DRAFT

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

Volume 2: Pilot Dynamometer-Based Emissions Measurements and MOVES Analysis

prepared for:

Alaska Department of Environmental Conservation

July 2011

prepared by:

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Finally, despite the support provided by all of the above, any opinions or errors in this report are solely attributable to Sierra Research, and are not the responsibility of our sponsors or other contributors.

the authors

Testing team members (left to right): Todd Thompson, Missy Jensen, Kelly Shaw, Jeremy Bahr, Steve Gano, Dennis McClement. Not pictured: Joan Hardesty. (Photo by Frank Di Genova)

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

Volume 2: Pilot Dynamometer-Based Emissions Measurements and MOVES Analysis

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1. INTRODUCTION AND SUMMARY

Low-temperature emission testing presents formidable technical challenges. Compounding these is the nature of particulate matter (PM) emissions, as noted by the U.S. Environmental Protection Agency (EPA) in its Kansas City study[1]:

> *...PM is a dynamic pollutant that is constantly being influenced by its environment therefore its formation is constantly changing both in the exhaust stream and in the ambient air. Our tests are a snapshot using specific methods under specific laboratory conditions. Real world PM may differ significantly.*

With this in mind, in the late fall and early winter of 2009, the Fairbanks Cold Temperature Test Facility was upgraded and modified[*] for dilution tunnel- and chassis dynamometer-based exhaust emission measurements of $PM_{2.5}$ and criteria pollutant gases. Pilot tests were then conducted in the winter of 2009-2010 on a selected set of four "normal emitter" and two "high emitter" gasoline-powered vehicles, one of which had induced defects.

The main purposes of the dynamometer pilot study were as follows:

1. To upgrade the Fairbanks Cold Temperature Test Facility to provide dilution tunnel-based chassis dynamometer measurement of exhaust $PM_{2.5}$[†] sampling;
2. To test a selected sample of vehicles to determine the impacts of temperature and plug-in upon $PM_{2.5}$ emissions for the same vehicle at different ambient temperatures; and
3. To assess how well the measured Fairbanks test results compare to emission estimates from the U.S. Environmental Protection Agency's MOVES emissions model, with particular interest in ambient temperature effects and Alaska wintertime driving behavior.

The pilot testing program was performed in February 2010, during which the start of test temperatures ranged from -24°F to +23°F. Each vehicle was tested with and without overnight block heater ("plug-in") operation and/or 5-minute warm-up idle, both of which are customary for overnight outdoor soaks in Fairbanks during the winter.

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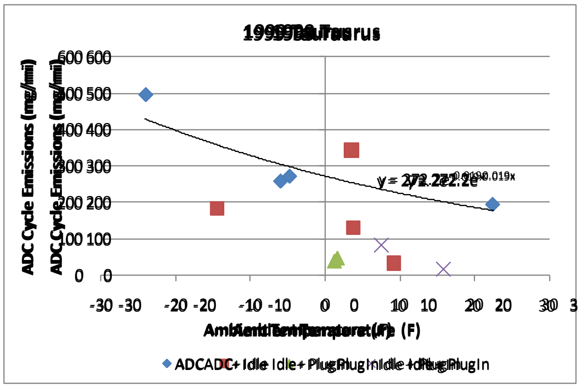
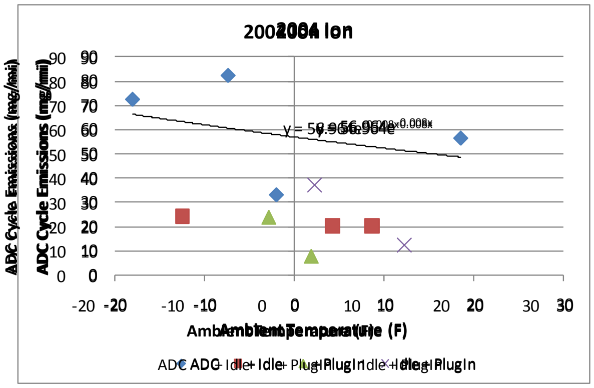
[*] The upgrades and modifications are described in detail in "Characterizing Vehicular Contributions to $PM_{2.5}$ in Fairbanks, Alaska; Volume 1: Dynamometer-Based Emissions Measurements, Vehicle Keep-Warm Activities and MOVES Analysis," prepared for DEC by Sierra Research, July 2011.

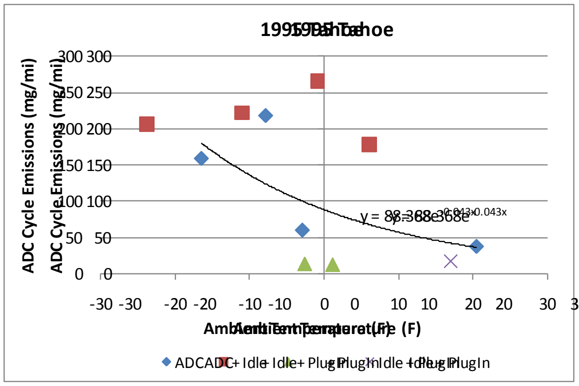
[†] "$PM_{2.5}$" refers to fine particles in atmosphere having an aerodynamic diameter smaller than 2.5 microns.

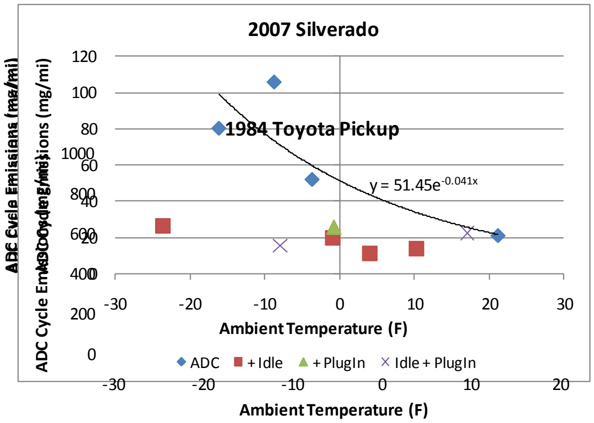
Figures 1-1 and 1-2 present the results for cold and hot test phases (analyzed using filter measurements) and for second-by-second testing (analyzed using filter-calibrated instrumental measurements). Although it represents a much smaller vehicle sample, pilot study results were consistent with results from the main study conducted in 2011, which are reported in Volume 1.

Figure 1-1
$PM_{2.5}$ Emission Trends vs Temperature for the Cold Alaska Drive Cycle (ADC) "Normal Emitters"

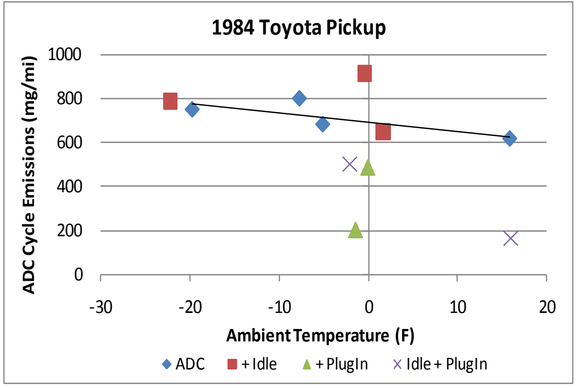


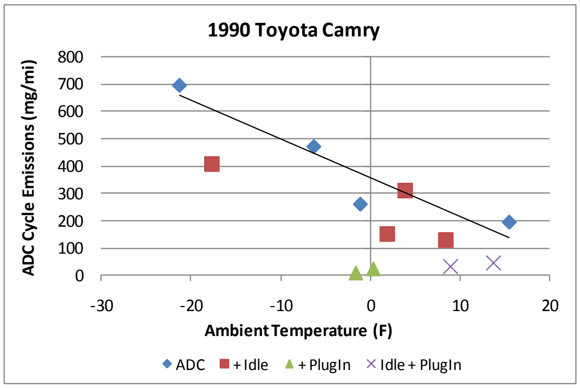






"High Emitters"





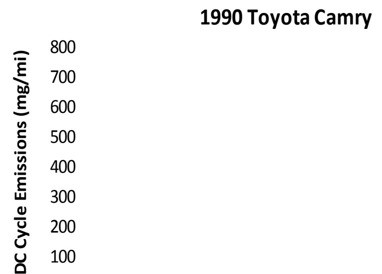
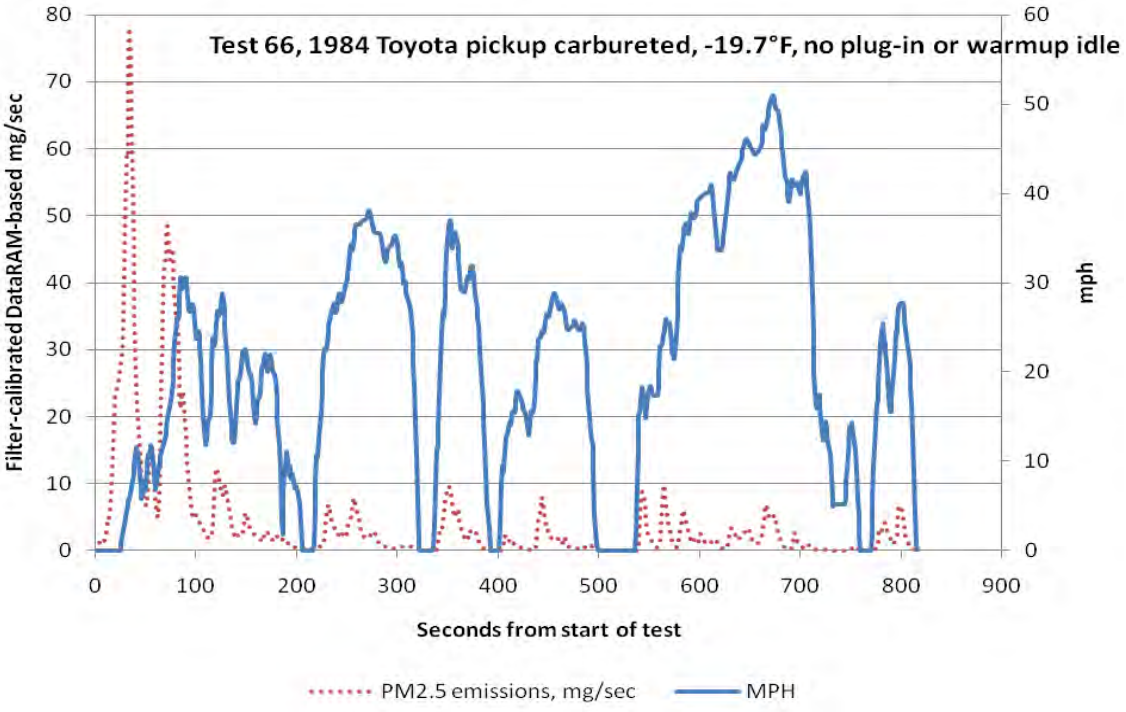
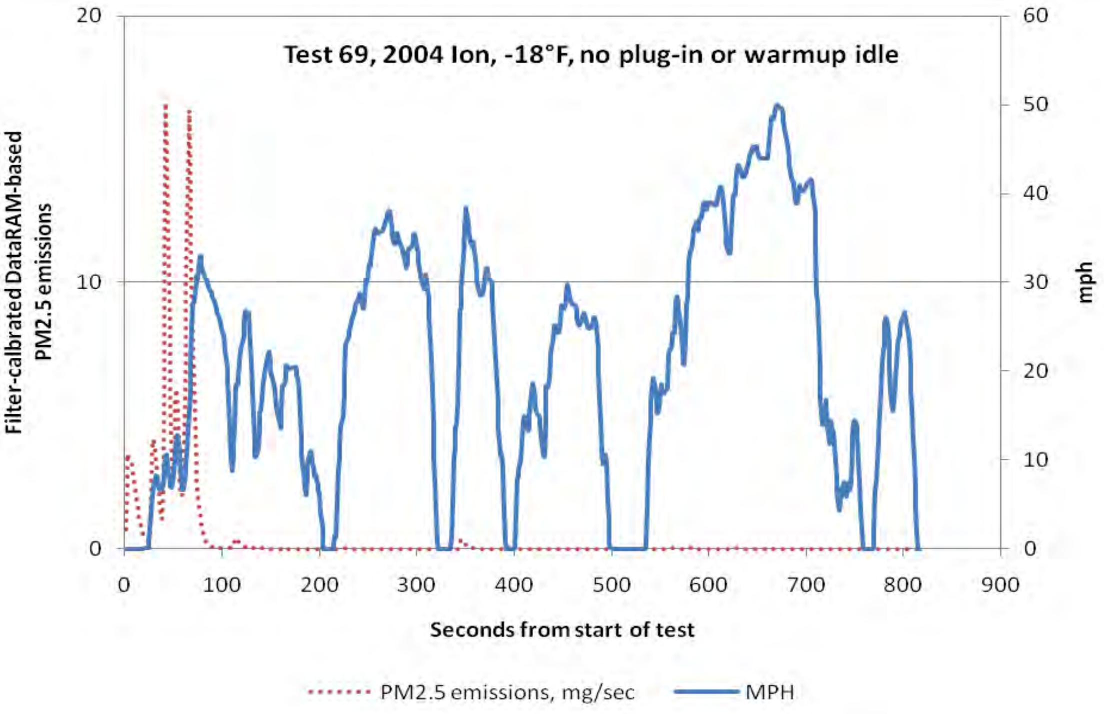


Figure 1-2a and b
Sample Dynamometer Drive Traces Contrasting
Second-by-Second $PM_{2.5}$ Emissions for a Cold ADC
“High Emitter”



“Normal Emitter”
(note change in PM scale)



Summarized below are the main findings from the dynamometer pilot study and the MOVES analysis. Subsequent sections describe the pilot dynamometer testing program that was conducted in 2009-2010 (Section 2), the dynamometer testing results (Sections 3 and 4), and comparison of specific results with MOVES (Section 5).

1.1 Main Findings from the Dynamometer Pilot Study

Findings based on an analysis of the results from the Fairbanks emissions measurement study, together with a detailed review of EPA's Kansas City study and other pertinent low temperature emissions studies, are summarized below.

1. Based on the testing in Fairbanks of a sample of four gasoline-powered "normal emitters" in the winter of 2009-2010, $PM_{2.5}$ emissions for the Cold ADC[*] increased exponentially with decreasing ambient temperature (even without plug-in or warm-up idle); however, the temperature sensitivity of ADC emissions was not as great as that reported in EPA's Kansas City Study using the LA92, which is a different driving cycle with a shorter initial phase. For the Fairbanks vehicles, which were tested over a temperature range of moderate winter temperatures (by Fairbanks standards), $PM_{2.5}$ emissions increased 31% for every 10°F drop in temperature (ambient temperature coefficient of -0.0268). Notably, the derived temperature coefficient for the Cold ADC of -0.0268 (standard error = 0.003) matched that found for the 32 vehicle sample in the main study in 2011, -0.0233 (0.0047), as reported in Volume 1. By contrast, the Kansas City Study reported a $PM_{2.5}$ emissions increase of 58% (nearly twice as much) for the same temperature drop (temperature coefficient of -0.0456). Considering the uncertainties of the two studies (±0.0084 and ±0.0052, respectively), the temperature sensitivity of $PM_{2.5}$ emissions from the sample of Alaskan vehicles when driving the Cold ADC is significantly lower than that of the cold FTP when the EPA's Kansas City results are extrapolated down to the full temperature range of the Alaska testing.

2. For the warm ("hot start") phase of testing, Fairbanks (and KC) vehicles showed, as expected, much lower base emissions than the cold start phase. However, the testing of "normal emitters" in Fairbanks showed no residual influence of ambient temperature in the hot phase, whereas KC testing showed a temperature sensitivity coefficient of -0.0318±0.0028, which predicts an increase of 37% in hot running emissions for every 10°F decrease in temperature (assuming that the KC temperature coefficient can be extrapolated to the colder range of Alaska winters). Although the reasons for this difference are not known, it should be noted that the Fairbanks testing was completed within a period of approximately one month, whereas the KC testing was conducted in a summer phase and a later winter phases—between those times, test vehicles were returned to customer service, different fuels could have been used, and other changes may have occurred.

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[*] Testing in Fairbanks utilized the 816-second long Alaska Drive Cycle (ADC), with a cold start, soak, and hot start test phase, somewhat analogous to the LA4 cycle used in the Federal Test Procedure.

3. The EPA's 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 under typical Alaskan winter temperatures.

4. Based on Fairbanks winter test results, block heater plug-in during overnight soak and a 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[*2]) reduced cold start $PM_{2.5}$ emissions by 74%. The incremental effect of combining warm-up idle with plug-in was to diminish the effectiveness of plug-in alone[†] (there was 80% reduction for plug-in alone). None of these effects is considered in MOVES, despite the fact that at temperatures below about -20°F, most gasoline vehicles will not start without assistance, and such starting is not even attempted in normal winter operation in Fairbanks.

5. Based on the Fairbanks winter test results, a series of modeling equations were developed to predict average $PM_{2.5}$ emission factors. This emissions modeling approach calculated Cold and Hot ADC base emissions of 111 and 6 mg/mi, respectively, for "normal emitters," and of 561 and 161 mg/mi, for Cold and Hot ADCs from "high emitters." For the Cold ADCs, the base emissions were adjusted to account for the following factors: effective temperature (using an exponential factor), ambient temperature, and (where applicable) warm-up idle and plug-in. In addition, a model-year-based age correction was applied for cold start of normal emitters, and fuel system-based corrections (carburetion vs. fuel injection), both hot and cold, were applied for high emitters.[‡]

6. Due to the ambient temperatures that prevailed at the time of plug-in testing, the plug-in benefit was measured only at temperatures close to zero. In an effort to fill the gap in assessing block heater effectiveness at lower temperatures, a coolant temperature-based "engineering model" was developed using "CarChip" data from just two (normal emitter) vehicles. The resulting modeled emissions estimate of the average emissions reductions from plug-in was consistent with data from all 4 normal emitters.

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[*] The use of radio-based remote start devices, locally referred to as "autostarts," is common and widely used in Fairbanks in winter to facilitate warm-up idle. Five- to ten-minute warm-up idles are most common.

[†] It is <u>not</u> normal practice in Fairbanks during the wintertime to drive a vehicle after an overnight or extended soak without a warm-up idle, even when using a block heater.

[‡] See Section 2.4 for further detail.

7. As a secondary objective of the dynamometer study, gaseous criteria pollutants were also measured. However, the data were limited due in part to instrument saturation during fuel enriched cold starts, and due to HC analyzer malfunction.*

1.2 Main Findings from the MOVES Analysis

EPA has done a very commendable job in designing and developing the MOVES model to provide a great degree of configurability toward accounting for emission effects of a wide range of vehicle fleet characteristics, driving patterns, ambient conditions, and fuel properties. However, as outlined below, this study reveals that Fairbanks has several unique patterns in wintertime vehicle driving and operation that do not widely occur outside Alaska, and that cannot be easily modeled using MOVES.

1. Plug-in Block Heater Usage – MOVES' design is simply not configured to account for the warmer thermal state of the engine and, to an extent, the catalyst when a vehicle is plugged in to a block heater under extreme cold soaks. MOVES dynamically calculates incremental starting exhaust emissions based on soak time-related and ambient temperature inputs. These internal starting emissions calculations cannot be easily revised to account for warmer engine/catalyst thermal states reflecting block heater use during outdoor Fairbanks engine-off periods. As noted earlier, the emissions impact of these warmer thermal states is significant—$PM_{2.5}$ emissions are roughly 75-80% lower compared to the case without plug-in.

2. Warm-up Idling – MOVES model outputs do not include warm-up idling rates that represent emissions associated with vehicle idling for extended periods when the vehicle is first started, as commonly occurs during the winter in Fairbanks. MOVES does output idling rates referred to as "extended idle," but this refers to heavy-duty trucks that are idled for extended periods between trips (e.g., to provide heat or power to the truck cab). These heavy truck extended idle rates are not representative of light-duty vehicle warm-up idling in Fairbanks. The underlying MySQL database that serves as the backbone of MOVES contains idling exhaust rates for each of the vehicle categories represented in MOVES, but these rates reflect fully-warmed up vehicles and are "reference" rates based on standard ambient conditions and fuel properties. Even these internally stored idle rates cannot be easily reconfigured to represent local warm-up idling rates in Fairbanks.

3. Mild Wintertime Driving Patterns – During winter in Fairbanks, the presence of snowy and icy road conditions forces motorists to drive more mildly than reflected in the default "dry road" driving cycles contained in MOVES. In its initial release of the MOVES2010 model, EPA designed the user interface in a manner that allows alternative driving cycles to be input only within the "Project Scale" execution mode. This execution mode is geared toward modeling of a

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[*] See Section 2.3 for further detail.

single project, such as an intersection or corridor re-design, rather than regional emissions to support a State Implementation Plan (SIP) or conformity planning inventory. In late August 2010, EPA released an updated version of MOVES2010 that enables users to input alternative database tables, include those representing default driving cycles in the model, when generating regional inventories. However, EPA has not yet officially released instructions or guidance for when and how users can input revised driving cycles via this generic table import feature.

As discussed later in Section 5, the first two factors will need to be addressed via post-processing adjustments performed outside and downstream of MOVES. These post-processing adjustments will need to account for the fact that the incremental plug-in benefits are strongly affected by the length of the soak period (i.e., the amount of time a vehicle is parked and plugged in).

For the third factor, an approach was developed, as detailed in Section 5, to edit the MOVES driving cycle database tables to reflect driving patterns based on the Alaska Driving Cycle—a cycle developed under an earlier study for use in representing wintertime driving in Alaska. It showed that MOVES-simulated $PM_{2.5}$ emissions over the ADC are roughly 22% lower than the default driving patterns represented in MOVES.

Additional findings from the MOVES analysis, beyond examination of the aforementioned unique wintertime Fairbanks patterns, are summarized below.

1. Initial comparisons of the limited sample of gasoline vehicle dynamometer test results from this study show significantly lower warmed-up exhaust $PM_{2.5}$ emission rates than represented in MOVES.

2. The difference in exhaust $PM_{2.5}$ emission rates between the test results and MOVES may be explained largely by the significant differences in the degree to which emissions are dependent on ambient temperature in this study, compared to EPA's findings from the Kansas City study that are incorporated in MOVES. Running exhaust $PM_{2.5}$ emissions in Fairbanks were found to exhibit much less dependence on temperature than represented in MOVES.

3. A temperature effect is difficult to discern because the ranges of ambient temperatures for which test measurements were collected in Fairbanks and Kansas City have little overlap.

4. EPA has yet to implement temperature dependence for Diesel exhaust emissions in MOVES. This is a reflection of the lack of ambient temperature testing studies for Diesel vehicles, rather than a criticism of MOVES. Nevertheless, the ability to represent Diesel emissions variations with ambient temperature in a future release of MOVES will make the model more effective in modeling vehicle

emissions in colder climates, especially those such as Fairbanks where PM emissions are important.

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2. DYNAMOMETER TESTING

2.1 Testing Plan and Revisions

In the fall and early winter of 2009, the Fairbanks Cold Temperature Test Facility was upgraded and modified for dilution tunnel- and chassis dynamometer-based exhaust emission measurements of $PM_{2.5}$ and criteria pollutant gases. The test facility and those upgrades and changes, are described and pictured in Volume 1[*] of this report.

Briefly, a pilot exhaust emission testing program was conducted in the winter of 2009-2010 on a selected set of four "normal emitter" and two "high emitter" gasoline-powered vehicles, one of which had induced defects. In order to address the project goals of evaluating the effects of temperature, plug-in and warm-up idle upon vehicular $PM_{2.5}$ emissions, a testing plan was devised that provided for testing of a sample of vehicles, each under a range of controlled or measured conditions, as summarized in Table 2-1. In the table, each "X" represents a single 2- or 3-phase cold start test with two Alaska Drive Cycles (ADCs), so each vehicle was nominally cold-start tested 12 times (including replicates). Each cold start test was conducted after an overnight soak outdoors, and vehicle conditioning consisted of the prior day's testing (or two days, in the case of Monday testing).

Testing of each vehicle at a minimum of two different ambient temperatures was needed so that the effect of temperature upon emissions could be evaluated. The targeted temperature ranges were -20°F to 0°F for colder temperature operation and +20°F to 0°F

Table 2-1
Targeted Test Matrix for Each Vehicle

+20 < T(°F) < 0		0 < T(°F) < -20			
No Plug-in		No Plug-in		With Plug-in	
Warm-up Idle	No Warm-up Idle	Warm-up Idle	No Warm-up Idle	Warm-up Idle	No Warm-up Idle
X	X	X	X	X	X
X	X	X	X	X	X

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[*] "Characterizing Vehicular Contributions to $PM_{2.5}$ in Fairbanks, Alaska; Volume 1: Dynamometer-Based Emissions Measurements, Vehicle Keep-Warm Activity and MOVES Analysis," prepared for DEC by Sierra Research, July 2011.

for warmer temperature operation. While this by no means covers the full range of winter temperatures in Fairbanks,* the intent for this test program was to sample within the range where most vehicles can still be cold-started without plug-in (above about -20°F), even though starting assistance might be required in some cases (it was), but below the temperature where it could be assumed that most Fairbanks residents would normally be expected to plug-in overnight during the winter months (about +20°F).

As reflected in the test matrix, when testing in the above-zero temperature regime, plug-in testing was not planned, as it was expected that emissions with plug-in would be relatively insensitive to ambient temperature over the relatively narrow above zero temperature window of the current test program.

Note that in this test design, plug-in and warm-up idle were controlled variables, but because vehicles were soaked outdoors and the test cell was exposed to outdoor temperatures, test temperature could be controlled only to the extent of choosing days and times of day for testing. This element was important in the execution of the study, as unseasonably warm temperatures during part of February required the test team to initiate testing at about 4 am on most days in order to complete most or all testing before noon, thereby taking advantage of cooler soak and test temperatures in the late evening and early morning hours.

Additional planned testing included make-up tests and testing with unheated dilution air.

<u>Problems Encountered and Changes Made after the Pilot Testing Program</u> – As problems and new issues were encountered during the pilot study, revisions to the test plan were made as warranted. Table 2-1 lists a number of the problems that occurred in the 2009-2010 Pilot Study and the actions that were taken to remedy them, either during or after the pilot study.

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* Fairbanks winter temperatures tend to range as low as about -45°F, with much lower record temperatures, and ambient 24-hour average $PM_{2.5}$ concentrations tend to increase as temperature decreases.

Table 2-2
Problems Encountered and Changes Implemented During or Following the Pilot Study Program

Pilot Study Problem	Remedial Action
Horiba HC analyzer originally could not be calibrated to spec; prevented propane recovery test in pilot program.	Replaced plugged capillary and calibrated analyzer to spec; ran propane recovery tests before, during and after 2011 dyno study.
CVS blower showed evidence of damage.	Replaced blower prior to 2011dyno study.
Needed for a more representative vehicle sample.	Used stratified random phone survey sample; increased sample size from 6 to 32.
Custom transfer tubes impractical for larger vehicle sample; mix of pipe sizes was problematic.	Replaced by more adaptable system of interchangeable pieces; fixed dilution tunnel in one location for FWD and RWD vehicles.
Original heating blankets failed mechanically.	Replaced with dedicated heaters for the interchangeable pieces, including heated flex tubes and thermostatically heated pipes.
Unnecessary flow bends and length; worn and dirty sampling "boots."	Shortened and straightened dilution air and CVS flows; all new sampling boots for 2011 study
Use of separate test (filter) phase for 5 minute warm-up idle limited throughput affordable.	After pilot study, ran 2-phase rather than 3-phase testing.
Comprehensive replicate testing not feasible for 30+ vehicle study.	Replicate testing removed from 2011 study plan although some replicates still occurred by happenstance.
Analog did not faithfully represent full dynamic range of PM analyzers.	Reprogrammed for digital communication between PM analyzers and Horiba computer.
Use of multiple drivers caused unnecessary variability in driving.	Used a single experienced driver.
Excessive tire/roll slip caused or contributed to drive trace "violations."	Scrubbed tires with Scotch-Brite before each test; reduced tire slip and improved driving.
Driver pendant failed early in 2011.	Replaced with 2-way radios; no more pendant.
Needed immediate ambient temperature readings onsite.	Used wireless ambient temperature probe for daily review and planning.
Pegging of HC&CO analyzers saturated A/D, occasional data corruption.	Installed isolation amplifiers for HC, CO prior to 2011 dyno study, eliminated data corruption; (analyzers still occasionally pegged).
Excessive static electricity slowed filter weighing.	Installed ground pads under balance/on floor, grounded wrist/shoe straps for operator, used anti-static spray; humidifier in the balance room in addition to the one in the filter equilibration box.

2.2 Vehicles Selected for Dynamometer Testing

Consistent with the goals, budget, and timing of the project, a sample size of six vehicles[*] was selected for testing. All of the vehicles were Alaska-licensed, street legal, participant-owned, in-use vehicles, and were recruited primarily through an e-mail inquiry to Borough employees.

Due to the limited sample size, it was not practical to rely on a random sample. Instead, three cars and three trucks were tested, drawing from common makes/models and a range of ages/mileages. In addition, two known visibly smoking vehicles were intentionally included in the study to ensure that the measurement system would be capable of distinguishing visible smokers from non-smokers (which it was). A seventh vehicle, a 2004 Dodge Caravan, was held for back-up and used for limited non-filter-based testing. It will not be discussed further here.

Before being accepted for testing, prospective test vehicles were screened for safe testability (e.g., no bald or studded tires, no significant exhaust leaks[†] or liquid leaks) and suitability (e.g., no fault codes set, meeting targets for the sample). All vehicle owners were required to sign a participation agreement, ensuring that their vehicles could be used in both planned phases of the test program. A consideration was also paid to vehicle owners and to volunteers who, in good faith, brought vehicles in for screening that were ultimately not needed or not accepted for testing. A summary description of the selected test vehicles, listed by model year, is provided in Table 2-2.

The first two vehicles listed in the table were the deliberately selected high PM emitters. The carbureted Toyota pickup originally had bald tires and an exhaust leak, but the owner agreed to replace both in order to participate in the test program. The Camry sedan was deliberately modified for the test program by removal of the catalyst and enrichment of the fuel mixture.[‡] Both the pickup and the Camry produced visible smoke upon cold start and during cold accelerations, and the pickup also produced extremely strong-smelling (unburned fuel) exhaust when started cold. The Tahoe required a new muffler and tailpipe. The last three listings, which are 1996 and later OBDII vehicles, received Carchips[§] for some or all of their testing, which allowed for logging of coolant temperature, air temperature, engine load, speed, and other parameters on a short-term basis.

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[*] 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.

[†] When first inspected, both the Toyota pickup and Tahoe had exhaust leaks, but the owners repaired those (at their own expense) as a condition of participation in the test program.

[‡] The modifications were performed by Kelly Shaw, former FNSB I/M referee.

[§] Davis Instruments, Vernon Hills, Illinois.

Table 2-3
Summary Description of Test Vehicles

Make and Model	Model Year	Engine (liters & cylinders)	Transmission	Starting Mileage	Other
Toyota pickup (high emitter)	1984	2.4 (4 cyl)	manual	202,469	carbureted; gas odor & visible smoke at start
Toyota Camry (high emitter)	1990	2.0 (4 cyl)	automatic	218,469	no cat or O_2 sensor; fuel system deliberately enriched; visible smoke at start*
Chevrolet Tahoe SUV	1995	5.7 (8 cyl)	automatic	107,660	
Ford Taurus Sedan	1999	3.0 (6 cyl.)	automatic	119,197	vacuum leak (discovered during testing)
Saturn Ion	2004	2.2 (4 cyl)	manual	71,160	
Chevrolet Silverado pickup (crew cab)	2007	4.8 (8 cyl)	automatic	21,183	

2.3 Data Collection and Quality Assurance

2.3.1 Data Collection

Initially, testing was scheduled to be performed in two phases: a cold temperature test phase in January 2010, and a subsequent warmer test phase in March. However, dynamometer maintenance issues and late delivery of the Sartorius balance delayed the start of testing until early February, at which time temperatures tended toward the warmer Phase 2 regime (+20 to 0°F). But a brief cold snap in late February, combined with early morning testing, afforded the opportunity to perform the desired testing at the colder Phase 1 target temperatures (0 to -20°F). Figure 2-1 shows the temperatures† at the start of each test.

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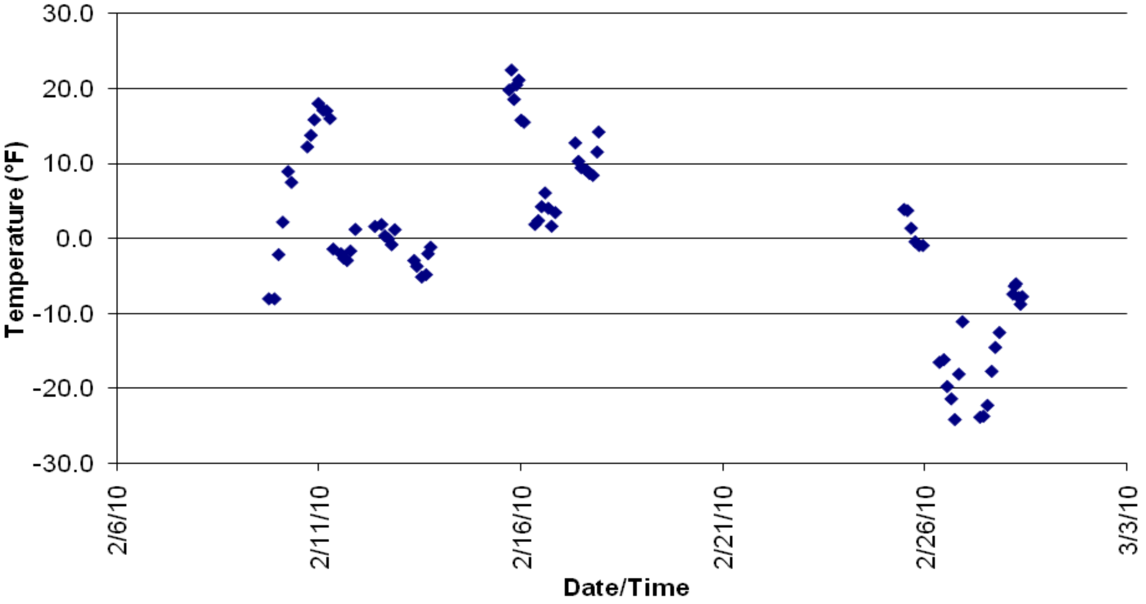
* For purposes of testing a high PM emitter, the Camry was induced to smoke by having the catalyst removed, the oxygen sensor disconnected, the evaporative canister connected to the manifold vacuum, and the fuel pressure raised about 5-8 psi due to a vacuum line disconnect. These modifications allowed it to run with 6-8% CO at the tailpipe, and with visible emissions upon cold start and warm-up.

† Temperatures are from the Fairbanks International Airport Temperature, interpolated to the start time of each test. The Airport is about 2 miles west of the test site.

Figure 2-1
Temperatures at Start of Each Test



The resulting test matrix is shown in Table 2-3, which categorizes each test number by vehicle, plug-in, and extended (warm-up) idle. Note that the more limited number of tests under the plug-in Yes (Y) category reflects the test design.

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 included the following:

- Invalidated filter results due to filter mishandling accidents, sample pump malfunction (freezing of outlet line), or operator error (failing to start sampling pump);

- Invalidated tests due to equipment malfunctions (premature termination of the drive trace), freezing of the sample pump outlet, driver error (failure to resume driving timely after the 10-minute soak or other failure to follow established driving procedures), and other fatal problems; and

- Some data being either flagged as qualified or invalidated as a result of quality assurance checks.

Table 2-4
Tests Numbers Arranged by Test Type

1984 Toyota

		Plug In	
		Y	N
Extended Idle	Y	006 017	048 052 057 061 073
	N	018 027	032 041 066 082

1990 Toyota

		Plug In	
		Y	N
Extended Idle	Y	008 012	043 055 058 074
	N	022 026	035 042 067 078

1995 Chevrolet

		Plug In	
		Y	N
Extended Idle	Y	016	046 050 056 062 070 071
	N	020 029	030 039 064 080

1999 Ford

		Plug In	
		Y	N
Extended Idle	Y	009 013	049 44 053 059 075
	N	023 024	033 037 068 079

2004 Saturn

		Plug In	
		Y	N
Extended Idle	Y	007 011	045 054 076
	N	021 025	034 069 038 077

2007 Chevrolet

		Plug In	
		Y	N
Extended Idle	Y	004 015	047 051 063 72
	N	028	031 040 065 081

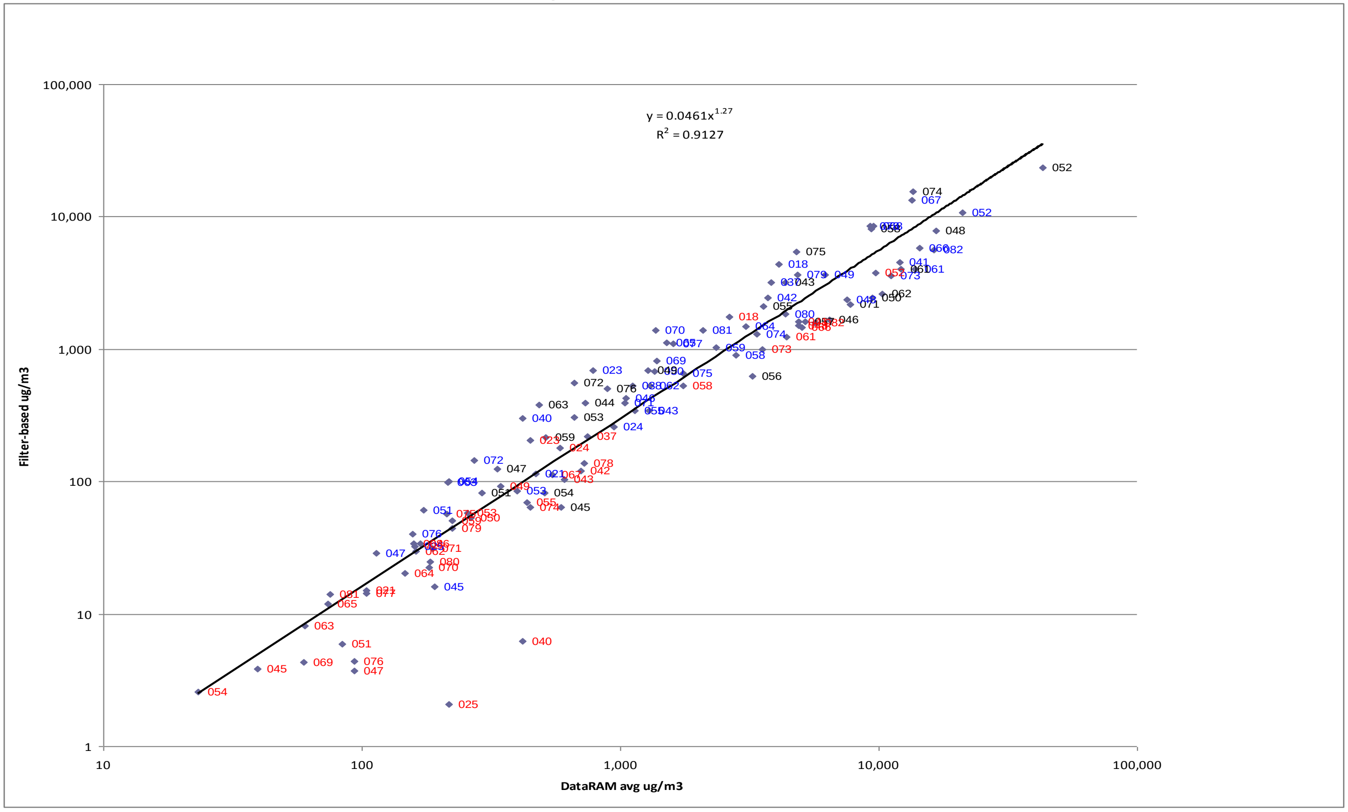
2.3.2 Quality Assurance

Particular attention in the study was devoted to quality assurance of the acquired data. As described below, a number of test results, portions of test results, and instrumental measurements, had to be qualified or invalidated as a result of quality assurance concerns.

Problems with downloading of data from both the DataRAM and DustTrak limited the availability of second-by-second data for the first several days of testing. In addition, both instruments were sometimes saturated at their maximum concentrations. This was a more serious problem with the DustTrak, due to its lower maximum concentration compared to the DataRAM; primarily for this reason, greater reliance was placed on the DataRAM for data analysis. However, data from both instruments were used to confirm low tunnel background (no more than 1-2 ug/m^3 PM$_{2.5}$) before the start of each test.

One of the Q/A tests performed was a simple comparison of the average sample concentrations by test phase as measured with a filter, and the corresponding average concentrations computed from second-by-second measurements using the factory-calibrated DataRAM. As shown in Figure 2-2, the comparison indicates a relatively

Figure 2-2



Note: label is test number: Warm-Up Idle (blue), Cold ADC (black), or Hot ADC (red) close relationship ($r^2 = 0.91$) between the two independent and differently based (nephelometry vs. gravimetric) measurement techniques over four orders of magnitude in concentration and a relatively wide range of operating and test conditions. The main region of difference (on a percentage basis) consisted of several hot start tests performed on clean vehicles at warm temperature or with plug-in (e.g., test numbers 25 and 40), when the filter measurement showed that relatively low concentrations (<10 ug/m^3) and relatively small variations in mass measurements could cause large percentage variations in filter-based concentration measurements.

Tunnel measurements of gaseous pollutants, a secondary objective for the testing, were problematic for two reasons. First, the Flame Ionization Detector (FID) used for total hydrocarbon measurements could not be calibrated to specification (and did not yield the usual straight-line calibration); second, during many tests the FID saturated, at least briefly, which appears to have affected other measurements in some cases. For these reasons, the HC emission results must be considered qualified for the pilot test program. In the final datasets, FID measurements, and in some cases other gaseous pollutant measurements, have been invalidated for portions of several tests (where FID saturation was apparently most severe).

###

3. DYNAMOMETER VEHICLE TESTING DATA

This section presents an overview of the vehicle testing data, identifying the important factors affecting $PM_{2.5}$ emissions and providing useful guidance to formulation and interpretation of the statistical analysis discussed in Section 4. A series of figures are presented that document the basic trends in emissions for the Cold and Hot ADC cycles, and for normal versus high-emissions vehicles, as functions of the following four factors examined in the vehicle testing:

- Ambient air temperature;
- Use of a warm-up idle preceding the drive on the cold ADC cycle;
- Use of an engine block heater before the cold ADC; and
- Use of both warm-up idle and a block heater before the cold ADC.

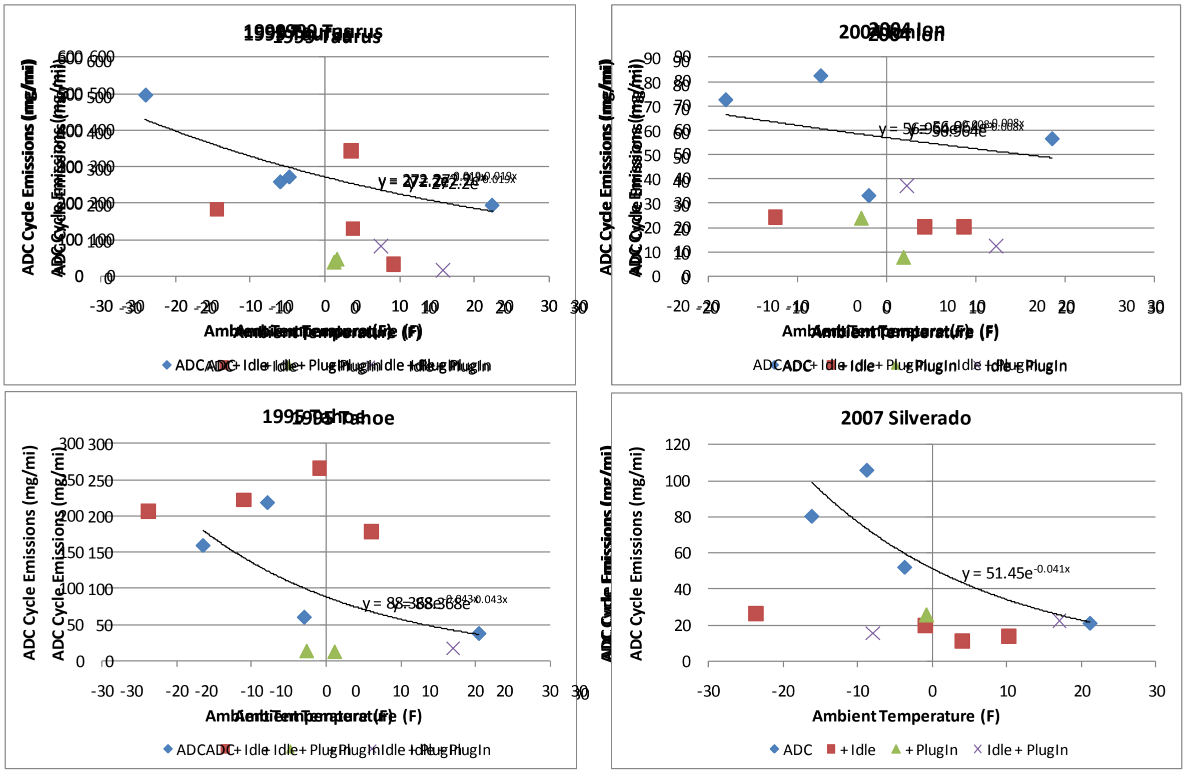
The group of normal vehicles consisted of the 1999 Taurus and 2004 Ion cars, and the 1995 Tahoe and 2007 Silverado trucks. The group of high-emissions vehicles consisted of the 1984 Toyota pickup and the 1990 Toyota Camry. The Hot ADC cycle was conducted following a ten-minute soak.

3.1 Cold ADC Cycle

Normal Vehicles – The group of four vehicles with normal emission levels can be considered to be a 2 x 2 matrix based on vehicle type (car versus truck) and age (newer versus older), as shown graphically in Figure 3-1. Cars form the first row and trucks form the second row of the figure, while older vehicles are at the left and newer vehicles are at the right. An exponential function trend line has been fit to the data to give a measure of the temperature sensitivity of emissions for the ADC test sequence; these trend lines are of the same mathematical form as will be fit in the statistical analysis. The vehicle test data suggest that the temperature sensitivity is less for cars than for trucks. The trend line coefficients are different for the two cars, although it is not known if the difference is statistically significant, while the two trucks have nearly the same coefficients.

Warm-up idle reduces emissions for both cars and for the newer truck, but increases emissions for the older truck. In all cases, plug-in prior to cold-start reduces emissions. Where warm-up idle has a benefit, it appears that plug-in alone is of comparable benefit,

Figure 3-1
Cold ADC $PM_{2.5}$ Emissions Trends vs Temperature: Normal Vehicles

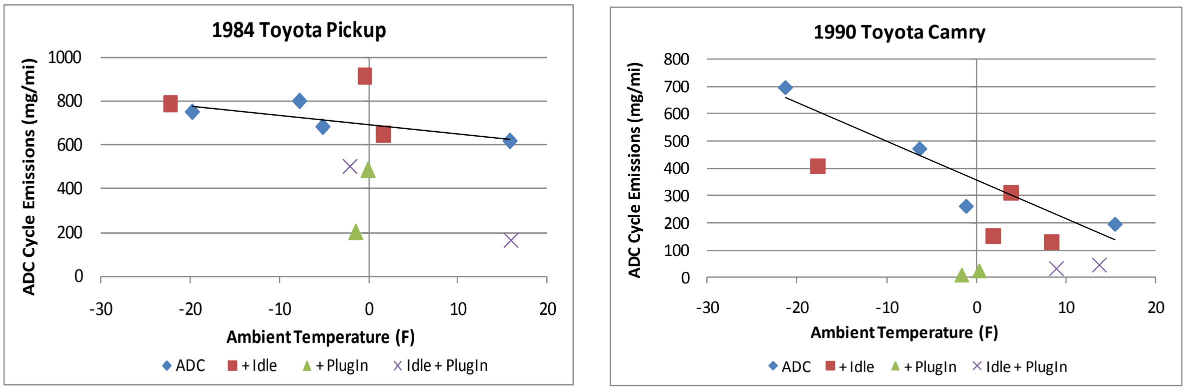


and there is no incremental benefit of adding the warm-up idle to plug-in. The data suggest that, for $PM_{2.5}$ emissions, operators do not need to idle the vehicle after start-up if they have used an engine block heater.

The quantitative modeling of these data will need to consider why $PM_{2.5}$ emissions are increased by the warm-up idle in the old truck, but are decreased by warm-up idle in the newer truck. If the data are combined, there is likely to be no net effect shown from warm-up idle in trucks.

<u>High-Emissions Vehicles</u> – The emissions effect of temperature and warm-up idle or plug-in is likely to depend on the nature of the fuel control and other emissions-related failure in a high-emissions vehicle. As Figure 3-2 shows, very different temperature sensitivities are seen for the two high-emissions vehicles, with the sensitivity being less for the older carbureted vehicle (which has somewhat higher emission levels) and greater for the newer vehicle. The warm-up idle has no emissions benefit for the older vehicle, and only a small benefit for the newer one. Plug-in prior to the cold ADC helps in both cases, but it is remarkable that plug-in is able to reduce $PM_{2.5}$ emissions for the newer vehicle (1990 Toyota) down to a level that approaches that of normal vehicles. Plug-in with warm-up idle has the same emissions effect as plug-in alone.

Figure 3-2
Cold ADC $PM_{2.5}$ Emissions Trends vs Temperature: High-Emissions Vehicles



3.2 Hot ADC Cycle

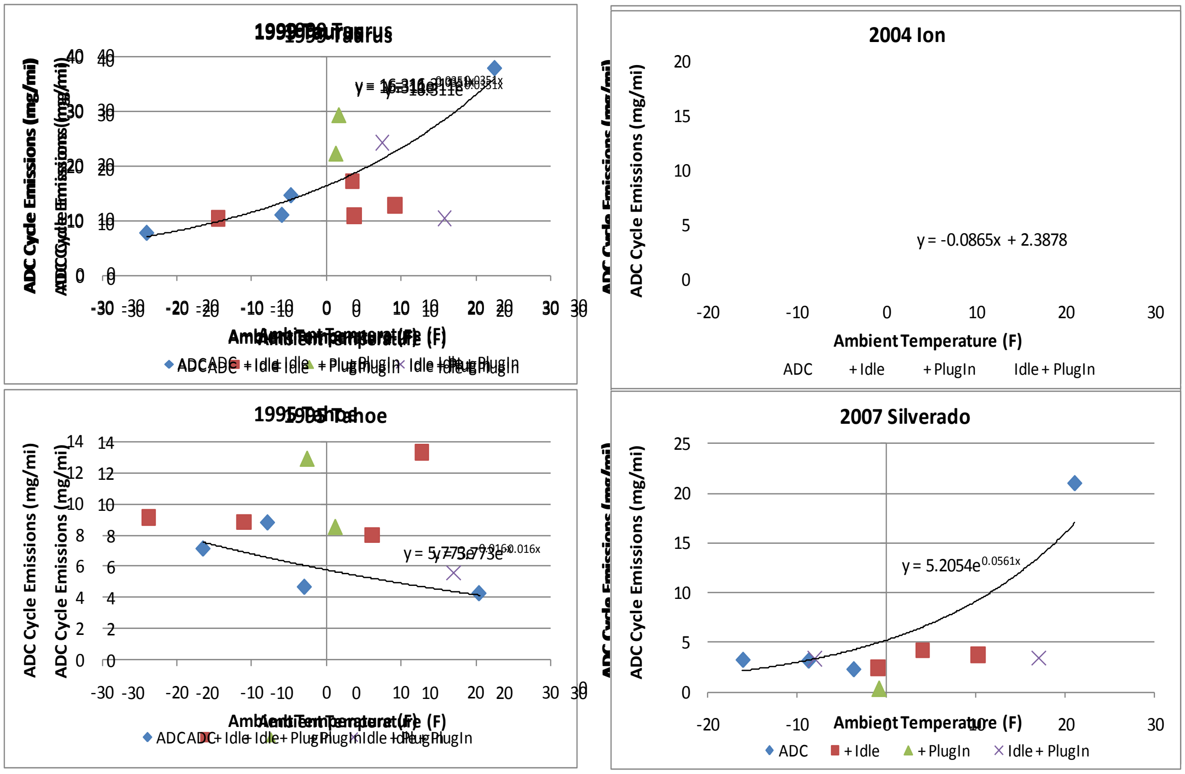
Normal Vehicles – The normal vehicles display a variety of trends with temperature, as Figure 3-3 shows, although the statistical significance of the trends is not known at this point. For two vehicles (the 1999 Ford and 2007 Chevrolet), it is not clear whether the apparent temperature sensitivity is primarily the result of the individual test data points at approximately 20°F. The trend lines shown on the charts are much less useful representations of the data than the stronger trend lines seen for the Cold ADC cycle.

For the 1999 Ford, the positive trend in $PM_{2.5}$ emissions is driven by the test point at 21°F; without this, a near-flat trend line would be estimated. Around that flat trend, warm-up idle would appear to have little effect, plug-in (that occurred prior to the cold ADC cycle) would appear to have an adverse effect, and the combination of idle plus plug-in would have no effect. If the 21°F test point is an outlier, the data for this vehicle suggest that no temperature sensitivity is present and no statistically significant effect of plug-in or idle can be detected.

For the 2004 Saturn, some sensitivity of emissions to colder temperatures is seen. Warm-up idle appears to have no effect, while plug-in may have an adverse effect, and idle plus plug-in clearly appears to have an adverse effect. Suggestions of this are contained in the data for the 1999 Ford (for plug-in at least), but it is not clear whether or not an adverse effect of this kind is real.

For the 1995 Chevrolet, trends not dissimilar to the 2004 Saturn are seen, showing some sensitivity of emissions to ambient temperature. Warm-up idle may have an adverse effect at the warmer temperatures. Plug-in and warm-up idle plus plug-in may also have adverse effects.

Figure 3-3
Hot ADC $PM_{2.5}$ Emissions Trends versus Temperature: Normal Vehicles



For the 2007 Silverado, no (or only slight) sensitivity of emissions to temperature would be seen, and there is no effect of warm-up idle or plug-in on emissions, except for the test point at 21°F. The 21°F data point looks very much like a break in the trend, and should be given further scrutiny as a possible outlier.

High-Emissions Vehicles – The Hot ADC emission levels of the two high-emissions vehicles are substantially different (see Figure 3-4), with the older vehicle continuing to have high $PM_{2.5}$ emissions, while the newer vehicle returns to emission levels similar to those of normal vehicles. Neither of the high-emissions vehicles displays sensitivity to the ambient temperature. The warm-up idle has no clear emissions benefit, and may have a disbenefit at warmer temperatures. Plug-in and warm-up idle with plug-in both have some emissions benefit, and there appears to be no incremental benefit associated with combining the warm-up idle with plug-in, compared to plug-in alone.

It appears that some emissions sensitivity to colder temperatures may remain in the Hot ADC cycle, but it may not be possible to estimate the smaller effect with confidence due to the small sample of vehicles that is presently available. It appears that plug-in (with or without idle) may exert an adverse effect on emissions, although it is not known if this effect is real.

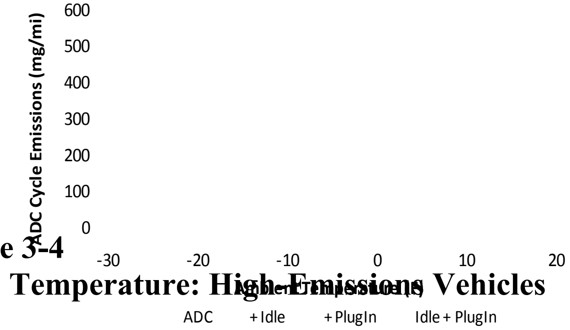
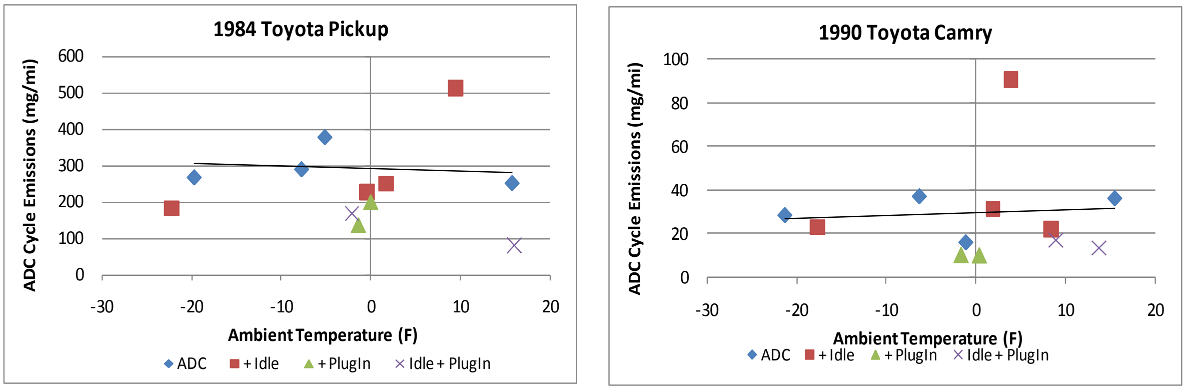
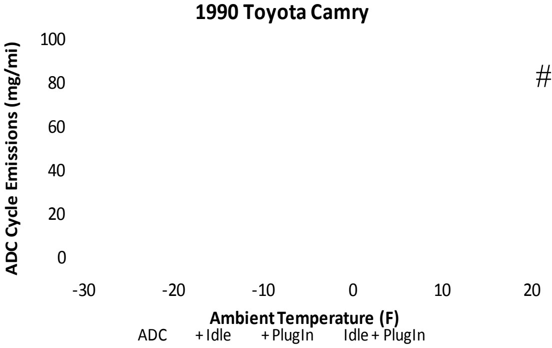


Figure 3-4
Hot ADC $PM_{2.5}$ Emissions Trends versus Temperature: High-Emissions Vehicles





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4. STATISTICAL ANALYSIS OF DYNAMOMETER DATA

The overview presented in the previous section clearly indicates that normal and high-emissions vehicles not only have substantially different emission levels, but also are influenced by ambient temperature, the warm-up idle, and plug-in to differing degrees. This finding led to the performance of a parallel statistical analysis for normal and high-emissions vehicles.

The review also indicated that several of the emissions tests deviate by wide margins in comparison to other tests. Given the small size of the dataset, the conduct of formal outlier tests was judged to be fruitless; instead, the test data were reviewed individually in an effort to identify suspect tests. Described below are the deletions that were made in the dataset.

- For the 1999 Taurus, the Hot ADC emissions for test number 37. This test, taken on the warmest day of the testing, showed emissions of 38 mg/mi compared to the range of 8-29 mg/mi under all other test conditions (both temperature and drive cycle variations).

- For the 2004 Ion, the Hot ADC emissions for test numbers 7 and 11. These tests, taken on the first and second days of testing at 2°F and 12°F, gave emissions of 15 mg/mi even though they used both warm-up idle and plug-in. The next highest test was 10 mg/mi; all others, with or without plug-in or warm-up idle, were below 5 mg/mi. A number of problems were encountered on the first day of testing, and may have affected the results for these two tests. In particular, traction control was left on (inadvertently) in the early part of test 7, and an engine stall (caused perhaps by driver inexperience with this particular standard transmission) and restart at about second 400 probably increased emissions for test 11. The 10mg/mi test was judged marginally suspect, but was left in the analysis.

- For the 2007 Silverado, the Hot ADC emissions for test number 40. This test, also taken on the warmest day of the testing, showed emissions of 21 mg/mi when all other tests were below 5 mg/mi.

That the four deletions were necessitated exclusively in the Hot ADC data is not surprising—any small difference in vehicle condition or handling or in test set-up can produce noticeable differences in measured emissions, given the very low emission levels of the normal vehicles on the Hot ADC cycle. No deletions were made for cold ADC emissions or for either of the high-emissions vehicles.

4.1 Statistical Analysis Procedures

The statistical analysis used multiple linear regression procedures to fit predictive models to the vehicle testing data. The predictive models provided the means to estimate the effect of temperature on $PM_{2.5}$ emissions, to test whether the warm-up idle or plug-in affect emissions, and to estimate the extent of the effects on emissions.

The analysis of $PM_{2.5}$ emissions was conducted for the group of four normal vehicles using a regression model for the natural log of $PM_{2.5}$ emissions as a function of the following effects that were tested in the experiment:

- The ambient test temperature in degrees Fahrenheit (°F);
- The effect of using a block heater, represented by the dummy variable dPlugin, which takes on the value of 1 whenever plug-in is used for a test (with or without warm-up idle) and a value of 0 otherwise;
- The effect of the warm-up idle alone, represented by the dummy variable dIdle, which takes on the value of 1 when a warm-up idle is performed without plug-in and a value of 0 otherwise (either no warm-up idle or warm-up idle combined with plug-in); and
- The incremental effect (if any) of adding warm-up idle to plug-in, represented by the dummy variable dIncrIdle, which takes on the value of 1 when both plug-in and warm-up idle were used for a test and a value of 0 otherwise.

The natural log form for emissions is consistent with the approach used for the Kansas City study and estimates the size of the emission effects in percentage terms. The structure of the dummy variables is that suggested by the vehicle test data, which indicate that plug-in has a more important emissions effect than warm-up idle, and that combining warm-up idle with plug-in has little (possibly no) incremental effect. The models were estimated using the SAS GLM procedure with the data from all vehicles combined, using an option in which vehicle-specific differences are “absorbed” so that the analysis is not influenced by the fact that the vehicles have different overall emission levels. Use of the ABSORB option is comparable to estimating separate intercepts for each vehicle.
The initial model described above was estimated first. Then, simplified models were formed by dropping the term with poorest statistical significance and re-estimating the model in a sequential fashion, until a final model with acceptable statistical significance had been selected.

4.1.1 Normal Vehicles

Cold ADC Emissions – In the initial model, the terms representing ambient temperature, the warm-up idle, and plug-in, are all found to have statistically significant* and directionally plausible effects on emissions. $PM_{2.5}$ emissions increased by 34% for every 10°F drop in ambient temperature. A warm-up idle alone reduced emissions by 41%, and use of a block heater alone reduced emissions by 80%. Warm-up idle tests were conducted at a range of temperatures, so the result can be interpreted as dropping the emissions line below that for the non-idle, non-plug-in ADC cycle by a constant percentage amount. Plug-in tests were, by happenstance, conducted only at temperatures very close to 0°F, so the estimated emissions reduction due to plug-in can be interpreted as applying only to that temperature. The incremental effect of combining warm-up idle with plug-in is to increase emissions above what would be estimated for plug-in alone; however, the estimated increase marginally fails to be statistically significant ($p=0.13$).

When the term representing the incremental effect of a warm-up idle combined with plug-in is removed and the simplified model is re-estimated, the three remaining terms are all statistically significant ($p \leq 0.05$) and have values very similar to those estimated in the initial model. Additional tests were conducted to determine if differences in the basic model could be detected based on vehicle type or age.

The first test examined whether the temperature sensitivity differs for the two trucks compared to the two cars, which was suggested by the graphical analysis. The statistical results indicate that the trucks might be somewhat more sensitive to temperature, but the difference is much too small to be statistically significant ($p=0.72$) in a dataset of this size. The null finding is not a surprise, because a differential effect would have to be very large to be found statistically significant with only two cars and two trucks.

A second test examined whether the temperature sensitivity of $PM_{2.5}$ emissions depends on the age of the vehicle, by representing the temperature coefficient in the form ($a + b \cdot Age$). The $b \cdot Age$ term could not be estimated with an acceptable level of statistical significance, leading to the conclusion that there is no evidence (in this small dataset) that the temperature sensitivity varies with age.

A final test examined whether the temperature sensitivity of $PM_{2.5}$ emissions differed for the warm-up idle tests, compared to that seen in the ADC cycle alone, beyond the sensitivity that would be implied by the mathematics of applying a constant percentage change to a varying emissions baseline. The statistical result indicated that warm-up idle tests might be somewhat more sensitive to temperature, but the difference is much too

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[*] Terms are judged to be statistically significant when they reach or exceed a 95% confidence level ($p=0.05$). The level of statistical significance achieved by specific terms is indicated in the discussion in terms of their p-levels. Given the small sample size and limited power of the available vehicle dataset, terms have been retained in final emissions models in some instances, even though the desired $p=0.05$ level of significance was not achieved, because the terms were judged to be important to making accurate emissions predictions.

small to be statistically significant (p=0.84), leading to the conclusion that there is no evidence (in this small dataset) that warm-up idle tests have a different sensitivity than the ADC cycle alone.

The statistical model for cold ADC emissions is tabulated in Table 4-1 and discussed below. The SAS absoption technique was not used because estimates of emissions differences among vehicles were desired. Instead, an overall intercept and dummy variables for vehicles 2, 3, and 4 are fit in the model to control for different emission levels by vehicle. Coefficients representing ambient temperature (TempF), warm-up idle (dIdle), and use of block heaters (dPlugin) were also fit and were found to be statistically significant at acceptable confidence levels.[*] The ambient coefficient is estimated to be -0.0268 for the cold ADC cycle, which produces a $PM_{2.5}$ emissions increase of +31% for every 10°F drop in ambient temperature. This result pertains to ambient temperature in the range +20°F down to -20°F. Notably, the derived temperature coefficient for the Cold ADC of -0.0268 (0.003) matched that found for the 32-vehicle sample in the main study in 2011 -0.0233 (0.0047).

Table 4-1
Statistical Model for Cold ADC Emissions: Normal Vehicles
$\ln(PM) = a + b \cdot dVeh_2 + c \cdot dVeh_3 + d \cdot dVeh_4 + e \cdot TempF + f \cdot dIdle + g \cdot dPlugIn$

Parameter	Coefficient	Prob > |t|	Estimated Effect (mg/mi or %)
a (Intercept)	5.3869	<0.0001	Int(Veh 1) = 219 mg/mi
b (dVeh2)	-1.4029	<0.0001	Int(Veh 2) = 54 mg/mi
c (dVeh3)	-0.5402	0.058	Int(Veh 3) = 127 mg/mi
d (dVeh4)	-1.5383	<0.0001	Int(Veh 4) = 47 mg/mi
e (TempF)	-0.0268	0.003	+31% per 10°F colder
f (dIdle)	-0.5230	0.034	-41%
g (dPlugIn)	-1.3323	<0.0001	-74%

In contrast, the Kansas City study (with a much larger, but older sample of vehicles) found a temperature coefficient of -0.0456 for the cold start FTP (Bag 1), producing a $PM_{2.5}$ emissions increase of +58% for every 10°F drop in ambient temperature. However, the Kansas City result pertains to an ambient temperature range from +90°F down to +12°F, rather than the much colder temperature range under which the Fairbanks testing was conducted. The uncertainty in this study's ADC coefficient is ±0.0084, or about 1 part in 3, while that of the Kansas City study's FTP coefficient is ±0.0052, or

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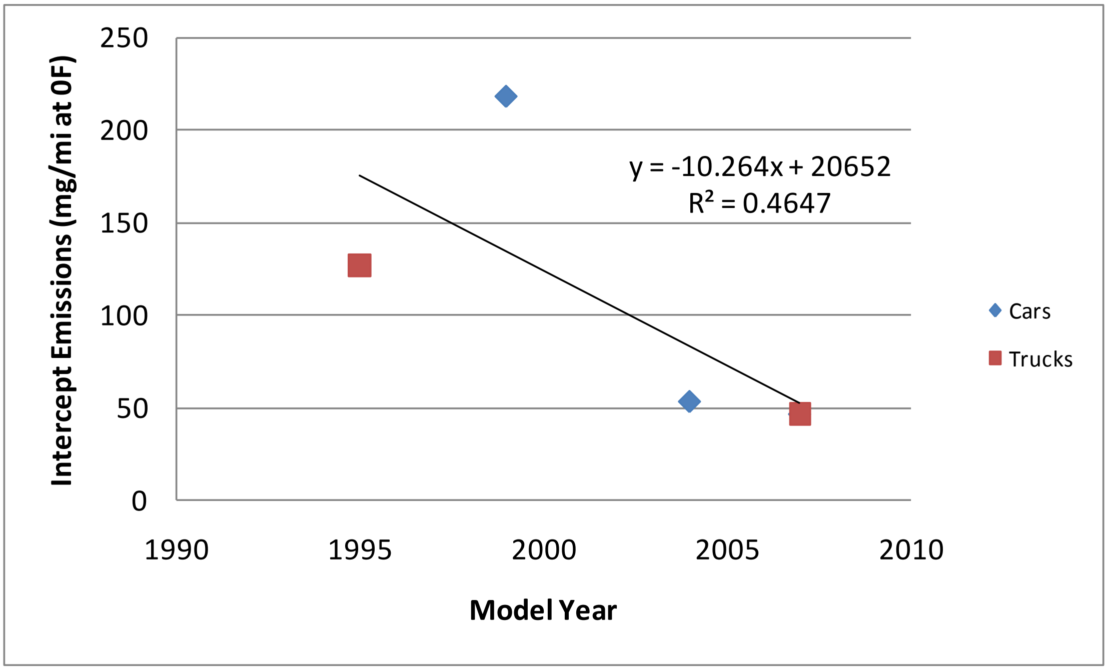
[*] Statistical significance is not germane to the intercept terms representing the emission levels of the different vehicles, which are included in the models as controls. All terms except for $dVeh_3$ are statistically significant at $p \leq 0.05$, and $dVeh_3$ just fails to reach that level.

about 1 part in 10. Given the uncertainties, the temperature sensitivity of the cold ADC cycle is significantly different (lower) than that of the cold FTP when the Kansas City result is extrapolated down to the temperature range of the Fairbanks testing. The difference, if real, most likely reflects the improved fuel control possible with newer, fuel-injected vehicles in the test fleet, compared to the wider range of vehicle model years (1975-2005) and greater prevalence of carbureted fuel control systems found in the Kansas City in-use fleet.

The table also shows the estimated emissions effects for vehicle differences and for warm-up idle and plug-in. The intercept term represents the base emission level for Vehicle 1—specifically, this is the estimated emissions at 0°F on the ADC cycle. The intercept value for Vehicle 2 is computed from the sum of the intercept and dVeh2 terms, etc. Vehicles 1 and 3 are the older car and truck, respectively; Vehicles 2 and 4 are the newer car and truck, respectively. As shown in the figure, there is an apparent difference in emission levels (at 0°F) for older vehicles compared to newer vehicles, but there is no significant difference between cars and trucks, particularly for newer cars and trucks, that can be detected with this small sample. These trends are shown graphically in Figure 4-1.

A warm-up idle preceding the drive away to begin the cold ADC cycle is estimated to reduce $PM_{2.5}$ emissions by 41%, while the use of an engine block heater prior to cold start is estimated to have almost twice the benefit (74%). As noted, there is no observable emissions benefit to combining the warm-up idle with use of a block heater. As has been noted, the warm-up idle tests span nearly the full range of temperatures

Figure 4-1
Age Dependence of PM Emissions at 0°F (Normal Vehicles)



encountered in the testing program. As a result, the estimated constant percentage effect can be applied across a wide range of ambient temperatures, resulting in a larger mg/mi benefit at colder temperatures (where emissions are higher) than at warmer temperatures (where emissions are lower). However, the circumstance is different for the plug-in tests, which were all conducted in the first few days of the first round of testing at temperatures near 0°F. The estimated constant percentage effect pertains only to temperatures close to 0°F, and no data are available on the plug-in effect at warmer or colder temperatures. As discussed in Section 4.2, an engineering model was developed to extend this limited result for plug-in to other temperatures.

Hot ADC Emissions – A similar analytical process was followed for the Hot ADC emissions of the four normal vehicles. As noted previously, four of the Hot ADC tests were identified as likely outliers and were excluded from the emissions data used here.

After a series of statistical models were examined, it was concluded that ambient temperature does not affect $PM_{2.5}$ emissions when normal vehicles start from a nearly or fully warmed-up state. Specifically, the initial model consisting of all terms related to temperature, warm-up idle, plug-in, and the combination of warm-up idle and plug-in, fails to achieve statistical significance for any of the terms. The model was progressively simplified by dropping terms in the order suggested by the strength of the effects on cold ADC emissions. However, dropping terms did not improve the statistical significance of the remaining terms. In the simplest model, the ambient temperature term achieved only a p=0.77 level of significance.

As result, the statistical model for Hot ADC emissions consists only of intercept terms representing the different emission levels of the four vehicles, as shown in Table 4-2. The constant Hot ADC emission levels are much lower than the cold ADC emissions for every vehicle and, in fact, approach the range where precise measurements of $PM_{2.5}$ emissions become difficult. These results are consistent with the graphical inspection of the data, once the four outlying tests are deleted. For the ADC cycle, the vehicle test data show no evidence that hot $PM_{2.5}$ emissions are influenced by ambient temperatures.

Table 4-2
Statistical Model for Hot ADC Emissions: Normal Vehicles
$\ln(PM) = a + b \cdot dVeh_2 + c \cdot dVeh_3 + d \cdot dVeh_4$

Parameter	Coefficient	Prob > |t|	Estimated Effect (mg/mi or %)
a (Intercept)	2.6562	<0.0001	Int(Veh 1) = 14 mg/mi
b ($dVeh_2$)	-1.6028	<0.0001	Int(Veh 2) = 3 mg/mi
c ($dVeh_3$)	-0.6006	0.035	Int(Veh 3) = 8 mg/mi
d ($dVeh_4$)	-1.7637	<0.0001	Int(Veh 4) = 2 mg/mi

This result is inconsistent with that reported for hot running $PM_{2.5}$ emissions in the Kansas City Study, which estimated a temperature sensitivity coefficient of -0.0318 ± 0.0028 (assuming that the Kansas City temperature coefficient can be extrapolated to the colder temperature range examined in this testing.) The Kansas City coefficient predicts an increase of +37% in hot running emissions for every 10°F drop in ambient temperature, and this response is not much smaller than the +58% increase per 10°F estimated for cold start emissions. It is unclear why the Kansas City Study found such strong temperature sensitivity for hot running emissions, but one possible explanation is that it tested a much older in-use fleet that included a large proportion of vehicles with carbureted fuel systems. Carbureted vehicles would need more fuel enrichment to start, even when warm, compared to generally newer vehicles in which fuel injectors atomize the fuel charge and more closely control enrichment during starting. Differences in fuel RVP and between the FTP and ADC cycles could also contribute to this difference.

4.1.2 High-Emissions Vehicles

The analysis conducted for the group of high-emissions vehicles was necessarily more limited because of the sample size. $PM_{2.5}$ emissions are dominated by the fuel control and other emissions-related failures that lead to overall high emissions for these vehicles. Further, with only two such vehicles, the dataset has limited statistical power, tests for statistical significance will be difficult to pass (except for the strongest effects), and it may not be possible to tell whether differences between the vehicles are related to a factor such as age, make, or technology that can be generalized to other vehicles, or are simply caused by their individual conditions. For this reason, analysis for only the two vehicles grouped together is presented and no tests were conducted for whether the vehicles differ in their performance.

Cold ADC Emissions – As for normal vehicles, the analysis was begun with a model that included four terms representing the effects tested in the experiment – that of ambient temperature, the warm-up idle before drive-away, the use of an engine block heater, and the incremental effect of including a warm-up idle with an engine block heater. The results showed that plug-in had a statistically significant effect ($p<0.01$) that reduced emissions, while none of the other effects reached an acceptable level of statistical significance. The temperature sensitivity term approached statistical significance ($p=0.11$), which is consistent with graphical trends presented earlier that suggest some increase in $PM_{2.5}$ emissions with colder temperatures. The benefit from plug-in (with or without warm-up idle) was shared by both vehicles in the graphs, although it appears to be stronger for the newer vehicle (1990 Toyota).

A series of simplified models were considered in a sequential manner, in which the term representing the warm-up idle was dropped, followed by the term representing an increment benefit from combining the warm-up idle with use of a block heater. This did not change the result that plug-in produced a statistically significant ($p<0.01$) reduction in $PM_{2.5}$ emissions. The temperature sensitivity continued to be proportionately small (compared to the cold-start sensitivity of normal vehicles) and of poor statistical significance ($p=0.21$). On engineering grounds, one would expect to find that the influence of temperature would be proportionately smaller compared to vehicles without such failures. For these reasons, the estimated temperature coefficient was retained in spite of its poor statistical significance.

Table 4-3 summarizes the statistical model for $PM_{2.5}$ emissions of high-emissions vehicles on the cold ADC cycle. The intercept terms (a and $b \cdot dVeh_2$) represent emissions for each of the two vehicles at 0°F and are very high compared to normal vehicles of similar model year and type. The temperature sensitivity of $PM_{2.5}$ emissions is estimated to be +19% for every 10°F drop in ambient temperature. This value is somewhat more than one-half the sensitivity of cleaner vehicles (+31% per 10°F), but it will produce emission changes that are as large as (or larger than) those for normal vehicles because of the much higher base emission level. Remarkably, plug-in prior to the cold ADC cycle is somewhat more effective in reducing $PM_{2.5}$ than in cleaner vehicles (-80% versus -74%), although the difference in the effect between high emissions and normal vehicles is not statistically significant in this small dataset.

Table 4-3
Statistical Model for High-Emissions Vehicles: Cold ADC
$\ln(PM) = a + b \cdot dVeh_2 + e \cdot TempF + g \cdot dPlugIn$

Parameter	Coefficient	Prob > |t|	Estimated Effect (mg/mi or %)
a (Intercept)	6.8416	<0.0001	Int(Veh 1) = 936 mg/mi
b (dVeh 2)	-1.4742	<0.0001	Int(Veh 2) = 214 mg/mi
e (TempF)	-0.01722	0.20	+19% per 10°F colder
g (dPlugIn)	-1.6086	<0.0001	-80%

Hot ADC Emissions – As for the Hot ADC emissions, the analysis began with a model that included the four terms tested in the experiment. The results showed that plug-in has a statistically significant effect ($p<0.01$) reducing emissions, while none of the other terms approached an acceptable level of statistical significance. However, the temperature sensitivity term approached statistical significance ($p=0.11$), consistent with the graphical trends shown previously that suggest some increase in $PM_{2.5}$ emissions with temperature. As was seen graphically, the benefit from plug-in (with or without warm-up idle) is shared by both vehicles.

The process of model simplification drops terms from the model in a sequential manner, producing a final model in which the ambient temperature term is positive ($PM_{2.5}$ emissions *increase* with *increasing* ambient temperature) but far from statistically significant ($p=0.39$). Because this result is directionally implausible, the temperature sensitivity term was dropped to produce the statistical model summarized in Table 4-4, which consists of intercept terms for the vehicles and an emissions benefit for plug-in.

Table 4-4
Statistical Model for High-Emissions Vehicles: Hot ADC
$\ln(PM) = a + b \cdot dVeh_2 + e \cdot TempF + g \cdot dPlugIn$

Parameter	Coefficient	Prob > |t|	Estimated Effect (mg/mi or %)
a (Intercept)	5.6747	<0.0001	Int(Veh 1) = 291 mg/mi
b (dVeh 2)	-2.2779	<0.0001	Int(Veh 2) = 30 mg/mi
e (TempF)	n/a	n/a	none
g (dPlugIn)	-0.8186	0.0001	-56%

The base emission levels of both vehicles are much lower than on the cold ADC, particularly for Vehicle 2, consistent with a reduced need for enrichment when the engine is warm. The statistically significant benefit for plug-in after the engine is warmed is somewhat surprising to us, because it suggests a residual effect long after start of the cold ADC cycle.

4.1.3 Summary

Table 4-5 summarizes the findings of the statistical analysis described above. As shown, $PM_{2.5}$ emissions were increased at colder temperatures during the Cold ADC in both normal and high-emissions vehicle groups. Allowing the vehicle to warm up after the cold ADC was beneficial, although plug-in was clearly more beneficial than idle and

Table 4-5
Summary of Findings Related to $PM_{2.5}$ Emissions

	Normal Vehicles (N=4)	High-Emissions Vehicles (N=2)
Cold ADC		
Base Emissions	Varied by vehicle	Varied by vehicle
Temperature Sensitivity (% per -10°F)	+31%	+19%
Plug-in Benefit	-74%	-80%
Pre-Idle Benefit (alone)	-41%	None
Pre-idle Benefit (with plug-in)	None	None
Hot ADC		
Base Emissions	Varied by vehicle	Varied by vehicle
Temperature Sensitivity (% per -10°F)	None	None
Plug-in Benefit	None	-56%
Pre-Idle Benefit (alone)	None	None
Pre-idle Benefit (with plug-in)	None	None

4.2 Engine Block Heater Performance Model

Use of engine block heaters is normal in Fairbanks to assure that vehicles can be started at cold temperatures. The vehicle testing demonstrates that use of engine block heaters is more effective than extended idle time at reducing $PM_{2.5}$ emissions during the cold ADC. Unfortunately, the plug-in tests were all conducted at ambient temperatures near 0°F. This means that the test data do not exist that are needed to determine how the emissions benefit of plug-in varies with ambient temperature.

In an effort to fill this gap, a simplified engineering model of the performance of engine block heaters was developed. The model is based on the assumption that the rise in engine coolant temperature caused by plug-in acts for emissions purposes as the equivalent of a warmer ambient temperature. That is, if the use of plug-in raises engine coolant temperature by 20°F, then $PM_{2.5}$ emissions are expected to be comparable to emissions without plug-in at an air temperature that is 20°F warmer.[*3] Two of the test vehicles (Ion and Silverado) were instrumented with a CarChip for a series of tests, including the ADC without warm-up idle or plug-in as a baseline and the ADC with plug-in (both with and without warm-up idle). These vehicles provide data that can be used to estimate the rise in coolant temperature caused by plug-in; the data are summarized in Table 4-6.

For each vehicle, the coolant and air intake temperatures at the start of the cold ADC test were extracted from the CarChip data. Because the temperatures were taken from the first 5 seconds of each test, it was possible to use plug-in tests with and without the warm-up idle to determine the effect of block heaters on coolant temperature. Although the recorded intake air temperatures generally track the airport temperatures for tests without plug-in, they are raised above ambient when using the block heater. Therefore, the airport temperature was used as the measure of ambient air temperature at the time of the cold ADC test.

Air temperatures can vary between the airport and the testing location; the actual temperature of the engine coolant at the time of the cold start will be affected in a complex way by the engine's thermal inertia, the diurnal temperature swing, and the time since the overnight low temperature was reached. Nevertheless, in the absence of plug-in there is a strong relationship between actual coolant temperatures and the airport temperature at the time of cold start (Figure 4-2). The linear relationship defined in the figure was used to estimate the baseline coolant temperature (i.e., the temperature in the absence of plug-in) that would be expected for each of the seven tests involving the use of an engine block heater. The coolant temperature rise attributed to plug-in was estimated as the observed temperature minus the expected baseline temperature and is reported in the preceding table as the estimated temperature rise.

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[*] This concept has been applied to the estimation of CO emissions under varying states of warm-up in Fairbanks and is described more fully in Reference 3.

Table 4-6
CarChip Data Showing the Effect of Plug-In on Engine Temperature

Vehicle	Test Cycle	Test No	Starting Coolant Temperature (°F)	Starting Intake Air Temperature (°F)	Airport Temperature (°F)	Expected Coolant Temperature (°F)	Estimated Temperature Rise (°F)
Ion	ADC	34	1.4	1.4	-2.0	n/a	n/a
	ADC	38	15.8	19.4	18.5	n/a	n/a
	ADC	69	-13.0	-2.2	-18.0	n/a	n/a
	ADC	77	-2.2	-5.8	-7.4	n/a	n/a
Silverado	ADC	31	8.6	3.2	-3.7	n/a	n/a
	ADC	40	17.6	21.2	21.1	n/a	n/a
	ADC	65	-5.8	-9.4	-16.1	n/a	n/a
	ADC	81	-4.0	-5.8	-8.7	n/a	n/a
Ion	Plug-In / Warm-upIdle	7	35.6	21.2	2.2	-2.2	37.8
	Plug-In / Warm-up Idle	11	46.4	33.8	12.2	10.7	35.7
	Plug-In / No Idle	21	41.0	26.6	-2.1	-7.7	48.7
	Plug-In / No Idle	25	42.8	24.8	1.9	-2.5	45.3
Silverado	Plug-In / Warm-up Idle	4	3.2	-5.8	-8.0	-15.2	18.4
	Plug-In / Warm-up Idle	15	28.4	32.0	17.1	16.9	11.5
	Plug-In / No Idle	28	19.4	15.8	-0.8	-6.0	25.4

Figure 4-2
Engine Coolant without Plug-in versus Airport Temperature

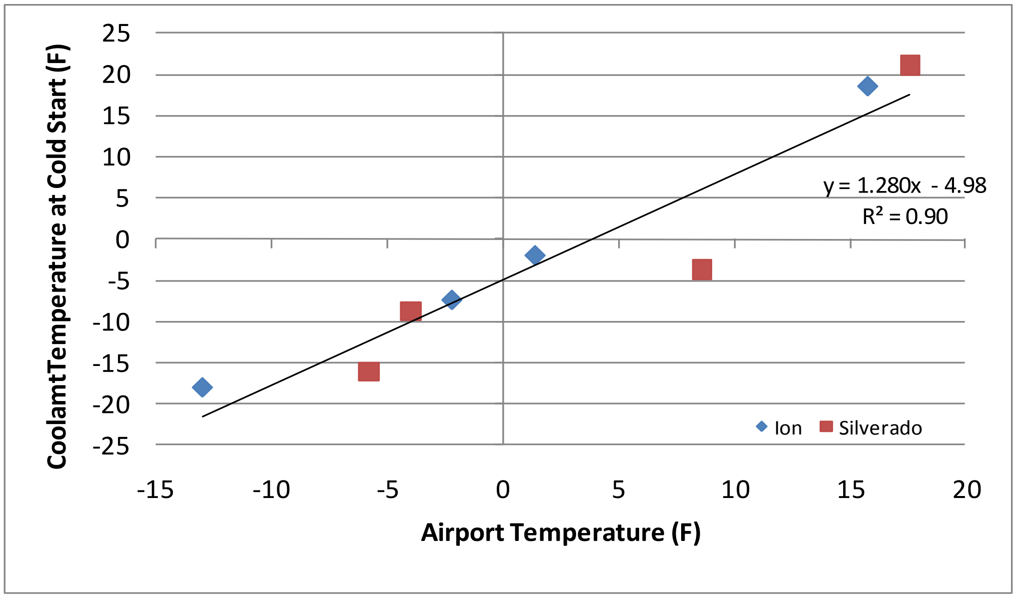

Figure 4-3 shows the estimated coolant temperature rise versus ambient air temperature for the two vehicles. The Ion heater held coolant temperature nearly constant as the air temperature fell (evidenced by a slope of almost -1.0), and it was able to achieve a temperature rise of 45°F when the air temperature was 0°F. The Silverado heater, which was OEM, allowed coolant temperature to fall, but at a slower rate than the air temperature (evidenced by its slope of -0.4), and it achieved, at most, a temperature rise of 25°F over the observed ambient temperature range. There are a number of different designs for engine block heaters, including some that are thermostatically controlled and others intended to run continuously when plugged in.[*] Heater wattage generally varies based on engine size to account for the engine block's thermal mass.

Given these differences, it is difficult to generalize from individual vehicles to the entire in-use fleet, particularly when data are available for only two vehicles. However, these two vehicles appear to establish a range of heater performance for small and large vehicles, although it is difficult to tell where, within the range, the overall fleet average may be located. For this analysis, the composite trend line formed by combining the data for the two vehicles was used to approximate an overall in-use fleet average. This trend line produced a temperature rise of 33°F at 0°F (i.e., coolant temperature of 33°F), a temperature rise of 40°F at -20°F (coolant temperature of 20°F) and a temperature rise of 49°F at -40°F (coolant temperature of 9°F).

The thesis of the performance model is that the emissions benefit of plug-in can be estimated by the difference between the emissions expected at the actual ambient

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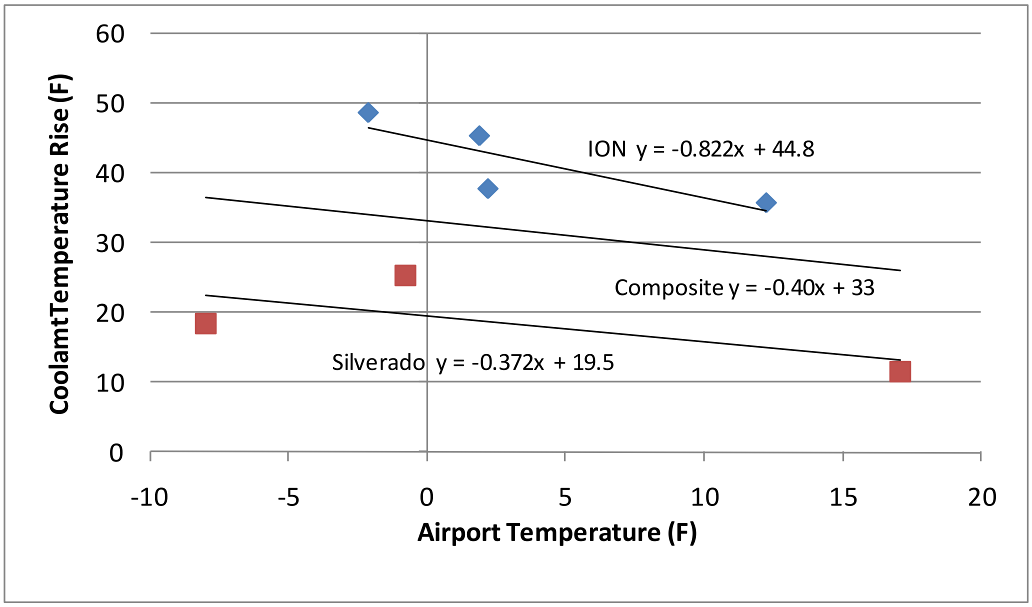
[*] Whether the ION's block heater is thermostatically controlled is not known; however, according to its label, the 2007 Silverado's block heater is thermostatically controlled. Furthermore, GM light-duty trucks since model year 2004 have turned off the block heater at air temperatures above 0°F, although the data for the 2007 Silverado suggest a 10°F temperature rise at air temperatures between 15°F and 20°F.

Figure 4-3
Coolant Temperature Rise due to Engine Plug-In

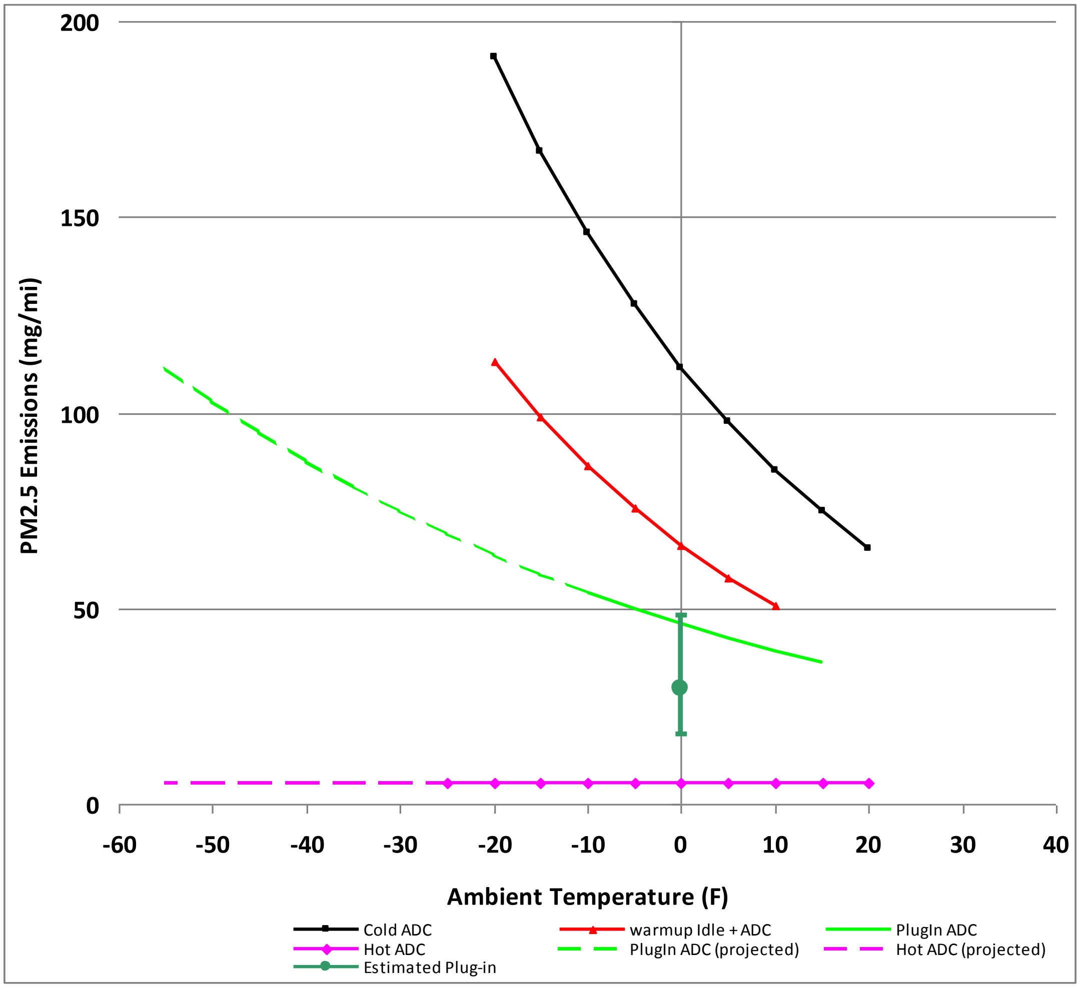


temperature (without plug-in) and the emissions expected at a warmer ambient temperature determined by the rise in engine coolant temperature. This can be tested by comparing emissions based on the performance model to the emissions benefit of plug-in estimated in the statistical analysis. For normal vehicles, the log-emissions coefficient representing the benefit of plug-in was -1.332 ± 0.248, which corresponds to an emissions reduction of 74% on average, with a ± 2 standard deviation range of 54% to 87%. There is a high degree of confidence (95%) that the actual benefit of plug-in lies within this range.

Figure 4-4 compares the predicted $PM_{2.5}$ emissions trends versus temperature for the average of the four normal vehicles. The ADC cycle without plug-in or warm-up idle (upper line) gives the baseline for emissions. The composite performance line, which is based on the results from the Silverado and Ion using the performance model, represents an estimate of the fleet-average benefit. The statistical estimate of the plug-in benefit derived from the full four-vehicle sample vehicle testing is shown at 0°F along with its ±2 standard deviation range.

The comparison indicates that the performance model is consistent with the statistical analysis within the accuracy achieved in the two analyses. However, the results also show that the performance model is on the conservative side of representing the emissions benefit of plug-in compared to the benefits observed in the vehicle testing. Predicted vehicle emissions would be lower if the fleet-average performance of block heaters is found to be comparable to the 2004 Ion (and the statistical estimate based on the vehicle testing). Vehicle emissions could also be higher if average performance is found to be more comparable to the 2007 Silverado.

Figure 4-4
Predicted PM Emissions Trends for Normal Vehicles



For purposes of extending the statistical estimate to temperatures other than 0°F, the composite plug-in line has been adopted as the best estimate that can be developed from this study.[*] These estimates are consistent with the statistical analysis and are somewhat conservative in their prediction of the emissions benefit at 0°F compared to the statistical estimate.

4.2.1 $PM_{2.5}$ Emission Factors

The results of the analysis led to the set of $PM_{2.5}$ emission factors and correction equations for ambient temperature and driving cycle summarized in Tables 4-7 and 4-8

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[*] Dashed lines in the figure show where the results are projected, i.e., outside the range of temperature measurements. Note too that results for Cold ADC and warm-up idle are not projected to temperatures below -20°F because most vehicles are not expected to start (without plug-in) after extended soak at that temperature, and such starting is generally not attempted in Fairbanks in normal operation.

Table 4-7
PM Emission Factors for Normal Vehicles
$E(T_{amb}, dIdle, dPlugIn) = (E_{0F} + dMY) * f(T_{eff}, dPlugIn) * g(dIdle)$

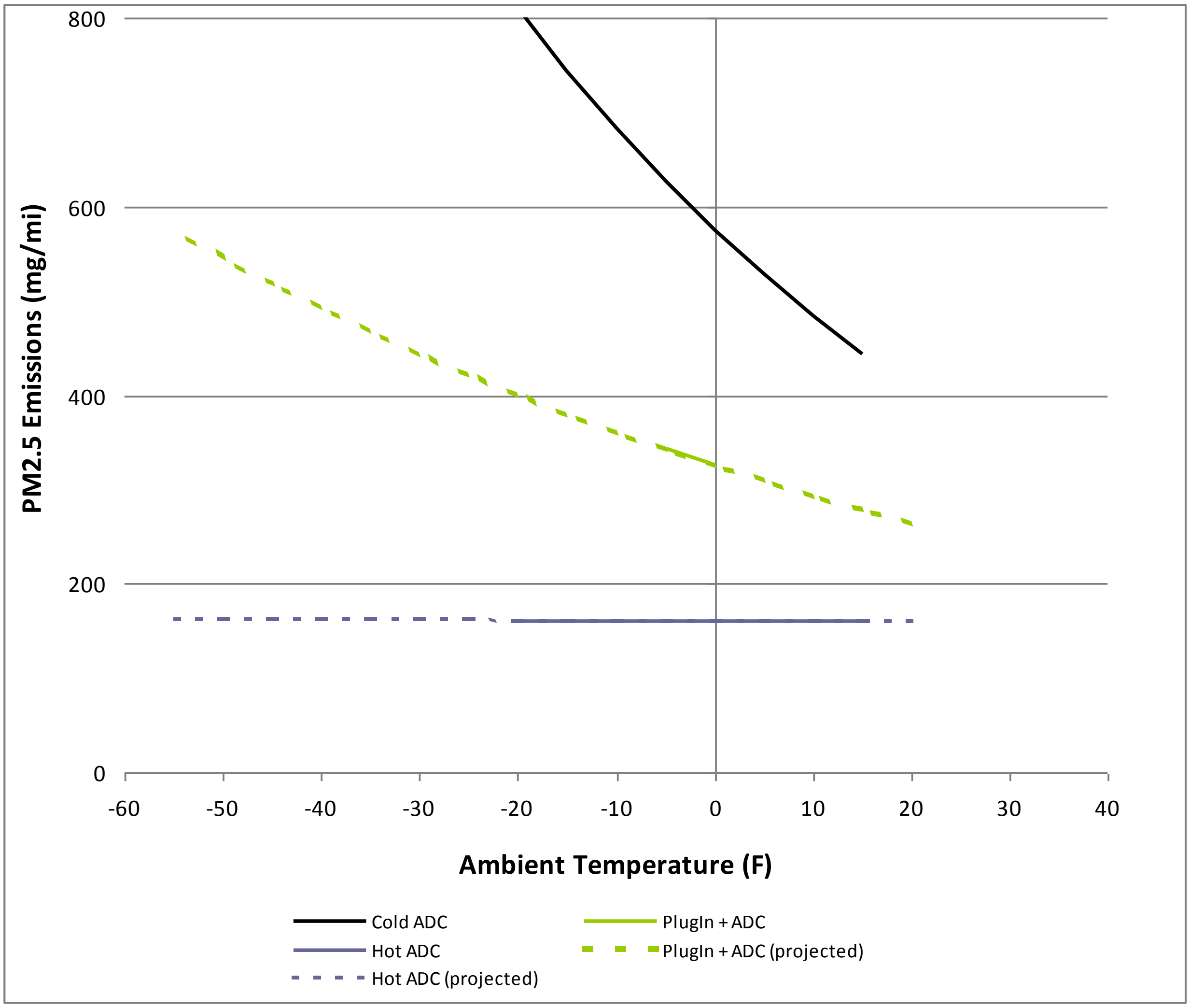
Cold ADC Emissions	**Units**	**Values**
Base Emissions at 0°F (E_{0F})	mg/mi	111
Temperature Correction $f(T_{eff}, dPlugIn)$	decimal	$f = cxp(-0.0267 \cdot T_{eff})$
Effective Temperature $T_{eff}(dPlugIn)$	°F	$T_{eff} = T_{amb} + dPlugIn \cdot \max(0, 33-0.40*T_{amb})$
Warm-up Idle Correction g(dIdle)	decimal	$g = cxp(-0.523 \cdot dIdle)$ when dPlugIn=0
	decimal	$g = 1$ when dPlugIn=1
Age Correction dMY	mg/mi	$dMY = -10.2 \cdot (MY-2001.25)$
Hot ADC Emissions	**Units**	**Values**
Base Emissions at 0°F (E_{0F})	mg/mi	6
Temperature Correction $f(T_{eff}, dPlugIn)$	decimal	n/a
Effective Temperature $T_{eff}(dPlugIn)$	°F	n/a
Plug-In Correction g(dPlugIn)	decimal	n/a
Warm-up Idle Correction g(dIdle)	decimal	n/a
Age Correction dMY	mg/mi	nil

Table 4-8
PM Emission Factors for High-Emissions Vehicles
$E(T_{amb}, dPlugIn) = (E_{0F} + dMY) * f(T_{eff}, dPlugIn) * g(dIdle) * h(PlugIn)$

Cold ADC Emissions	**Unit**	**Values**
Base Emissions at 0°F (E_{0F})	mg/mi	561
Temperature Correction $f(T_{eff}, dPlugIn)$	decimal	$f = cxp(-0.0172 \cdot T_{eff})$
Effective Temperature $T_{eff}(dPlugIn)$	°F	$T_{eff} = T_{amb} + dPlugIn \cdot \max(0, 33-0.40*T_{amb})$
Plug-In Correction h(dPlugIn)	decimal	h = 1 (not applicable)
Warm-up Idle Correction g(dIdle)	decimal	g = 1 (not applicable)
Age Correction dMY	mg/mi	dMY = +361 if carbureted
		dMY = -361 if fuel-injected
Hot ADC Emissions	**Unit**	**Values**
Base Emissions at 0°F (E_{0F})	mg/mi	161
Temperature Correction $f(T_{eff}, dPlugIn)$	decimal	f = 1 (not applicable)
Effective Temperature $T_{eff}(dPlugIn)$	°F	n/a
Plug-In Correction h(PlugIn)	decimal	$h = \exp(-1.724 \cdot dPlugIn)$
Warm-up Idle Correction g(dIdle)	decimal	g = 1 (not applicable)
Age Correction dMY	mg/mi	dMY = +110 if carbureted
		dMY = -110 if fuel-injected

for normal and high-emissions vehicles, respectively, and presented graphically in Figures 4-4 and 4-5. Due to the simple form of the Hot ADC equations, the emission factors are given in the form of Cold ADC and Hot ADC emission factor equations. The cold-start offset factor required by the MOVES mobile source emissions model is easily calculated by subtracting the calculated Hot ADC emissions from the calculated cold ADC emissions. Both Cold and Hot ADC emission factor equations are stated relative to base emissions of 0°F. The emissions at any other temperature are calculated by supplying a non-zero value of T_{amb}.

Figure 4-5
Predicted PM Emissions for High-Emissions Vehicles



For normal vehicles, the base emissions factor (at 0°F) is set at 111 mg/mi for the cold ADC cycle, but is differentiated between newer and older vehicles by an age correction. Emissions increase with lower ambient temperature according to the temperature correction function f. The temperature correction incorporates the benefit of engine block heaters by estimating an effective ambient temperature T_{eff} based on the average performance of block heaters as estimated in this study. An additional correction is applied when a warm-up idle is used, but the benefit is set to zero if combined with plug-in. The base emission for the Hot ADC cycle is a constant 6 mg/mi and is not corrected for ambient temperature, warm-up idle or plug-in.

For high-emissions vehicles, the base emissions factor (at 0°F) is set at 575 mg/mi for the cold ADC cycle, but is differentiated between newer and older vehicles by an age correction factor that is tied to fuel system control (carbureted versus fuel injection) rather than to vehicle age or model year. Emissions increase with lower ambient temperature according to the temperature correction function f, which represents the benefit due to use of block heaters through the calculation of an effective ambient temperature. There is no emissions benefit estimated for the use of a warm-up idle alone or in combination with plug-in.

The base emission factor for Hot ADC emissions is estimated at 161 mg/mi, but is also differentiated by an age correction based on fuel system type. There is no effect of ambient temperature or warm-up idle on emissions, but use of a block heater prior to the cold ADC cycle is estimated to reduce emissions.
These emission factors and correction factor equations will be adapted for use in the MOVES model and used to develop inventory estimates for the contribution of mobile sources to the wintertime $PM_{2.5}$ problem in Fairbanks.

4.2.2 Gaseous Emission Factors

Vehicle emissions of HC, CO, NOx, and CO_2 were also recorded in the testing program. Although they were not the focus of the study, the test data provide an opportunity to compare aspects of the corresponding gaseous emission factors in the MOVES model with that of the Fairbanks fleet. Table 4-9 summarizes the effects of ambient temperature, plug-in and warm-up idle on the gaseous emissions of the test vehicles. As explained earlier, the HC emissions results are qualified due to the problems noted with calibration and performance of the instrument and, intermittently, with problems resulting from saturation of the HC analyzer (exposure to concentrations in excess of the maximum range of the instrument). As a result of these effects, 38 out of 70 tests (primarily of the high emitters) had periods ranging from a few seconds to several minutes shortly after engine start when data from one or more analyzers had to be invalidated. Not surprisingly, the longer periods of instrument pegging tended to occur with the two high-emitter vehicles, which were responsible for 20 of the 38 problem tests. In those cases, the average cold start ADC emissions, the associated emission factors (average g/mi for a cold ADC), and the cold start increment calculated from them would represent only a lower-bound estimate of the true values.

Table 4-9
Summary of Effects Represented in Gaseous Emissions Factors

	HC[*]	CO	NOx	CO_2
Normal Emitters				
Cold ADC				
Temperature coefficient	-0.0085	-0.0056	-0.0103	-0.0023
Plug-in effect	√	√	√	None
Warm-up Idle effect	+20%	None	None	+14%
Hot ADC				
Temperature sensitive	none	-0.0195	-0.0125	-0.0020
Plug-in effect	-65%	√	None	-13%
Warm-up Idle effect	-60%	None	None	-13%
High Emitters				
Cold ADC				
Temperature coefficient	none	None	-0.0129	-0.0076
Plug-in effect	-12%	-29%	None	+ 5%
Warm-up Idle effect	+25%	None	-24%	+10%
Hot ADC				
Temperature sensitive	none	None	-0.0097	-0.0073
Plug-in effect	none	-8%	None	None
Warm-up Idle effect	none	None	-17%	+4%

√ = The emissions benefit is represented through engine block heater model. Otherwise, the benefit is represented by a fixed percentage reduction.

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[*] HC emissions estimates are qualified. See narrative.

5. MOVES ANALYSIS

The final analytical task of the study consisted of assessing how well EPA's new MOVES (Motor Vehicle Emissions Simulator) model represents different aspects of wintertime vehicular emissions in Fairbanks. This assessment was based on comparing the gasoline vehicle dynamometer test results from this study with output emission rate estimates from MOVES. (The comparisons presented here are based on the MOVES2010a release of the model.) It was originally envisioned that Diesel vehicle emission rates from MOVES could be compared to those developed from the on-road Diesel plume-following measurements. However, as discussed in the preceding section, it was difficult to collect and reliably interpret exhaust plume results from the Diesel vehicles that were followed. Thus, the comparisons between MOVES and test results presented in the section were limited to those for light-duty gasoline-fueled vehicles and were focused on $PM_{2.5}$ emissions.

5.1 Running Exhaust Comparisons by Operating Mode

Operating Mode Bins – The MOVES model has been designed by EPA to represent vehicle emissions at a finer scale than its predecessors: earlier models estimated trip-based emission rates, but MOVES accounts for emission rate differences that are affected by different driving patterns within a trip. Within MOVES, these different driving patterns are referred to as operating mode bins. For running (i.e., warmed-up) exhaust emissions, the key concept underlying the definition of operating modes is "vehicle-specific power" (VSP).[4] This parameter represents the tractive power exerted by a vehicle to move itself and its cargo or passengers and accounts for aerodynamic drag and rolling resistance. It is estimated in terms of a vehicle's speed and weight, as shown in the following equation:

$$\text{VSP} = (\text{A}v_t + \text{B}v_t^2 + \text{C}v_t^3 + mv_ta_t) / m$$

In this form, VSP (kW/tonne) is estimated in terms of the following vehicle variables:

- Speed at time t, v_t (m/sec);
- Acceleration a_t (m/sec^2);
- Mass m (tonne) (usually referred to as "weight"); and
- Track-road load coefficients A, B, and C, representing rolling resistance, rotational resistance, and aerodynamic drag, in units of kW-sec/m, kW-sec^2/m^{2,} and kW-sec^3/m^3, respectively.

Note that this version of the equation does not include the term accounting for effects of road grade, because the data used in this analysis were measured on chassis dynamometers configured to simulate level driving.

On the basis of VSP, speed, and acceleration, a total of 23 operating modes are defined for running exhaust processes, as shown in Table 5-1. Aside from deceleration/braking, which is defined in terms of acceleration, and idle, which is defined in terms of speed alone, the remaining 21 modes are defined in terms of VSP within broad speed classes. Two of the modes represent "coasting," where VSP < 0, and the remainder represent "cruise/acceleration," with VSP ranging from 0 to over 30 kW/tonne.

Table 5-1
MOVES Running Exhaust Operating Mode Bins

Bin ID	Description
0	Braking
1	Idling
11	Low Speed Coasting; VSP< 0; 1<=Speed<25
12	Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25
13	Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25
14	Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25
15	Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25
16	Cruise/Acceleration; 12<=VSP; 1<=Speed<25
21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50
22	Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50
23	Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50
24	Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50
25	Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50
26	Cruise/Acceleration; 12<=VSP; 25<=Speed<50
27	Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50
28	Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50
29	Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50
30	Cruise/Acceleration; 30<=VSP; 25<=Speed<50
33	Cruise/Acceleration; VSP< 6; 50<=Speed
35	Cruise/Acceleration; 6<=VSP<12; 50<=Speed
36	Cruise/Acceleration; 12 <= VSP; 50<=Speed
37	Cruise/Acceleration; 12<=VSP<18; 50<=Speed
38	Cruise/Acceleration; 18<=VSP<24; 50<=Speed
39	Cruise/Acceleration; 24<=VSP<30; 50<=Speed
40	Cruise/Acceleration; 30<=VSP; 50<=Speed

EPA's premise in designing MOVES to represent warmed-up exhaust emission rates by operating mode bin is that emission rates in these bins are independent of driving cycles or trip patterns. The relative frequencies of operation by bin for any driving cycle or trip pattern can then be used within MOVES to calculate composite emissions over the driving cycle from a weighted average of emissions rates for each operating mode bin it contains. MOVES is based on different driving cycles than that on which the dynamometer test results were measured, the ADC. As a result, a direct comparison of total cycle or trip emissions between the ADC and default trip patterns contained in MOVES will reflect different operating mode distributions that affect emissions and result in a biased comparison. (This bias is further discussed and quantified in Section 5.3.) Thus, a comparison of warmed-up exhaust $PM_{2.5}$ emission rates by operating mode bin between the gasoline vehicle dynamometer test results and MOVES was performed.

<u>Binned Test Measurement Emission Rates</u> – First, the second-by-second dynamometer test measurements of $PM_{2.5}$ emissions were calibrated against the filter measurements by applying the ratio of filter-measured emissions for each test against those collected from the modal measurements. The VSP and operating mode bin for each second-by-second test measurement were then calculated from the speed, acceleration, mass, and track road load coefficients[*] for each vehicle using the equation and bin definitions listed earlier in this sub-section. The filter-adjusted second-by-second $PM_{2.5}$ measurements for each test were then allocated into one of the 23 running exhaust operating mode bins. Since these comparisons were performed for warmed-up exhaust measurements, the Cold ADC and Warm-Up Idle tests/segments were not included in this analysis; only Hot ADC second-by-second measurements were used. Mean emission $PM_{2.5}$ rates (in g/hour) were calculated from the total number of single-second measurements in each operating mode bin. Separate means for tests with and without plug-ins were computed and averaged across all six vehicles in the Fairbanks test sample.

<u>Binned MOVES Emission Rates</u> – Basic running exhaust $PM_{2.5}$ emission rates by operating mode bin were extracted from the *EmissionRateByAge* table in the ***MOVESDB20100830*** database. (The emission rates by individual operating mode bin cannot be output by the model and had to be extracted from its database.) Rates from this table were culled for MOVES pollutant/process codes 11101 and 11201, which represent organic and elemental carbon-based running exhaust $PM_{2.5}$ (in g/hour). (The organic and element carbon rates were summed to represent total exhaust $PM_{2.5}$). These rates are further stratified by fuel type (gas vs. Diesel), regulatory class (passenger cars, light trucks, etc.), model year, and vehicle age group (in years). Specific rate records were then extracted that corresponded to the fuel type (gasoline), regulatory class (passenger cars and light trucks), model years, and vehicle ages of the six-vehicle test fleet. Table 2-2, presented earlier, shows a list of the model year and vehicle type/regulatory class of each of the tested vehicles. Vehicle age was determined by subtracting 2009 from the model year, and the vehicle was then assigned into one of the seven age groups used by MOVES in the *EmissionRateByAge* table: (1) 0-3 years; (2) 4-5 years; (3) 6-7 years; (4) 8-9 years; (5) 10-14 years; (6) 15-19 years; and (7) 20 or more years. Thus, the set of extracted rate records represented the specific fuel, vehicle types, model years, and ages of each of the six vehicles in the Fairbanks test fleet. MOVES-based emission rates by operating mode were extracted to represent each of the vehicle type, model year, and

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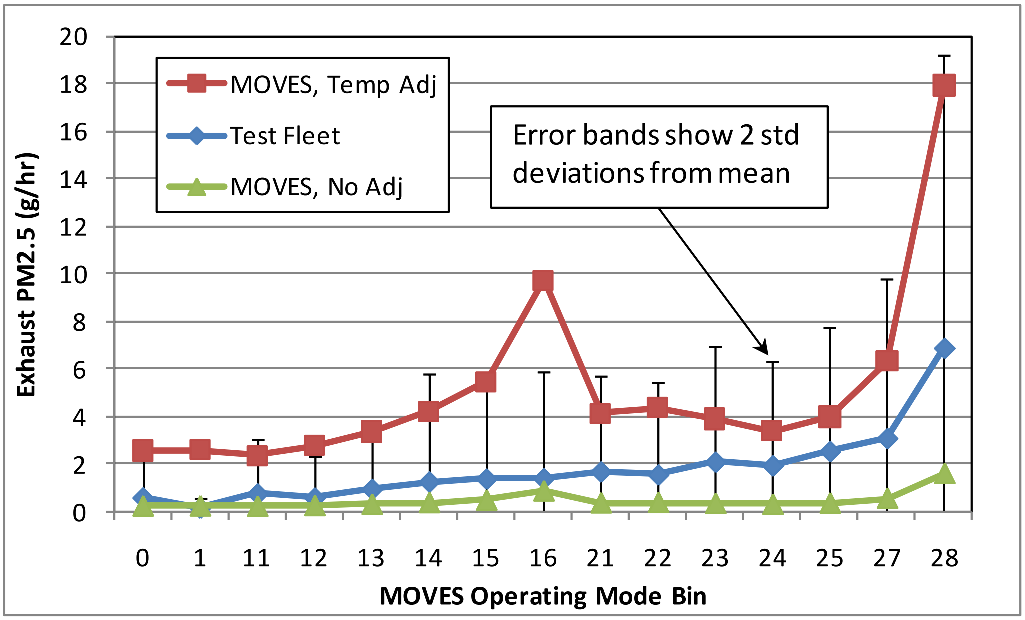
[*] Track road load coefficients for each vehicle were obtained from make, model, and engine-size-specific data in Sierra's I/M Lookup Table.

age combinations of the six vehicles in the Fairbanks test fleet for direct comparison. As with the test fleet, the rates in each bin were then averaged across each of the six vehicle type, model year, and age combinations. This approach ensures the distributions of vehicle type, model year, and test fleet age are equivalently represented in the MOVES-based emission rates.

Figure 5-1 compares MOVES exhaust $PM_{2.5}$ emission rates by operating mode to those of the Fairbanks test fleet without plug-ins. Two sets of MOVES rates are shown: (1) those adjusted to match ambient temperatures of the test measurements (MOVES, Temp Adj); and (2) those at the reference temperature of 75°F (MOVES, No Adj). Error bands plotted for the Test Fleet rates show the spread of individual single-second measurements within each operating mode bin, representing two standard deviations from the plotted means.

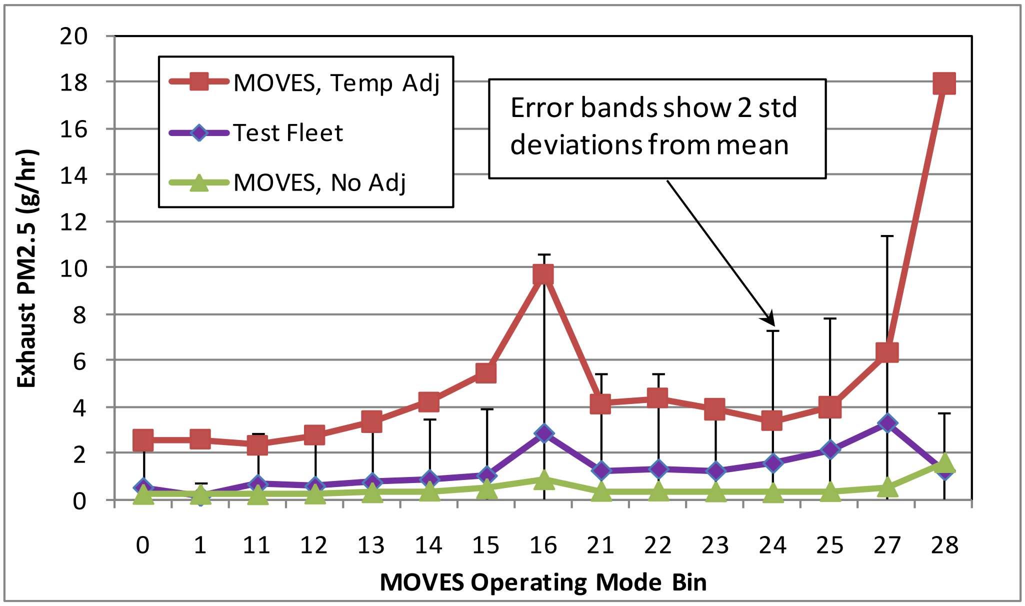
Figure 5-1
Running Exhaust $PM_{2.5}$ Emission Rates by Operating Mode Bin
Fairbanks Fleet Hot ADC No Plug-In Tests vs. MOVES



As seen in Figure 5-1, the temperature-adjusted MOVES rates are always significantly higher than those for the Fairbanks test fleet. For a couple of the bins, the MOVES rates are even above the 95th percentile (2 standard deviations) of measured emission rates within the bin. As expected, the unadjusted MOVES emission rates, representing running exhaust $PM_{2.5}$ at 75°F, are always well below the test fleet rates, which were measured at an average ambient temperature of -2.1°F. These unadjusted MOVES rates were plotted to show the magnitude of the ambient temperature adjustment in MOVES to correct emission rates from a reference temperature of 75°F to the observed -2.1°F average temperature.

Figure 5-2 presents a similar comparison for plugged-in Hot ADC tests against corresponding MOVES-based emission rates by operating mode bin. The running exhaust Fairbanks fleet emission rates by operating mode bin for plug-in tests shown in Figure 5-2 are similar to those for non-plugged-in Fairbanks tests plotted in Figure 5-1. This is not surprising since both sets of rates are for fully warmed-up tests; the effects of plugging in are largely limited to cold start operation prior to complete warm-up. Again as in Figure 5-1, Figure 5-2 shows that the temperature-adjusted MOVES rates by operating mode bin are significantly higher than the averages tabulated from the test fleet measurements.

Figure 5-2
Running Exhaust $PM_{2.5}$ Emission Rates by Operating Mode Bin
Fairbanks Fleet Hot ADC Plug-In Tests vs. MOVES



As seen in both Figures 5-1 and 5-2, when compared for the same mix of vehicle types, model years, and ages in the Fairbanks test fleet and adjusted to the tested ambient temperatures, MOVES' running exhaust $PM_{2.5}$ rates for every operating mode bin are noticeably higher than measured from the dynamometer tests. Since EPA's premise in using operating mode-based emission rates in MOVES is that these bins are independent of driving patterns or cycles, the question is then why are the average emission rates by bin from the test result so much lower than represented by MOVES, especially since the rates across bins follow similar up and down patterns to those in MOVES (except for Bin 28 plug-in tests and Bin 16 tests without plug-ins).

The following sub-section examines differences in ambient temperature effects between the test measurements and MOVES and may help to answer this question.

5.2 Ambient Temperature PM Effects

Exhaust emissions in MOVES as a function of ambient temperature are based on dynamometer testing of several hundred vehicles in Kansas City during 2004.[1] Table 5-2 compares the effective "ambient temperature slopes," defined as the relative increase in $PM_{2.5}$ emissions per 10 °F drop in ambient temperature, between those in MOVES (based on the Kansas City Study) and the Fairbanks dynamometer measurements. Comparisons for both incremental cold start and running exhaust are presented.

Table 5-2
Exhaust $PM_{2.5}$ Ambient Temperature Slopes
Fairbanks Test Sample vs. MOVES/KC Study Data

	Relative PM Emissions Increase (%) per 10°F Temperature Drop	
Source	Cold Start Increment	Running
MOVES/KC Study	59%	37%
Fairbanks Study	31% normals, 19% high-emitters	No statistically significant slope

The comparisons in Table 5-2 indicate markedly different PM temperature slopes, with the smaller sample of Fairbanks data showing no statistically discernable temperature effect for warmed-up running exhaust emissions, while MOVES reflects a 37% increase in running exhaust $PM_{2.5}$ per 10°F drop in ambient temperature. For the cold-start increment, MOVES also contains a temperature slope (59%) that is roughly double that seen in the Fairbanks measurements.

From the Kansas City Study, EPA concluded that emissions are exponentially related to ambient temperature as follows:

$$\text{PM}(T) = \text{B} \exp[\text{M} \times T]$$

where T is the ambient temperature (°F), and B and M are fitted constants (M is the temperature "slope" coefficient).

However, PM cold start and running exhaust emission relationships developed by EPA from this exponential form show significant scatter in the individual measurements from the Kansas City data, with coefficients of determination (R^2) of roughly 0.22 and 0.05, respectively. There is also very little overlap in the range of ambient temperatures over which the Kansas City Study and Fairbanks measurements were performed: the Kansas City data included few measurements below 20°F; the Fairbanks measurements were largely collected below 20°F. EPA also compared its derived temperature slopes from Kansas City data collected between 20°F and 75°F to those from a limited sample of tests from two vehicles measured in an earlier study by the EPA Office of Research and

Development (ORD) that ranged down to -20°F, and found the ORD measurements to generally follow this slope. However, the fact that the ORD study included only two vehicles suggests broader sampling at cold temperatures is necessary to more conclusively determine the effect of ambient temperature on $PM_{2.5}$ exhaust emissions in the range of wintertime temperatures in Fairbanks.

5.3 Comparison of Driving Pattern Effects

The design of MOVES does not allow either milder wintertime Alaska driving patterns or warm-up idling to be accounted for when running the model to generate regional or county-scale emission estimates via inputs accessible through the model's user interface.[*] However, different driving patterns and warm-up idling of any prescribed period (e.g., five minutes) can be simulated within MOVES using an undocumented method of directly editing a specific table in the underlying MOVES database.

MOVES uses a library of driving cycles by vehicle type and average speed to dynamically calculate operating mode distributions for the user input travel fraction in each speed bin. These calculations are performed in the Operating Mode Distribution Generator (OMDG) step within MOVES, as described in the MOVES Software Design and Reference Manual.[5]

The *DriveScheduleSecond* table in the MySQL-based MOVES default database contains second-by-second speed traces for each of over 40 separate driving cycles used in this internal "cycle library" by MOVES to generate operating mode distributions and calculate modally based emissions. The model uses somewhat complex internal logic to perform these calculations by vehicle type, roadway type, and input speed bin. It was found that the operating mode distribution represented by the milder Alaska Driving Cycle (ADC) could be produced within this internal logic by substituting the 816-second speed trace of the ADC for each of the over 40 speed traces contained in the cycle library within the *DriveScheduleSecond* table.

A modified version of the *DriveScheduleSecond* table reflecting the ADC was created and stored within the input database for a county-scale simulation of the calendar year 2008 Fairbanks fleet using wintertime fleet characteristics and travel activity from the recent FMATS LRTP $PM_{2.5}$ Conformity analysis.

In addition, a similarly modified *DriveScheduleSecond* table was also created to reflect the ADC preceded by a five-minute warm-up idle. This approach is not straightforward and would require separate executions of the MOVES for each warm-up idle length considered. It also applies the warm-up idle to all trips of a specific vehicle type, irrespective of the time of day or prior soak period.

Table 5-3 compares the results of three county-scale MOVES runs performed to examine the effects of Alaska driving patterns: (1) default driving cycles contained in the model;

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[*] Although MOVES allows users to input a driving cycle for project-scale runs, this capability is not included in the user interface for county-scale runs, which is the execution mode upon which SIP and regional conformity inventories must be based.

(2) the ADC; and (3) the ADC with a five-minute warm-up idle. As highlighted at the bottom of Table 5-3, MOVES-calculated emissions using the ADC and the ADC with warm-up idle range from 8% to 39% lower, depending on pollutant.

Table 5-3
Comparison of MOVES Emissions (tons/day) from Different Driving Cycles
2008 Winter Fairbanks Light-Duty Passenger Vehicle Fleet

	Emissions (tons per average winter day)			
Driving Cycle(s)	$PM_{2.5}$	NOx	SOx	CO
MOVES Default	0.273	3.322	0.039	70.89
ADC	0.213	2.400	0.028	65.00
5-Min Idle + ADC	0.203	2.146	0.024	63.30
% Change vs. Default: ADC	**-22.2%**	**-27.8%**	**-29.5%**	**-8.3%**
% Change vs. Default: Idle + ADC	**-25.8%**	**-35.4%**	**-39.2%**	**-10.7%**

The fact that Idle+ADC emissions are lower than the ADC by itself (without warm-up idle) is directionally consistent with the incremental benefits of warm-up idling discussed earlier in Section 4. As seen in Table 5-3 (from the difference of the shaded rows), incremental benefits from warm-up idling range, according to MOVES, from 3.6% for $PM_{2.5}$ to nearly 10% for SOx for the Fairbanks light-duty passenger vehicle fleet. Warm-up idle benefits for $PM_{2.5}$ of 41% cited earlier in Section 2.4 cannot be directly compared to these incremental 3.6% MOVES benefit reflected in Table 5-3. The measured benefits reported in Section 3.4 were for normal-emitter vehicles measured over a cold start ADC; the MOVES-based results reported in Table 5-3 are not based on a full cold start, but a mixture of warm and cold starts using default soak distributions contained in MOVES.

A series of “project-scale” MOVES runs reflecting specific pre-soak states (e.g., fully cold) should be conducted for more direct comparison to the Cold ADC measurements collected from Fairbanks dynamometer testing. These project-scale runs will also be able to determine whether warm-up idling as estimated by MOVES in this manner can reflect different levels of warm-up. It is recommended that this be performed after a broader sample of dynamometer measurements are collected this upcoming winter.

5.4 Treatment of Plug-In Effects

Plug-in effects cannot be addressed within MOVES. To account for emission differences for vehicle trips occurring after the vehicle was plugged-in to an engine block heater, MOVES output emission rates would need to be adjusted in post-processing to reflect plug-in benefits.

As reported earlier in Section 4, plug-in benefits for $PM_{2.5}$ over the Cold-Start ADC were found to be 74%, but negligible for Hot-Start ADC tests of normal-emitting vehicles.

Given this significant difference in the emission benefit of plug-ins between vehicles started cold and fully warmed-up, it will also be necessary to develop a relationship for this benefit as a function of the pre-soak time of a vehicle.

When MOVES is executed for SIP inventory purposes in "county-scale" mode, it simulates trip and engine-off soak activity for an entire fleet of vehicles, which is reflected in distributions of soak times by time of day. Thus, any plug-in benefit post-processing adjustments must be able to account for the distributions of soak times that are dynamically calculated during MOVES' execution, but not contained in the primary output database. This will not be a trivial exercise and will need to account for diminished plug-in benefits as the soak time prior to a trip decreases.

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6. REFERENCES

1. "Kansas City PM Characterization Study, Final Report," EPA420-R-08-009, April 2008.

2. Di Genova, F., et al, "Autostart Use and Emissions Characterization Study," prepared for Fairbanks North Star Borough by Sierra Research, May 2007.

3. Carlson, T., "Users Guide to AKMOBILE6 – Alaska Winter Vehicle CO Emission Factor Model," Report No. SR07-10-01, prepared for the Alaska Department of Environmental Conservation by Sierra Research, October 22, 2007.

4. "Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2009) Draft Report," U.S. Environmental Protection Agency, Report No. EPA-420-P-09-002, August 2009.

5. "Draft Motor Vehicle Emission Simulator (MOVES) 2009 Software Design and Reference Manual," Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Report No. EPA-420-B-09-007, March 2009.

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