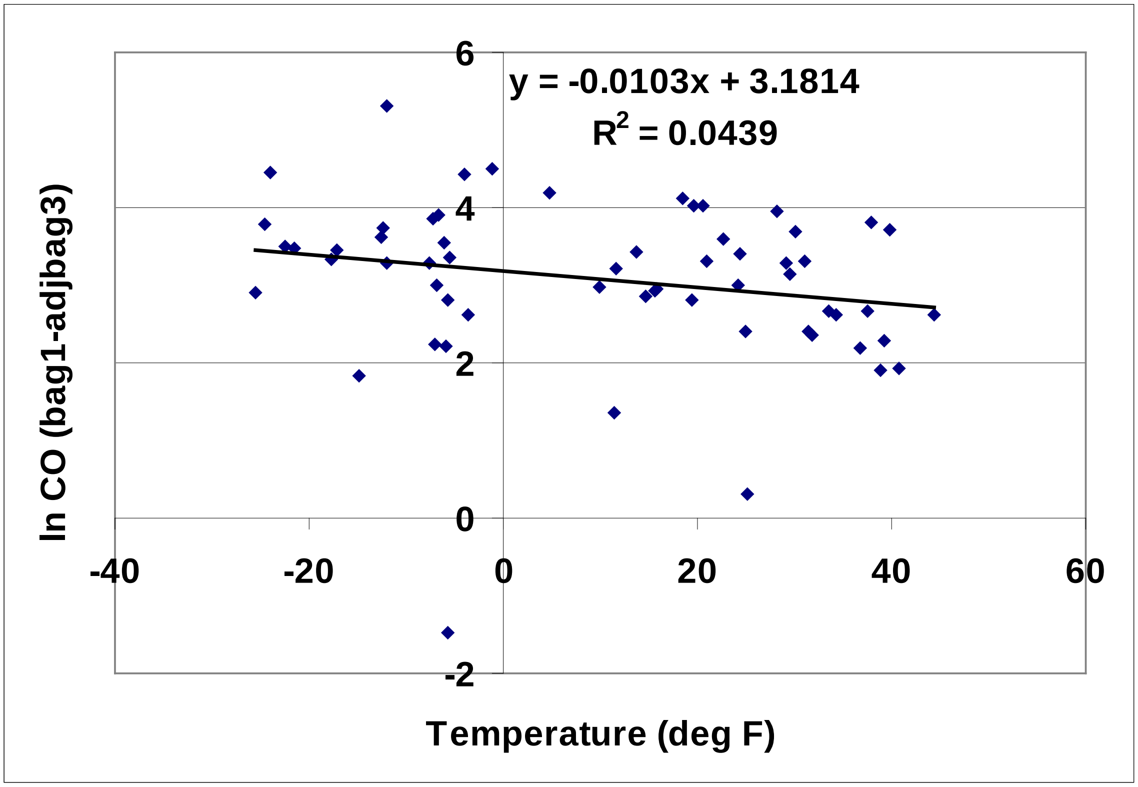
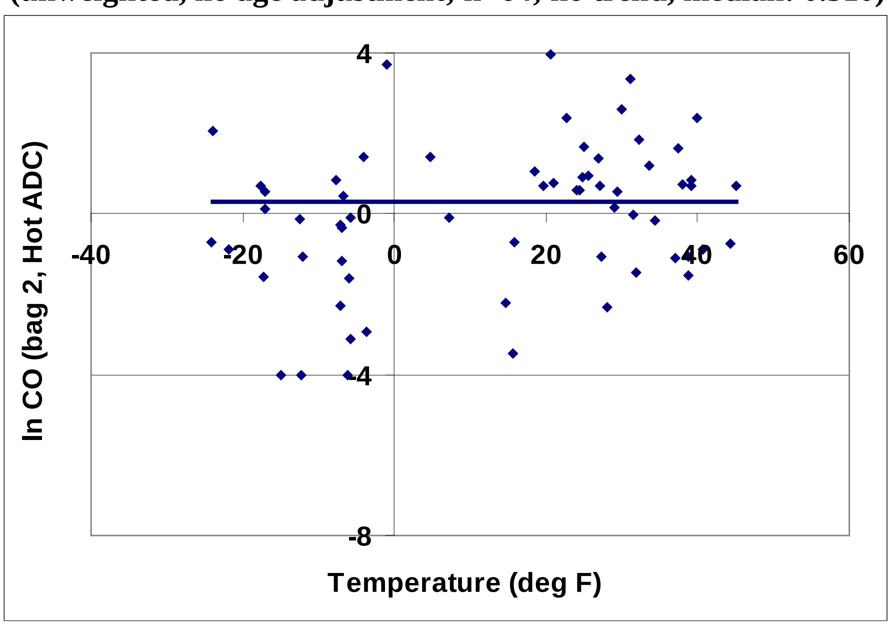


Figure 3-18
Fairbanks Ln CO Running Emissions vs. Ambient Temperature
(unweighted, no age adjustment; n=64; no trend, median: 0.310)



Tables 3-10 through 3-13 summarize the results of a statistical analysis of the gaseous pollutant emissions for Cold and Hot ADCs, as well as the calculated plug-in benefits. In each case, the results reflect regression analyses that were weighted to the Kansas City sample to make results as comparable as possible to the Kansas City study results for gaseous emissions.[*]

The absence of a temperature effect in running emissions for HC, CO, and NOx is indicated by the "zero" temperature coefficients in Tables 3-10 through 3-12. This finding matches what was reported by EPA from the Kansas City study and, as a result, EPA has no temperature adjustment for running emissions of HC, CO, or NOx in MOVES.[26,27,†]

Temperature dependency was observed for gaseous pollutant start emissions, both in Fairbanks and elsewhere, although the effects are more difficult to compare, due in part to the complexity of EPA's statistical analysis which varies by pollutant gas, model year group, and temperature range, and the fact that EPA's analysis of gaseous pollutants examined not only Kansas City data, but also a large body of data from other sources. The most straightforward and perhaps useful comparison is the correlation of composite PM and HC, uncorrected for temperature, which is shown in Figure 3-19. Despite differences in temperature range, fleets, drive cycles, bag definitions, and more, the relationship between HC and PM from Fairbanks as shown in the figure and represented by the best-fit trend line reasonably matches that found in Kansas City, as shown in Figure 3-20 (which is a reproduction of Figure 23 of the Kansas City PM report).

The next section extends the comparison of the temperature sensitivity of Fairbanks emissions to that found in MOVES for start increment.

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[*] EPA's emission factor computations in MOVES

[†] According to the same reference, EPA recognized that the Mobile Source Air Toxic rule, which established cold temperature HC standards starting with model year 2010 vehicles, will reduce HC emissions. However, having found "little or no temperature dependency" in running emissions, EPA configured MOVES to assume "MSAT will only affect engine start emissions."

Table 3-10 **HC Emission Factors** **$\ln(E_{i,j}) = A_i + B * AmbTemp_j + C * dPlug\text{-}In_j$**			
Regression Statistics (Cold ADC Cycle) N = 103 R^2 = 0.84 (0.63 due to vehicle-specific emissions differences) Weighted to Kansas City vehicle distributions			
Cold ADC Emissions	**Units**	**Coefficient (Std Error)**	**Computation of Percentage Emissions Effect dE**
Base Emissions at +20F	g/mi	4.0 (0.5)	
Temperature Coefficient B	decimal	-0.0186 (0.0030)	dE = cxp(-0.0186 · AmbTemp) - 1
Plug-In Coefficient C	decimal	-1.21 (0.13)	dE = cxp(-1.21 · dPlug-In) - 1
Regression Statistics (Hot ADC Cycle) N = 101 R^2 = 0.85 (0.85 due to vehicle-specific emissions differences) Weighted to Kansas City vehicle distributions			
Hot ADC Emissions			
Base Emissions at +20F	g/mi	0.63 (0.13)	
Temperature Coefficient B	decimal	Zero	None
Plug-In Coefficient C	decimal	Zero	None

Table 3-11
CO Emission Factors
$$\ln(E_{i,j}) = A_i + B * AmbTemp_j + C * dPlug\text{-}In_j$$

Regression Statistics (Cold ADC Cycle)
N = 103
R^2 = 0.93 (0.80 due to vehicle-specific emissions differences)
Weighted to Kansas City vehicle distributions

Cold ADC Emissions	**Units**	**Coefficient (Std Error)**	Computation of Percentage Emissions Effect dE
Base Emissions at +20F	g/mi	36.7 (4.6)	
Temperature Coefficient B	decimal	-0.0110 (0.0021)	dE = cxp(-0.0110 · AmbTemp) - 1
Plug-In Coefficient C	decimal	-1.04 (0.09)	dE = cxp(-1.04 · dPlug-In) - 1

Regression Statistics (Hot ADC Cycle)
N = 99
R^2 = 0.85 (0.84 due to vehicle-specific emissions differences)
Weighted to Kansas City vehicle distributions

Hot ADC Emissions			
Base Emissions at +20F	g/mi	5.6 (1.5)	
Temperature Coefficient B	decimal	Zero	None
Plug-In Coefficient C	decimal	-0.37 (0.17)	dE = cxp(-0.37 · dPlug-In) - 1

Table 3-12
NO_x Emission Factors
$\ln(E_{i,j}) = A_i + B * AmbTemp_j + C * dPlug\text{-}In_j$

Regression Statistics (Cold ADC Cycle)
N = 101
R^2 = 0.91 (0.91 due to vehicle-specific emissions differences)
Weighted to Kansas City vehicle distributions

Cold ADC Emissions	**Units**	**Coefficient (Std Error)**	Computation of Percentage Emissions Effect dE
Base Emissions at +20F	g/mi	1.37 (0.16)	
Temperature Coefficient B	decimal	Zero	None
Plug-In Coefficient C	decimal	Zero	None

Regression Statistics (Hot ADC Cycle)
N = 99
R^2 = 0.95 (0.95 due to vehicle-specific emissions differences)
Weighted to Kansas City vehicle distributions

Hot ADC Emissions			
Base Emissions at +20F	g/mi	1.09 (0.15)	
Temperature Coefficient B	decimal	Zero	None
Plug-In Coefficient C	decimal	Zero	None

Table 3-13
CO_2 Emission Factors
$\ln(E_{i,j}) = A_i + B * AmbTemp_j + C * dPlug\text{-}In_j$

Regression Statistics (Cold ADC Cycle)
N = 103
R^2 = 0.99 (0.96 due to vehicle-specific emissions differences)
Weighted to Kansas City vehicle distributions

Cold ADC Emissions	**Units**	**Coefficient (Std Error)**	Computation of Percentage Emissions Effect dE
Base Emissions at +20F	g/mi	942 (50)	
Temperature Coefficient B	decimal	-0.00268 (0.00027)	dE = cxp(-0.00268 · AmbTemp) - 1
Plug-In Coefficient C	decimal	-0.027 (0.011)	dE = cxp(-0.027 · dPlug-In) - 1

Regression Statistics (Hot ADC Cycle)
N = 102
R^2 = 0.98 (0.96 due to vehicle-specific emissions differences)
Weighted to Kansas City vehicle distributions

Hot ADC Emissions			
Base Emissions at +20F	g/mi	621 (25)	
Temperature Coefficient B	decimal	-0.00207 (0.00023)	dE = cxp(-0.00207 · AmbTemp) - 1
Plug-In Coefficient C	decimal	Zero	None

Figure 3-19
$PM_{2.5}$ Correlation with HC for Composite Emissions (wtd. 0.43/0.57) with Trend (not temperature- or MY-adjusted or weighted to KC, n=97)

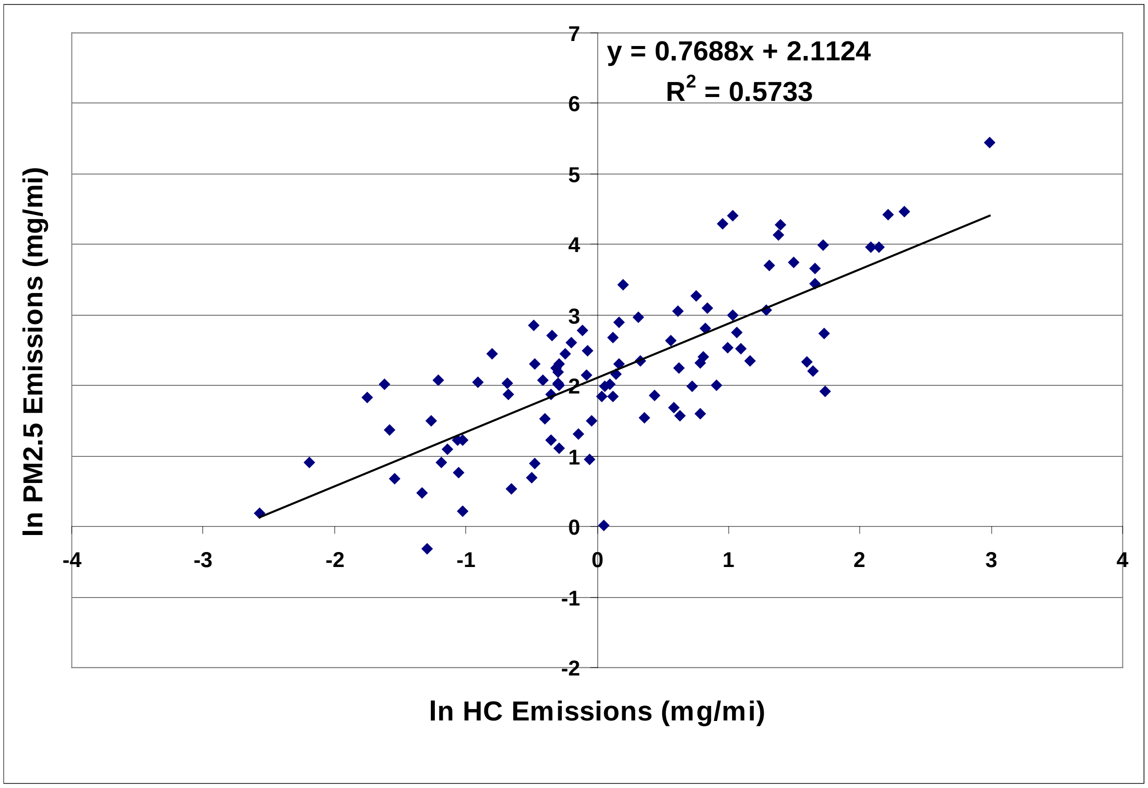
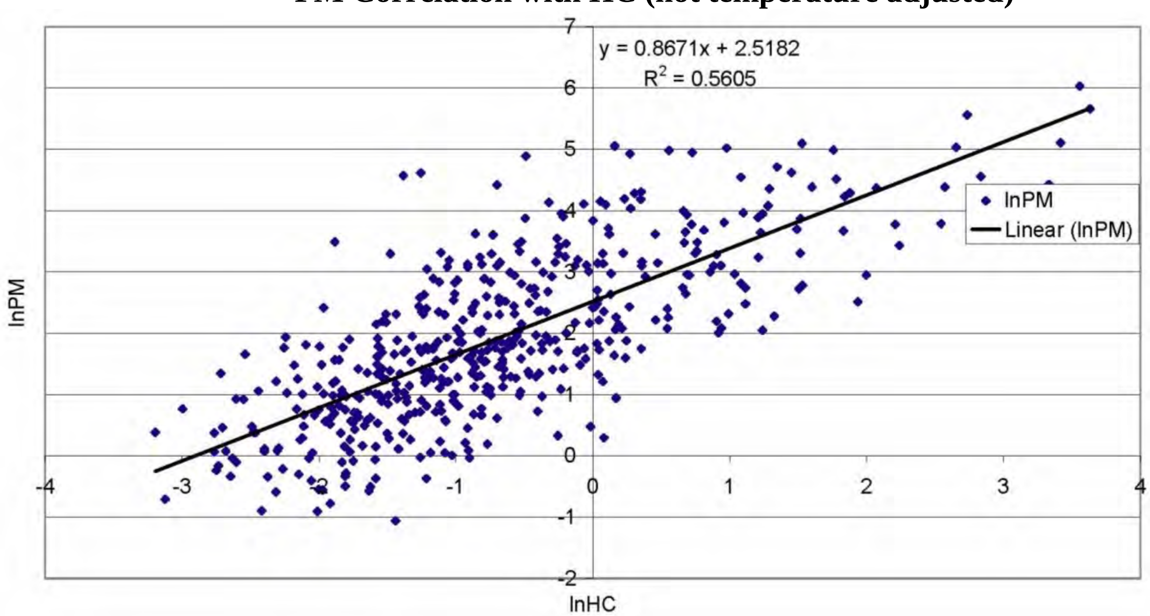


Figure 3-20 (EPA KC PM report Fig 23)
PM Correlation with HC (not temperature adjusted)



3.4.6 Comparisons with Emission Factors in MOVES

An analysis was conducted to estimate temperature correction factors in a form that can be compared to the correction factors used in the EPA MOVES model. Because only ambient temperature is involved in the comparison, the vehicle tests that used engine block heaters during the overnight cold soak were initially removed from the dataset. The remaining data were then subdivided into three model year groups:

- Group 1: Model year 1996 and later vehicles;
- Group 2: Model year 1991 to 1995 vehicles; and
- Group 3: Model year 1981 to 1990 vehicles.

The sample sizes were relatively small in each group: 36 tests in Group 1, 15 tests in Group 2, and 13 tests in Group 3 for HC. No model year 1980 or earlier vehicles were tested.

The dependent variable in the analysis is the Starting emissions increment, defined as the difference between measured emissions on the Cold ADC cycle and "idle-adjusted" emissions on the Hot ADC cycle (as described previously). Starting emissions were converted to units of grams per start based on the 4.74 mi length of the ADC cycle to be consistent with the definition of temperature correction factors for MOVES.

It should be noted that this method of defining Starting Emissions differs from that used in the Kansas City study in two important ways:

- Starting emissions are based on the emissions differential between two complete drives, rather than the Bag 1, Bag 2, and Bag 3 partitioning of LA92 emissions in the Kansas City study; and

- Starting emissions will necessarily contain all of the emissions temperature sensitivity because the Hot ADC drive has been shown to be unaffected by ambient temperature. The Kansas City study apportioned the total temperature sensitivity it measured between Starting Emissions and Running Emissions, so that its temperature sensitivity is more than that of Starting Emissions alone.

PM Temperature Correction Factors – For PM emissions, temperature correction factors were estimated in two ways based on the log(PM) form of the equation used both in MOVES and in the analysis of PM emissions presented here. The first method employed the non-plug-in subset of the vehicle testing data, in which the engine was not heated during the cold soak. This choice reduced the size of the dataset and the temperature range that was covered to approximately -20°F, but it controlled the dataset so that it is affected solely by ambient temperature and not by plug-in. The second method employs all of the testing data and estimates an extended model that contains effects for both temperature and plug-in. This choice increases the sample size and extends the temperature range to colder temperatures, but its temperature effect is estimated in conjunction with the emissions effect of plug-in. The results of these two analyses are summarized in Table 3-14.

For the temperature sensitivity of Starting PM emissions, very good agreement was observed between the vehicle testing data and the results of the Kansas City Study. A temperature coefficient of -0.0443 ± 0.0074 was estimated using the first method (non-plug-in tests only), which was almost identical to the -0.0456 temperature coefficient estimated in the Kansas City study. A temperature coefficient of -0.0380 ± 0.0083 was estimated using the second method (all data); when the uncertainties are considered, this coefficient is not statistically different from that estimated using the first method or from the coefficient estimated in the Kansas City study.

Table 3-14
Temperature Correction Factors for PM Starting Emissions
Weighted to Kansas City vehicle distributions

Non-Plug In Tests: $\ln(E_{i,j}) = A_i + B * AmbTemp_j$
$N = 58$
$R^2 = 0.86$ (0.65 due to vehicle-specific emissions differences)

	Units	Coefficient (Std Error)	EPA MOVES Coefficients
Base Emissions at +20F	g/mi	20.2 (4.3)	n/a
Temperature Coefficient B	decimal	-0.0443 (0.0074)	-0.0463
Plug-In Coefficient C	decimal	None	None

Full Dataset: $\ln(E_{i,j}) = A_i + B * AmbTemp_j + C * dPlug\text{-}In_j$
$N = 89$
$R^2 = 0.64$ (0.48 due to vehicle-specific emissions differences)

	Units	Coefficient (Std Error)	EPA MOVES Coefficients
Base Emissions at +20F	g/mi	18.4 (3.3)	n/a
Temperature Coefficient B	decimal	-0.0380 (0.0083)	-0.0463
Plug-In Coefficient C	decimal	-1.59 (0.36)	None

The coefficient estimated using the second method is preferred because it is based on more data and the full range of temperatures encountered in the testing. However, the conclusion is the same regardless of which method is chosen: the vehicle testing at cold temperatures supports a temperature sensitivity coefficient for Starting emissions that is comparable to, or somewhat smaller than, the coefficient estimated in the Kansas City study and used in the EPA MOVES model.

However, regardless of the similarity in coefficients for Starting emissions, the Fairbanks vehicle testing indicates a substantially smaller total sensitivity to ambient temperature than seen in the Kansas City study. This is because, as noted previously, the Hot ADC cycle was found to be unaffected by ambient temperature and therefore the temperature sensitivity of Starting emissions represents the entire effect of temperature on exhaust emissions. In the Kansas City study, the temperature sensitivity of Starting emissions was only part of the effect and Running emissions were found to have a temperature coefficient almost as large (-0.0318).

<u>Temperature Correction Factors for Gaseous Pollutants</u> – Temperature correction factors for gaseous pollutants were estimated from the Fairbanks vehicle testing for comparison to the values used by EPA in the MOVES model. The estimates were based on the functional form used by EPA for each pollutant and subdivided by model year in a manner that allows a general comparison. Because the effect of plug-in is not captured in EPA's analysis of gaseous pollutants, the comparison was restricted to the non-plug-in vehicle testing. The dataset of all tests could be used in other work to develop more general temperature correction factors that accounted for the emission effect of plug-in.

The temperature correction factor models were estimated using the absorption technique previously described. This technique is equivalent to fitting a dummy variable to represent the unique emissions level of each vehicle. The R^2 statistics cited here include the contribution from the vehicle absorption. The vehicle sample was weighted to match the distribution of vehicles in the Kansas City study. Table 3-15 summarizes the results for the temperature correction factors for HC, CO, and NOx.

For the gaseous pollutants, there is general agreement on the magnitudes of the temperature correction factors and on the conclusion that the temperature sensitivity is confined to Starting emissions. For HC, the temperature coefficients estimated for Groups 1 and 2 (1996 and later vehicles and 1991-1989 vehicles) are only slightly smaller than the 0.0029 g/°F coefficient used in MOVES for 1990 and later model year vehicles. The temperature coefficient for Group 3 (1981-1990 vehicles) is consistent with a composite of the individual values used in MOVES for the three vehicle groups in that model year range.

For CO, the temperature sensitivities estimated in this analysis for Groups 1 and 2 (-0.14 g/°F and -1.34 g/°F, respectively) bracketed the composite -1.14 g/°F coefficient used in MOVES for model year 1990 and later vehicles; the temperature coefficient for Group 3 was consistent, again, with a composite of the individual values used in MOVES. For NOx, MOVES uses a temperature sensitivity of -0.0094 g/°F as a composite for the entire fleet. In the current analysis, the NOx temperature coefficient did not appear to vary significantly with model year, but a smaller coefficient of -0.0024 g/°F was found.

Table 3-15 Temperature Correction Factors for Gaseous Pollutants Weighted to Kansas City Vehicle Distributions					
	Analysis of Alaska Vehicle Testing				**EPA MOVES**
	Model Years	Functional Form	R^2	Temperature Coefficient (k)	Temperature Coefficient (k)
HC	1996 and later	$E (g) = E_{75} + k*(T-75)^2$	0.90	+0.0018 (0.0003)	0.0029
	1991-1995	$E (g) = E_{75} + k*(T-75)^2$	0.96	+0.0022 (0.0002)	
	1986-1990	$E (g) = E_{75} + k*(T-75)$	0.82	-1.04 (0.36)	0.0024[a/]
	1983-1985				-0.3607
	1981-1982				-0.4136
	Pre-1981	No vehicles tested	n/a	n/a	-0.6307
CO	1996 and later	$E (g) = E_{75} + k*(T-75)$	0.90	-0.67 (0.23)	-1.14
	1991-1995	$E (g) = E_{75} + k*(T-75)$	0.91	-1.60 (0.43)	
	1986-1990	$E (g) = E_{75} + k*(T-75)$	0.98	-5.41 (0.82)	-1.09
	1983-1985				-4.24
	1981-1982				-4.63
	Pre-1981	No vehicles tested	n/a	n/a	-4.68
NOx	All Years	$E (mg/mi) = E_{75} + k*(T-75)$	0.85	-0.011 (0.005)	-0.0094

[a] EPA MOVES uses the quadratic functional form for HC in this model year group.

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4. STATE OF ENGINE WARM-UP IN FAIRBANKS

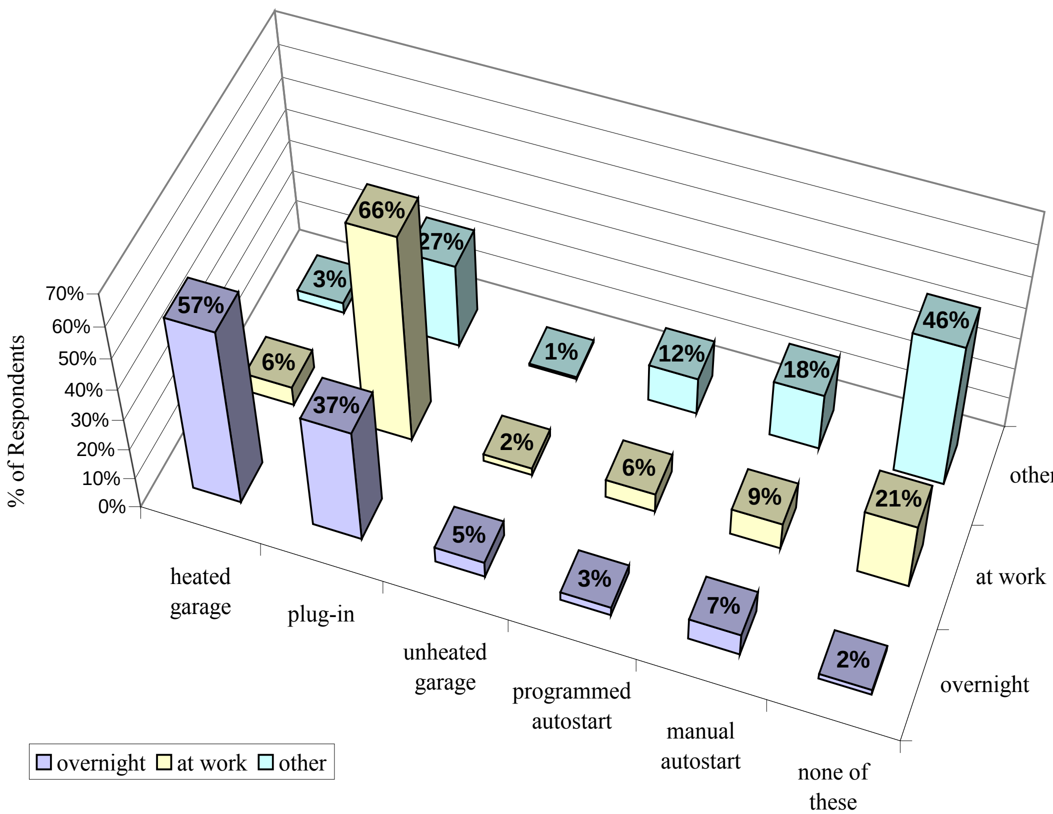
Section 3 documented how vehicular PM emissions varied depending upon ambient temperature and the effects of block heater plug-in. In this section, the state of engine warm-up for typical vehicles in customer service in Fairbanks is discussed, beginning with an overview of engine "keep warm" activities in Fairbanks. The state of engine warm-up is then reviewed, based on coolant temperatures at engine startup from the dynamometer testing (with and without plug-in) and from data logging of on-road vehicles in customer service.

4.1 Block Heater Plug-in and Other "Keep Warm" Activities in Fairbanks

Essentially all gasoline-powered vehicles that operate in Fairbanks winters are equipped with plug-in engine block heaters. The plug-ins are widely used when vehicles are parked outside in winter for more than a few hours. In a random phone survey of 300 households conducted in 2005 as part of a study of autostart devices,[5] Sierra found that 66% of respondents used a block heater when parked at work in winter. FNSB code requires major employers to provide plug-in outlets to power them at low temperatures.[*] For longer soaks, e.g. when parked overnight at home, more than 37% used plug-in (57% had heated garages); in all, fewer than 2% of respondents did not use any of the listed overnight keep-warm strategies shown in Figure 4-1.[†] The high usage rates are a practical necessity, for without these keep-warm efforts, starting of vehicles at low temperatures would be less dependable, more time-consuming (could require battery boost or other starting aids like injection of ether), would result in an extended period of cold in the passenger compartment,[5] and would result in greater engine wear.[28] Taken together, these factors are a powerful and effective motivator for vehicle owners to keep engines warm in Fairbanks winter.

[*] FNSB Code Chapter 8.20.10 requires that employers or businesses with a total of 275 or more parking spaces provide power to the outlets at parking spaces intended for more than two hours of use. Power is required when temperatures drop below 21°F, but may be cycled on alternate hours to conserve power.
[†] Percentages shown in the figure for each location add to more than 100% because many respondents report using more than one keep-warm strategy, e.g., an unheated garage plus plug-in.

Figure 4-1
Methods for Vehicle "Keep Warm" and Warm-up During Overnight, at Work and Other Times



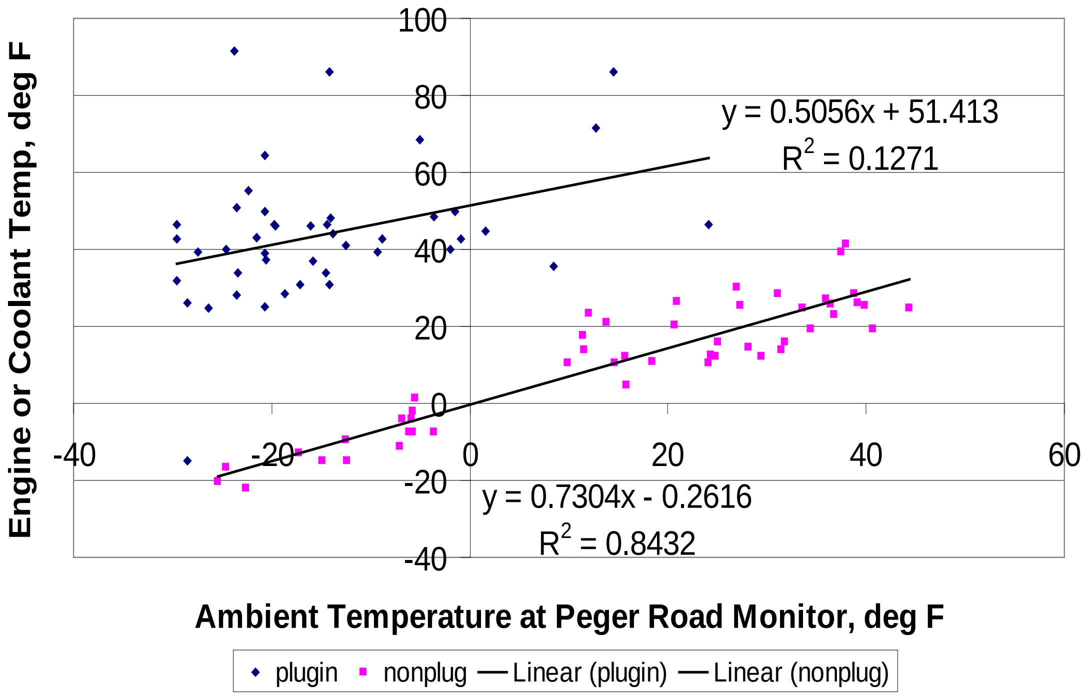
In order to document the effect of plug-in and ambient temperatures on engine temperature, portions of the dynamometer testing for the current study were conducted with a CarChipPro datalogger* installed in the test vehicles. This device logs data whenever the engine is running, including various vehicle parameters such as speed, coolant temperature, etc. An earlier version of the same datalogger, the CarChip EX, was used in the 2005-2006 Autostart study[5] to record trips and log engine coolant temperature and other parameters (discussed later in this section). Both models plug into the under-dash assembly line data link (also known as the OBDII or On-Board Diagnostic version II) connector of most 1996 and later model year cars and light duty trucks. Engine and oil temperature measurement data are typically not available through the OBDII port, so engine coolant temperature is used herein as a surrogate for engine temperature.

* Davis Instruments, Oakland, CA.

Of the 33 vehicles successfully tested in 2010-2011, 19 were OBDII compatible. For the remainder of vehicles, an attempt was made (with higher priority in the March testing*) to measure engine temperature at the start of each test using either a scan tool or, more frequently, a noncontact infrared thermometer (Fluke†, Model 80T-IR). Following daily calibration checks,‡ the IR measurements of engine temperature were made at multiple locations on the top of each engine and an average of the readings was recorded.

The results from engine and coolant temperature measurements are summarized in Figure 4-2, which also shows the corresponding ambient temperature measurements collected by FNSB at its Peger Road monitoring station. Both trend lines are statistically significant, and a comparison of the two shows that plug-in increased engine temperatures by about 50°F over non-plug-in engine temperatures.

Figure 4-2
Coolant Temperature vs. Peger Road Ambient Temperature at Start of Test for Plug-in (Upper Points) & Nonplug (Lower Points & Best-Fit Linear Regressions)



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* This change in the testing protocol was motivated by the large effect of plugin upon emissions and coolant temperatures that was observed from preliminary analysis of results from the March test phase.
† Fluke Corporation, Everett, WA.
‡ At least once a day before making IR measurements, the IR thermometer was checked against a continuously temperature-monitored fitting (for the propane injection system) in the Horiba IM240 system cabinet. However, IR measurements were not feasible below -0.4°F, the minimum instrument range. This restricted measurements at the lowest ambient temperatures for tests where plug-in was not used.

4.2 Instrumented Vehicle Data on State of Engine Warm-Up

As part of the characterization of vehicle activity in the current study, OBDII-compatible dyno test vehicles were monitored for a week or more while in customer service using CarChip EX data loggers. The loggers were installed and removed by FNSB Borough staffers, and this was usually performed before or after one of the vehicle's two phases of dyno testing (either in January or March). Unfortunately, several problems occurred with the data logging,* and it was possible to capture data from only a limited number of the test vehicles in 2011. However, the resulting data were merged with the corresponding CarChip data from the aforementioned Autostart study, resulting in a dataset covering about 1,000 engine starts of 20 vehicles. The period of sampling in 2006 (Autostart) ranged from November to December, and that for the current study ranged from January to April 2011—essentially providing sampling through what is generally considered the Fairbanks winter period. Different engine parameters were recorded in the two studies, but both included logging of engine coolant temperatures every ten seconds. As a final step in data assembly, both datasets were merged with temperature data from Fairbanks International Airport. The results, along with interpretative information, are summarized in a series of figures, shown below.

Figure 4-3 plots engine coolant temperature at startup vs. ambient temperature, with each engine start represented by a data point. The ambient temperatures ranged from about -40 to +30°F, and starting coolant temperatures ranged from near ambient (for just a few engine starts) up to about 200°F, which is a common thermostat opening temperature. These data suggest that the vast majority of engine starts occur with coolant temperatures well above ambient temperature, and that this is most pronounced at the coldest ambient temperatures. This result is not surprising, for two reasons. First, vehicle operators in Fairbanks winters, by necessity, are known to employ keep-warm activities, which help to maintain higher engine temperatures between drives. Secondly, without such activities, most gasoline vehicles simply would not start, or would not start readily, at the lowest temperatures shown.

Additional insight into the pattern of coolant temperatures can be gained by examining soak times, which are shown in Figure 4-4 for the same set of in-use engine starts. In this figure, starting coolant temperatures (minus the corresponding ambient temperatures) are plotted on a logarithmic scale because the log of the temperature difference is expected to be proportional to soak time.[16] The proportionality constant depends on engine size. The steeper and less steep diagonal lines in the figure represent engine cool-down for the smallest (1.6 liter) and largest (5.7 liter) engines in the vehicle sample, respectively.

* A portion of the data were lost or otherwise unobtainable due to an unexplained Carchip or vehicle problem, problems in the data retrieval, lack of time in the winter season, or unavailability of the vehicles for logging.

Figure 4-3
Engine Coolant at Startup vs. Ambient Temperature
for 20 In-Use Vehicles, n=957 Starts

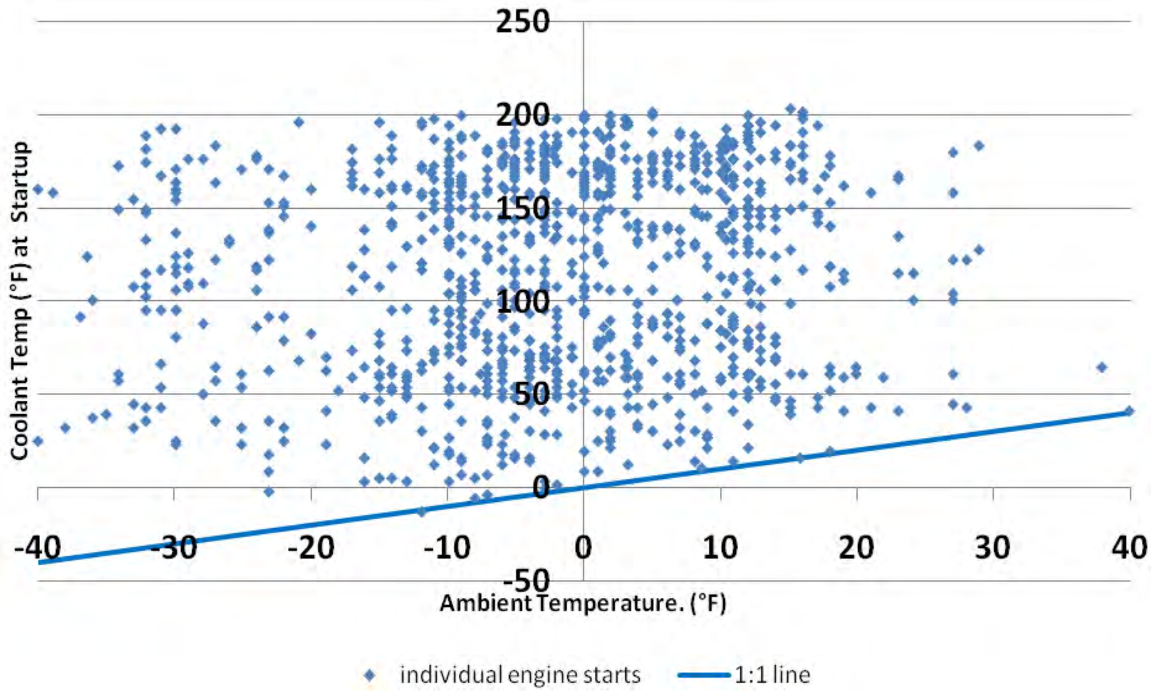
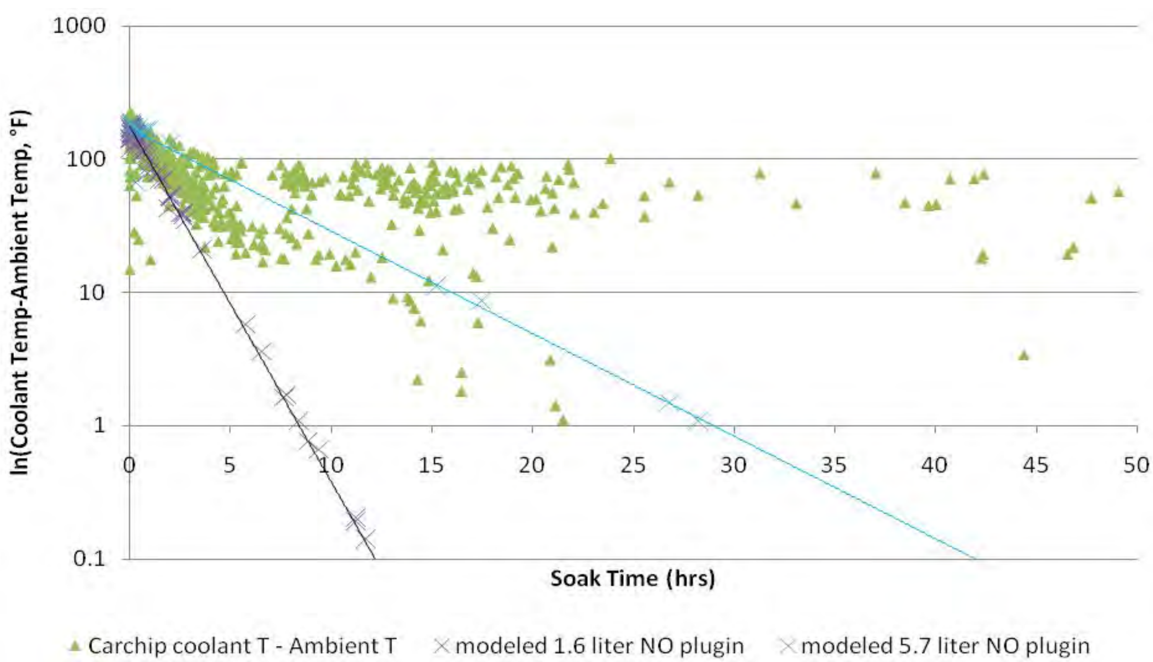


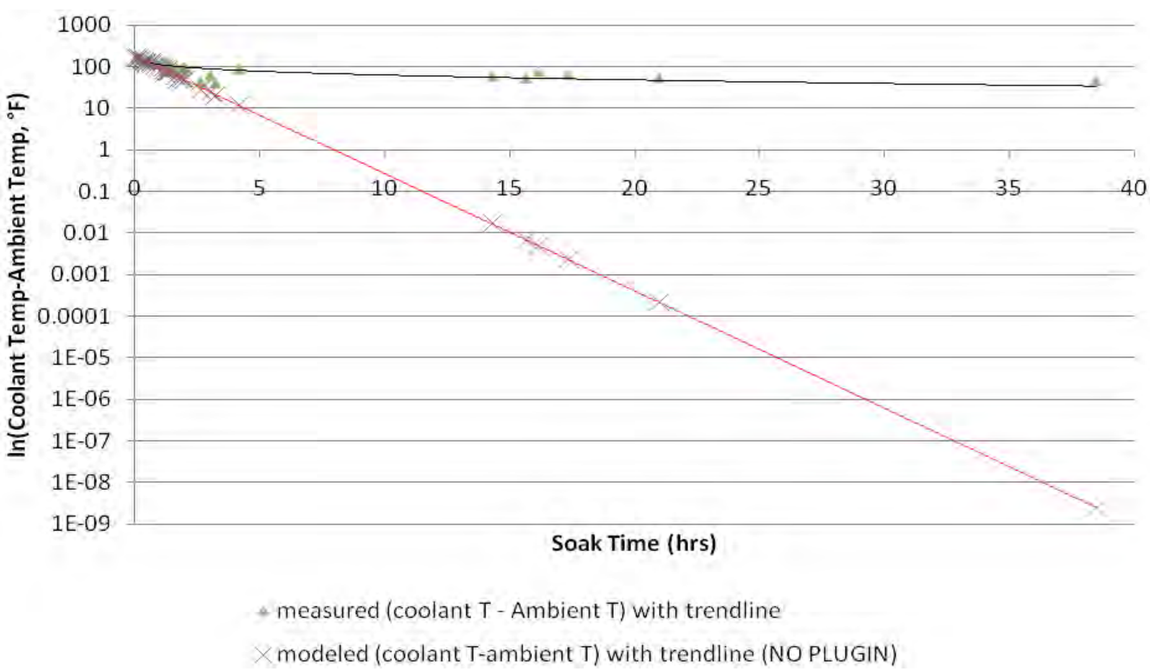
Figure 4-4
Effect of Soak Time upon Engine Cool-Down



Along each diagonal, expected temperature differences are calculated and are shown as crosses. These modeled temperature differences (like the measured temperature differences that are shown as triangles) are based in part on the ambient temperatures at time of engine start. But the modeled values here are also based on the coolant temperature from the end of the preceding drive, the engine size of each vehicle in the sample,* and an estimated rate constant (see AKMOBILE6 documentation for more details of the calculation). The diagonal lines themselves are best-fit linear regressions and define a region where, for short soak times, the starting coolant temperatures can be reasonably estimated from the simple engine cool-down model (assuming that the previous trip ended fully warmed up and the engine cools down to approach ambient temperature with no "keep warm" activity).

To better illustrate the modeled ambient temperature cool-down, Figure 4-5 shows the measured- and cool-down-modeled temperature differences for all the starts of a single vehicle, which happens to be a model year 2000 Honda Civic having 34 starts.

Figure 4-5
Start of Trip Coolant Temperature Less Ambient Temperature vs. Soak Time, Shows Measured (Top) and Modeled (Bottom) Temperature Differences with Trend Lines for a Model Year 2000, 1.6 Liter Honda Civic (n=34 trips)



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* This calculation is more detailed than the one used in AKMOBILE6. AKMOBILE6 assumes the previous trip was fully warmed up at shutdown, that the thermostat setpoint and final coolant temperatures were 190°F for all vehicles and all trips, and that all vehicles had a default engine size of 2.7 liters.

The upper data points (triangles) and trend line in the figure show the observed temperature differences as a function of soak time. For each of the upper points, there is a corresponding lower point (cross) which shows the temperature difference that would be expected assuming engine cool-down without any keep-warm activity. For example, considering just one engine start in this figure, a soak of just under 5 hours resulted in a temperature difference (coolant-ambient) of just under 100°F, whereas a normal engine cool-down at ambient temperature was expected to result in a difference of 10°F. Larger differences are apparent for the longer soaks.

Returning to Figure 4-4, it was noted that the modeled temperature differences capture the effects of short soaks, which tend to not require keep-warm activity. For example, most Fairbanks drivers do not plug-in during brief one- to two-hour shopping excursions. Indeed, as noted earlier, Borough code does not require larger businesses and employers to provide powered outlets for parking that is intended to be less than two hours. These short-soak engine cool-downs are shown in greater detail in Figure 4-6, which is from the same dataset as Figure 4-4 but with an expanded the scale for soak times of less than six hours.

Figure 4-6 also shows that the vast majority of starts follow very short soaks (less than two hours). Furthermore, it shows that as soak time increases, the data tend more toward larger differences (i.e., warmer coolant temperatures) than predicted by the lower and upper limit cool-down model predictions corresponding to 1.6 to 5.7 liter engines. This trend appears to begin with a few starts after a two-hour soak time, and increases to most of the starts for soaks of seven to eight hours (not shown in this figure).

Figure 4-6
Measured Coolant Temperatures Less Ambient Temperatures vs. Soak Time Diagonals Shows Modeled Cool-Down for 5.7- (Upper) and 1.6-Liter (Lower) Engines (Assumes No "Keep Warm" Activity)

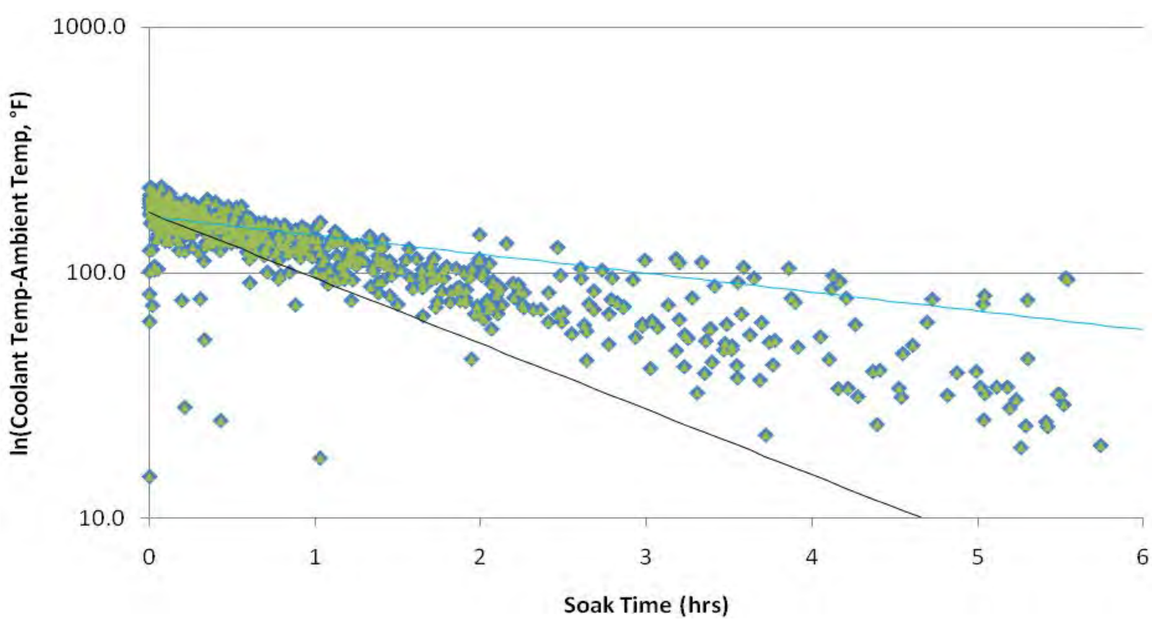

Figure 4-4 also shows that engine starts after soak times greater than six hours have starting coolant temperatures that are elevated consistently and well above ambient temperature. Two important questions about these extended soak engine starts are whether they more closely resemble hot or cold starts, and whether that is affected by ambient temperature. This is addressed in Figures 4-7 and 4-8 from the standpoint of engine/coolant temperature.

Figure 4-7 depicts engine starts as a function of soak time and ambient temperature, comparing starts that occurred with coolant temperature closer to the overnight engine temperatures found in the dyno testing program ("+" in the figure) with starts that were closer to the ambient cool-down model ("o"). The approximate boundary lines drawn on the figure show no matches to the plug-in model at ambient temperatures above about 20°F, which tends to agree with the common notion among Fairbanks residents* that they can stop plugging in when temperatures are above 20 °F (and tend to do so, both for convenience and to save on electricity bills). Conversely, at temperatures below about -20°F, there are essentially no starts without plug-in type coolant temperatures, except for very short soak times where non-plug-in starts are the norm. At intermediate temperatures, and for soaks shorter than six hours, there is a range of coolant temperatures indicating, we believe, a range of application of keep-warm activities.

Figure 4-8 displays, by ambient temperature range, the average startup engine temperatures for soak times longer than six hours. The three bins below +20°F generally correspond to a roughly even distribution of average daily temperatures for FNSB $PM_{2.5}$ design days.† In each of the temperature ranges shown in the figure, there are two vertical bars. The blue bar on the left in each pair represents the average coolant temperature at startup from in-use driving. In the case of ambient temperatures of -20°F or less (the left-hand pair), the average coolant temperature was 39°F (from n=17 starts), well above even the -20°F upper limit of ambient temperature in this range. The right-hand (red) bar in the pair provides an independent point of comparison for the starting coolant temperature of dyno-tested vehicles that were plugged in overnight, based on the previously shown relationship between engine temperature and ambient temperature for plug-ins (Figure 4-2) evaluated at the average temperature for this range of in-use starts (-30.3°F). Based on similar calculations for the other three temperature ranges shown, coolant temperatures resulting from overnight plug-in reasonably match the average temperatures observed in the in-use sample in three of the four temperature ranges; however, the comparison for the temperature range greater than 20°F must be qualified due to the relatively small sample from in-use vehicles (only six engine starts).

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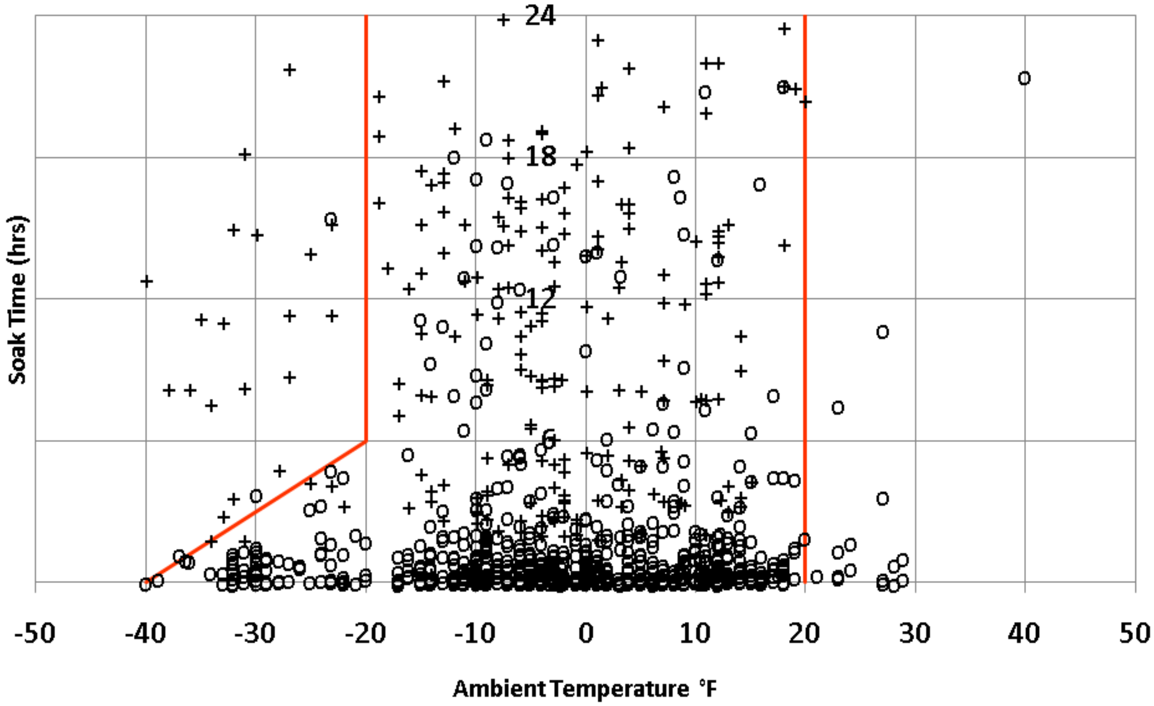
* Personal communication with FNSB staff members.

† For comparison, out of 35 tentatively identified "design days," 12 had an average daily temperature of less than -20°F, 13 days wwere between -20°F and 0°F, and 10 days were between 0°F and 20°F. Daily minimum temperatures tend to be about 10°F colder than daily average temperatures.

Figure 4-7
Soak Time vs. Ambient Temperature, Showing Starts for Which Coolant Temperature is Closer to Plug-in(+) or a Cool-Down Model(o)



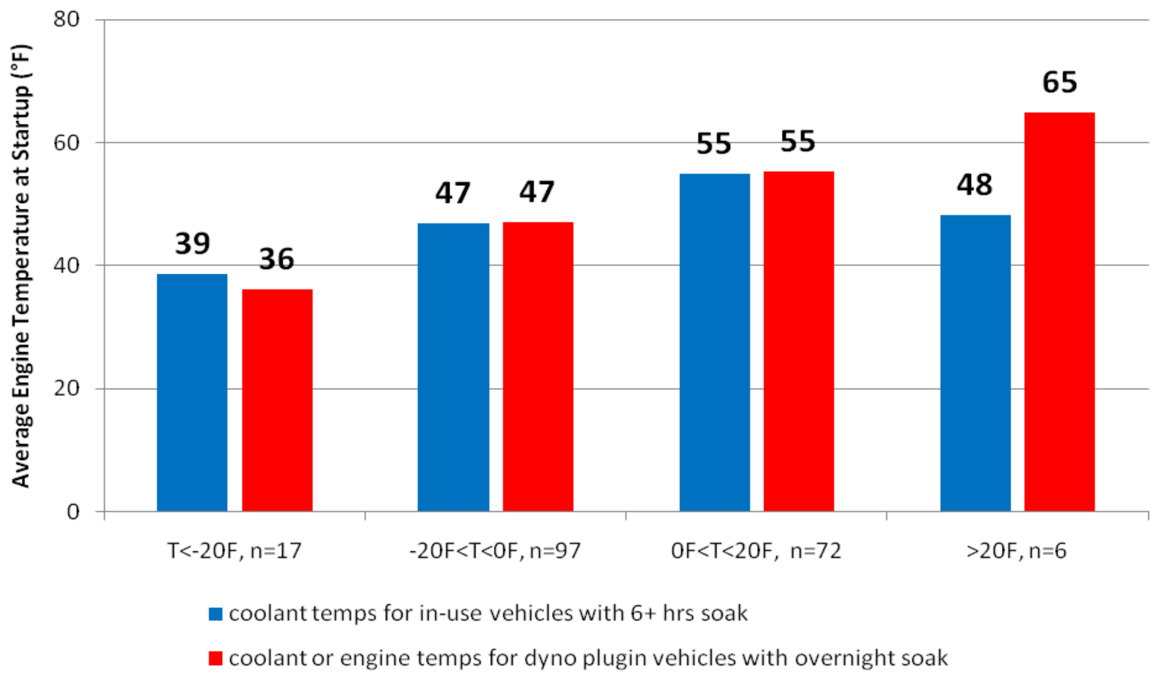
These average in-use coolant temperature data demonstrate that coolant temperatures at engine startup in Fairbanks winters are well above ambient temperatures and appear to reflect deliberate and effective engine "keep warm" actions by vehicle operators in Fairbanks. In addition, the elevated in-use coolant temperatures for longer soaks tend to be much higher than expected cool-down temperatures, and are a better match to the elevated startup coolant levels observed with overnight plug-ins (in the dyno testing program).

Finally, there are several important caveats to the in-use data, as outlined below.

- The in-use data sample is limited in size and roughly half of the dataset is from the aforementioned Autostart study survey, which, although based on a random telephone survey, was limited for reasons of practicality to vehicles having autostart. Whether and how these aspects of the data may limit their representativeness are unknown.

- The comparisons shown were not intended to prove, nor do they prove, that the in-use vehicles with longer soaks and elevated coolant temperatures were necessarily plugged in prior their engine starts at the various temperature ranges. The main reason for this is that the effect on coolant temperatures from heated garaging of vehicles* cannot be distinguished from that of plug-in (the former is much more common in Fairbanks for overnight soaks). But if starting coolant temperatures were similar for these two keep-warm strategies, the cold start PM effects for vehicles in heated garages may be lower than for plug-ins because not only the engine but also the transmission and other drive train components would be expected to have lower friction losses.

Figure 4-8
Effect of Ambient Temperature on Avg. Startup Engine Temperature for In-Use Vehicles with Soak >6hrs (blue) & Dyno-Tested Vehicles with Overnight Plug-in (red)



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* We are not aware of any published data on the average temperature of heated garages in Fairbanks in winter, but a temperature range of about 50-65°F appears plausible. This range brackets the estimated coolant temperature (51.4°F) for outdoor plug-in at an ambient temperature of 0°F, which is the average winter temperature in Fairbanks. This range also “captures” the daily “cold start” (after overnight or longer soak) coolant temperature range of vehicle number 28, which was 59.0 to 64.4°F for 14 starts (average starting coolant temperature 61.1°F); the owner said he parked in a heated garage with thermostat set to about 60°F.

5. ANALYSIS RESULTS APPLIED TO THE FAIRBANKS EMISSIONS INVENTORY FOR LIGHT DUTY GAS VEHICLES

This section relates what was learned from Fairbanks dynamometer testing temperature dependencies and plug-in effects, along with soak times and coolant temperatures, to relative emission inventory estimates in Fairbanks. This is neither intended nor able to replace an emission inventory or emission inventory model, but rather to show how an emission inventory estimate for the Fairbanks winter climate may be influenced by several key aspects of the data, including temperature dependency and plug-in.

Focusing on PM emissions, this section begins with a comparison of emission trends from Fairbanks and Kansas City. Results using a MOVES-based approach are then compared with MOVES outputs adjusted outside the model to account for expected Fairbanks design day temperatures.

5.1 $PM_{2.5}$ Emission Trends based on Fairbanks and Kansas City Testing

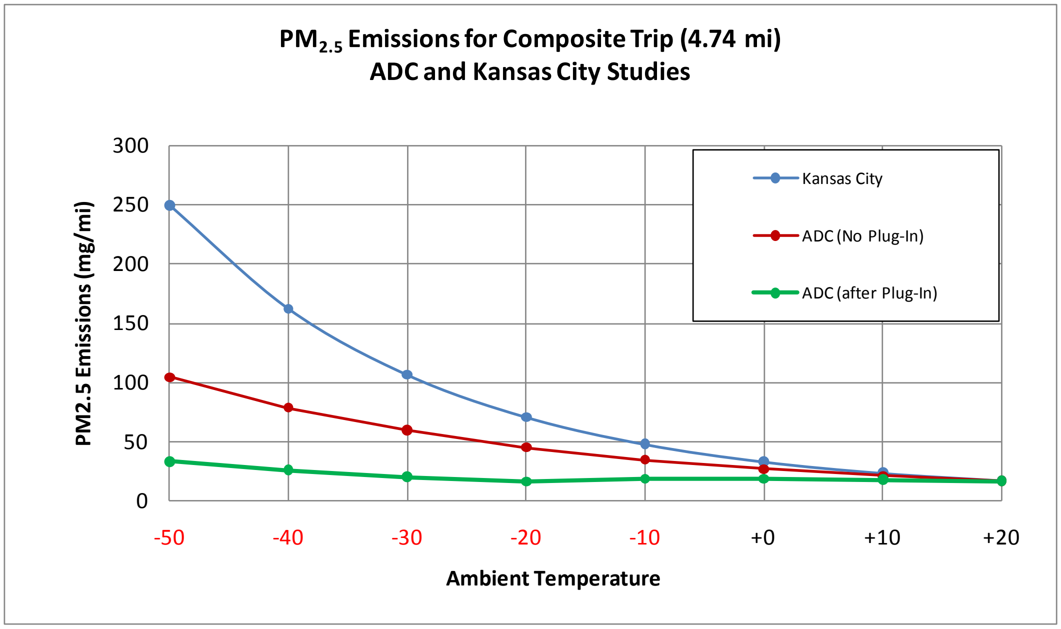
Figure 5-1 compares $PM_{2.5}$ emission trends as predicted by the Kansas City study* to trends based on the Alaska Drive Cycle testing. Two ADC lines are shown: no plug-in, and a simple plug-in scenario (0% plug-in at +20°F, 100% at -20°F, and linear interpolation between). In all cases here, the basis for comparison is a 43/57 weighted (Cold ADC/Hot ADC) composite trip of 4.74 mi length.

While the lines diverge markedly at low temperatures, it is important to note that the Kansas City and Fairbanks studies give almost the same fleet-average emission factors at +20°F, which is the temperature regime where both studies overlap (albeit slightly). The close correspondence of the Kansas City and Fairbanks data at the upper range of Fairbanks temperatures shown tends to support the quality of the data from both programs and the fairness of the comparison. However, the Fairbanks measurements pick up below +20°F, where the Kansas City measurements study left off, and indicate that the temperature sensitivity below that is much less than at the higher Kansas City temperature range.

* It should be noted that the Kansas City emission factor lines are based on an adjusted treatment of temperature sensitivity and the method of forming a composite trip, as discussed in Section 3. This near-perfect correspondence at +20°F would not result from using the Kansas City PM Study Report, Figures 12 and 13 alone.

The Fairbanks plug-in scenario shows that plug-in usage can hold emissions constant or even force them down slightly when the entire fleet is plugged-in at -20°F.

Figure 5-1 $PM_{2.5}$ Emissions for Composite Trip (4.74 mi) ADC and Kansas City Studies



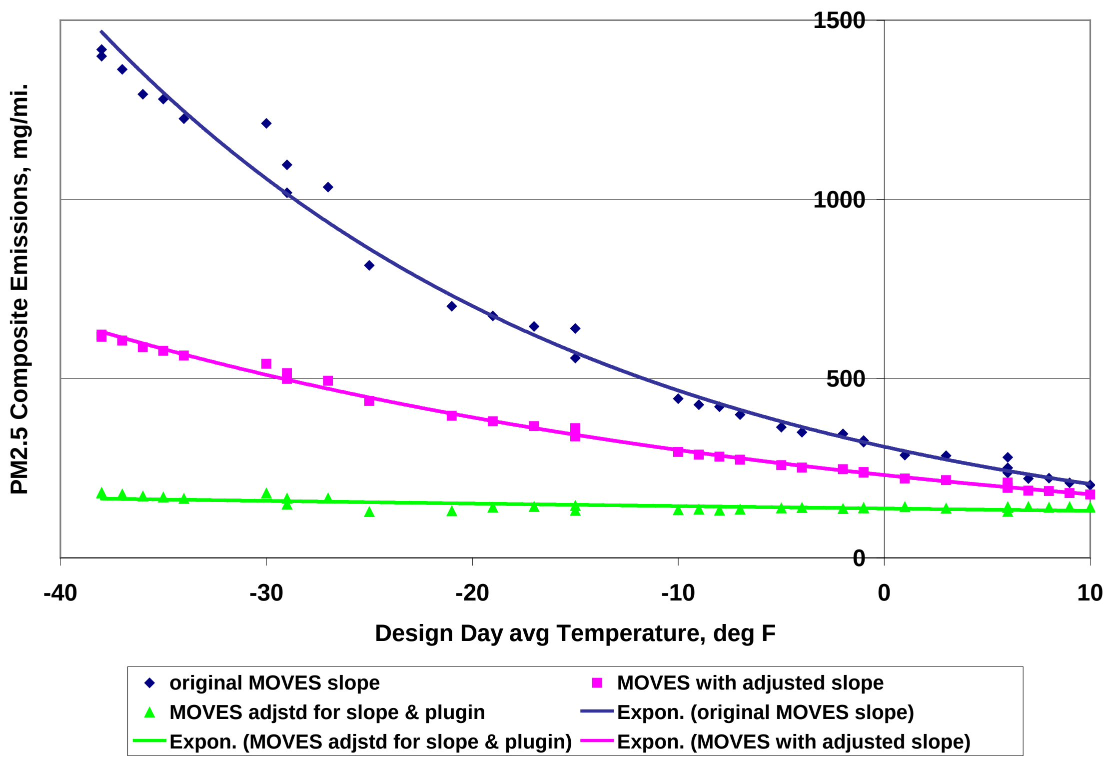
5.2 Composite Emission Trends in Fairbanks for an Adjusted MOVES Analysis

To more closely address the Fairbanks inventory case, composite emissions for the 35 tentatively selected Fairbanks $PM_{2.5}$ design days from 2008 are estimated and compared. Again, the intent is not to substitute for a detailed inventory but to provide an informed estimate of the effect of several theoretical emissions adjustments to MOVES outputs for Fairbanks.

Figure 5-2 plots composite emissions versus average design day temperatures for three alternative emission estimates. In each case, the composite estimate is based on the assumption of four daily trips (roughly corresponding to the 43/57 split). Two trips are assumed to be cold starts that occur at the actual minimum and maximum temperature of that design day, which are often early morning and sometime in the afternoon, and two are hot starts. The resulting composite emissions for the day are computed as an average of those four trips and plotted as one point in the figure. For each estimation method, an exponential curve is drawn through the corresponding points.

The first, and highest curve shown, is a MOVES-based estimate of composite emissions. It is based on the temperature coefficient that is currently in MOVES and is not adjusted for plug-in. The second curve is another MOVES-like estimate but using the lower temperature slope derived from Fairbanks testing (with Kansas City sample weightings). The third estimate is the same as second, except that the effect of plug-in has been factored in.

Figure 5-2 Composite Emissions vs. Average Daily $PM_{2.5}$ Design Day Temperature for 3 Theoretical Emission Estimates



The figure shows that at temperatures above the range of Fairbanks average design days, the three alternative estimates are again close (and at 20°F and above, the second and third estimates are identical, because there is no plug-in). But at more typical design day temperatures, and increasingly for the most serious episode days, the estimates diverge widely due to both the difference in temperature slopes and the necessary use and effect of plug-in. If neither correction is made to MOVES, the estimates shown suggest that emissions from gasoline-powered on-road vehicles will be overestimated for the lowest temperature day by about 680%.

6. FINDINGS AND RECOMMENDATIONS

6.1 Findings from Dynamometer Testing and Related Research

Chassis dynamometer-based exhaust emission measurements of $PM_{2.5}$ and criteria pollutant gases were conducted in the winter of 2011 to determine the effect of ambient temperature and plug-in upon exhaust emissions. Using a chassis dynamometer, dilution tunnel, and upgraded CVS sampling system, both filter- and continuous analyzer-based measurements were made of $PM_{2.5}$ and gaseous criteria pollutants. The equipment and procedures generally complied with those specified in the Federal Code of Regulations, with adaptations for the low temperatures. A stratified random sample of 32 Fairbanks light-duty gasoline vehicles was tested. Following overnight soak, more than 100 cold-start tests were successfully completed. Each vehicle nominally received three tests: one plug-in, and two non-plug-ins (at different temperatures). Each test included two phases—referred to as a Cold ADC (Alaska Drive Cycle) and Hot ADC—which were separated by a 10-minute soak (engine off). The Cold ADC drive was preceded by a 5-minute warm-up idle, which is common practice in Fairbanks. The Alaska Drive Cycle is a time speed driving pattern designed to represent on-road driving in Alaska in winter. It is 816 seconds in duration and 4.7 miles long. The testing was conducted at the Fairbanks Cold Temperature Test Facility between January 12 and March 26, 2011, over an ambient temperature range of -30° F to 44°F (avg. 2°F).

Results from the Fairbanks emissions measurement study are summarized below.

1. Use of block heaters ("plug-in"), heated garages, and extended warm-up idle for light duty vehicles are all normal activities and/or practical necessities in Fairbanks in winter that can significantly affect $PM_{2.5}$ emissions. However, examination of these effects, which are critical in Fairbanks but less important in locations in the lower 48 states, was beyond the scope of EPA's Kansas City PM Emissions Characterization Study and of current EPA guidance for using MOVES.[*] In addition, the PM emission factors in MOVES, including the temperature corrections of those emission factors, are derived from measurements made in Kansas City, where the minimum temperature for the testing was +12°F.[†] That Kansas City minimum temperature exceeds the long-term average monthly

[*] Sierra believes that both MOVES and the Kansas City Study are ambitious, pioneering efforts that have substantially advanced the art of emission measurement and engineering. But neither was designed to apply to Fairbanks-like winter conditions and, without further adjustment, they don't apply well.

[†] At this and higher temperatures, block heater plug-in is not typically required for gasoline-powered vehicles, and it was not used in the Kansas City Study.

temperature in Fairbanks for the months of November through March[29] and is well above the -12°F average daily temperature for $PM_{2.5}$ design day episodes in Fairbanks.[30] Other "low temperature" vehicle PM emission studies used to support or help corroborate MOVES had only a limited number of vehicles and tests, conducted testing only down to about -20 or 0°F, and did not include analysis of plug-in, heated garaging, or warm-up idle. As a result of the above limitations, any modeling of Fairbanks PM emissions using MOVES must necessarily rely upon extrapolations of effects measured at higher temperatures, neglect the effects of plug-in and extended idle, and/or neglect other real effects that significantly influence emissions. The results from emission testing in Fairbanks in the winter of 2011 (summarized below) confirm that such extrapolation and assumptions are not technically supportable and could result in overestimating the $PM_{2.5}$ emissions from light-duty gasoline vehicles by up to 680%.

2. $PM_{2.5}$ emissions from a "Cold ADC" test—representing a morning cold start, warm-up idle, and drive ("Cold ADC")—had an average baseline value of 27.5 mg/mi at an ambient temperature of 20°F. These emissions (assuming vehicles were not garaged or plugged in) increased exponentially by 26.2% for each 10°F drop in ambient temperature below 20°F (temperature coefficient of 0.0233). By contrast, the EPA-sponsored Kansas City Study reported a $PM_{2.5}$ emissions increase of 58% (more than twice as much) for the same temperature drop (temperature coefficient of -0.0456).

3. For the warm ("hot start") phase of testing, Fairbanks (and Kansas City) vehicles showed, as expected, much lower base $PM_{2.5}$ emissions than the cold start phase. However, the testing of Fairbanks vehicles showed no residual influence of ambient temperature in the hot phase, whereas Kansas City testing showed a temperature sensitivity coefficient of -.0318±0.0028, which predicts an increase of 37% in "stabilized, hot running" emissions for every 10°F decrease in temperature (assuming that the KC temperature coefficient is extrapolated to the colder range of Alaska winters). While the reasons for the difference are not all known, it is noted that the Fairbanks testing had a much longer first phase (300 seconds of warm-up idle plus 816-second ADC = 1,116 seconds) compared to 310 seconds for the first phase of the LA92 cycle used in Kansas City, and the Fairbanks cold starts began with a 5-minute warm-up idle; both of these factors are expected to reduce the influence of temperature. In addition, all of the Fairbanks 32-vehicle testing was completed within 2½ months, whereas the KC testing was conducted in a summer phase and a later winter phase, between which different fuels could have been used and other changes may have occurred.

The EPA-sponsored Kansas City study collected data under different conditions and for an older fleet (with a smaller fraction of low-temperature certified vehicles) than the Fairbanks study. For example, the Kansas City data were collected in the temperature range from +90°F to +12°F. Thus, application of the Kansas City data to Fairbanks winter temperatures requires extrapolation of temperature effects outside the range in which the data were collected. It is unclear whether the KC fleet $PM_{2.5}$ measurements at temperatures as high as +90°F have the same reliability as emissions measurements collected in Fairbanks at typical Alaskan winter temperatures.

5. Based on Fairbanks winter test results, cold-start $PM_{2.5}$ emissions were reduced by 74% after block heater plug-in during overnight soak and 5-minute warm-up idle after engine start (which together is the common practice for vehicles parked outside overnight or for extended periods in Fairbanks in winter). Neither plug-in nor warm-up idle of light-duty gasoline vehicles is considered in MOVES, despite the fact that most gasoline vehicles will not start reliably without starting assist at temperatures below about -20°F, and such starting is not routinely attempted in normal winter operation in Fairbanks.

6. Based on filter-calibrated continuous analyzer measurements from non-plug-in Cold ADC dyno drives, most of the $PM_{2.5}$ was emitted within the first 2 minutes after engine start, i.e., probably before the catalyst "lit off" and the vehicle's emission control system entered close-loop operation. In addition to startup, $PM_{2.5}$ emissions tended to "spike" during the high power accelerations. Compared to the foregoing two types of events, $PM_{2.5}$ emissions at almost all other times were negligible for most vehicles, regardless of temperature (this may not be true or for "high-emitting vehicles").

7. As a secondary objective of the dynamometer study, gaseous criteria pollutants were also measured and results are presented for the temperature dependencies of those emissions.

6.2 Findings about State of Engine Warm-Up in Fairbanks in Winter

Summarized below are observations based upon a review of earlier telephone survey data; an examination of electronically logged vehicle activity data, including soak times and engine coolant temperature data; ambient temperature measurements at several locations; and upon coolant and other engine temperature data collected during dyno testing.

1. Plug-in engine block heaters are ubiquitous in the Fairbanks winter vehicle population, and they are widely used when vehicles are parked outside for more than a few hours. This is documented by phone survey data showing that for overnight parking at home, heated garaging is the most common vehicle "keep warm" strategy (used by 57% of phone survey respondents) and plug-in is the next (37%). For vehicles parked at work, plug-in (66%) is the most common keep-warm activity.

2. For overnight outdoor soaks of dyno test vehicles, the average difference between starting engine (or coolant) temperature and ambient temperature was less than

5°F. That is, non-plugged-in vehicles tended to equilibrate overnight to nearly ambient temperature. In contrast, plugged-in vehicles had engine temperatures that were, on average, 56°F higher than ambient temperature (which is likely similar to heated garage temperatures).

3. From instrumented vehicle data, vehicles in Fairbanks typically exhibit markedly elevated coolant temperatures at engine start after extended soaks compared to what would be expected based on ambient temperature cool-down. For soak times longer than six hours, and for the three ambient temperatures ranges of below -20°F, -20°F to 0°F, and 0°F to +20°F, the average startup coolant temperatures of in-use vehicles ranged from 39°F to 55°F and closely matched that of plugged in vehicles. (For shorter soak times, the corresponding average coolant temperatures at start ranged from 119°F to 135°F, indicating partially warmed-up engines.) These elevated coolant temperatures are almost certainly due to "keep warm" efforts by operators.

4. Instrumented vehicle data suggest that, except for very short soak periods (less than two hours), plug-in is used almost universally for engine starts at ambient temperatures below -20°F. While it is possible to start some newer gasoline-powered vehicles at ambient temperatures below -20°F, this is neither recommended nor normal practice in Fairbanks.

5. Limited instrumented vehicle data indicate that plug-in is not used at ambient temperatures above 20°F. In this temperature range, starting coolant temperatures for all soak durations better matched a cool-down model than a plug-in model. However, this temperature range is above that for most tentatively identified Fairbanks "Design Day" conditions.

6.3 Findings from Plume Following and Related Research

Conclusions based upon on-road measurements of $PM_{2.5}/CO_2$ ratios in the exhaust plumes of six vehicles previously tested on a dynamometer and upon a sampling of more than 1,000 plumes from pseudo-randomly selected on-road target vehicles of various types in Fairbanks are summarized below.

1. An on-road measured plume ratio* of 0.215 ug/m^3 $PM_{2.5}$ per ppm of CO_2 during accelerations could be used to distinguish two "high emitters" from four "normal emitters" in a dynamometer pilot study sample of light-duty gasoline-powered vehicles. Thus, it could serve as a threshold to distinguish normal from high emitters. Based on this threshold ratio and the results from sampling acceleration

* Five-second ratio of vehicle-emitted $PM_{2.5}$ and CO_2 concentrations after subtracting estimated background contributions.

plumes from a pseudo-randomly selected sample of 630[*] on-road vehicle plumes, 7.5% of the on-road fleet in Fairbanks would be classified as high emitters.

2. Additional information from license plate lookups of 549 vehicles from the on-road sample of plume ratios revealed the following rank order, beginning with the highest average emission emissions ratio: heavy-duty Diesel trucks (ratio 0.408) > heavy-duty gas trucks (0.326) > Diesel-powered vehicles (0.245) > light-duty Diesel trucks (0.202) > and light-duty gas trucks (0.071).

The equipment, methods, and more detailed results from the on-road, plume-following emission study are contained in Volume 4 of this report.

6.4 Recommendations for Further Study

Based on the results of this study, several actions, as summarized below, are recommended to help achieve DEC achieve its goal of determining the extent to which motor vehicles contribute to the existing $PM_{2.5}$ problem in Fairbanks

1. To begin to understand the effect of Fairbanks winter temperatures upon Diesel emissions, which are currently modeled in MOVES as having no temperature dependency, it is recommended to design and conduct a pilot dynamometer exhaust measurement[†] study of a small number of light-duty Diesels in Fairbanks.

2. Mainly in support of item 1, but also to enhance the current (limited) database on state of engine warm-up under certain conditions, a more comprehensive data logging survey of on-road vehicles is recommended. The survey should begin before the onset of winter temperatures and continue until well after the end of winter in order to capture the effects of both winter keep-warm activities and to identify the fall and spring transition temperatures. It is recommended that the survey include, as a minimum, coolant temperatures, air temperatures, and fuel system status (i.e., the onset of closed loop operation). It is further recommended that Diesel and gasoline vehicles of all sizes be included, and that first priority be given to characterizing the state of warm-up of light-duty Diesel vehicles, as this information will be needed to design a study protocol for item 3. Finally, it is suggested that each vehicle owner in the survey be asked how they park their vehicle overnight (heated garage, unheated garage, outdoor plug-in, outdoor non-plug-in, programmable autostart, or other).

3. To assist in quantifying the effect of temperature upon Diesel-powered vehicles and to obtain a larger, more representative sample for heavy-duty vehicles, both

[*] This represents the subsample whose license plates could be read, thereby permitting exclusion of duplicate counts of the same vehicle.
[†] Recommendations for system maintenance/modifications prior to further testing have been provided separately.

Diesel and gasoline, DEC should consider a limited continuation of more targeted on-road plume following for these categories, including on-road sampling (ideally of the same vehicles), that covers a range of temperatures.

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