Report No. SR2012-09-01

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

prepared for:

Fairbanks North Star Borough

September 11, 2012

prepared by:

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Acknowledgement

The success of this study to characterize vehicular emissions in Fairbanks is due in large part to the unwavering support of DEC's Director of Air Quality Alice Edwards, and that of the Director of Fairbanks North Star Borough's Transportation Department, Glenn Miller. Without their continuing support, this project would have gone nowhere. We also wish to acknowledge here Cindy Heil, DEC's conscientious and resourceful contract manager, and Dr. Jim Conner, FNSB's Air Quality Specialist, who afforded the use of essential personnel and equipment at critical stages throughout the study. The most important contributions of many other FNSB staff members, through CMAQ support, are too lengthy to list here but are highlighted in the report.

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1. SUMMARY

In December 2008, Fairbanks was designated by the U.S. Environmental Protection Agency (EPA) as a $PM_{2.5}$* nonattainment area. When that designation was later formalized by notice in the Federal Register, the State of Alaska was placed on a three-year statutory timetable for preparing and submitting a State Implementation Plan (SIP) to achieve and maintain the national ambient air quality standard for $PM_{2.5}$. In 2009, in anticipation of the formal designation and to support development of the Plan and an effective emission control strategy, DEC sponsored a multi-year study to measure and characterize vehicular emissions of $PM_{2.5}$ and its precursors from mobile sources in Fairbank in the winter. Using funds from the Congestion Mitigation and Air Quality (CMAQ) program, the Fairbanks North Star Borough contributed to that effort by providing the critical staffing needed to conduct vehicle emission testing at the Fairbanks Cold Temperature Test Facility and to perform a range of necessary associated activities. This CMAQ-sponsored staffing support was in addition to substantial facilities support and other in-kind support provided by the Borough.

The subject vehicle emission testing was conducted in the winters of 2009–2010 and 2010–2011 by Sierra Research, and has been documented in a report provided to DEC.[1†] The resulting quantification of vehicle emissions is being relied upon, together with information from the U.S. EPA's MOVES model[2] and results from the EPA-sponsored Kansas City vehicle PM emissions study,[3] to formulate the Fairbanks $PM_{2.5}$ SIP. More specifically, the subject study has measured and documented the exhaust emissions from a representative sample of light duty gasoline powered vehicles in Fairbanks in winter. Furthermore, the $PM_{2.5}$ emissions inventory which has been developed as a result of the study, has shown that on-road vehicles are the second largest category of $PM_{2.5}$ emissions in the nonattainment area (after residential space heating), contributing 18-26% of directly emitted $PM_{2.5}$ in the vicinity of the State Office Building monitoring site and a similar fraction near the North Pole site.

The current report provides background on the Alaska wintertime vehicle characterization study and the CMAQ-sponsored FNSB staff contributions to it. The major elements of the CMAQ-funded portion of the vehicle characterization study were as follows:

- Staff support for dynamometer testing of light-duty gasoline vehicles;
- Staff support for collection of instrumented vehicle data for determining state of engine warm-up in Fairbanks; and
- Staff support for on-road "plume following" that included sampling of plumes from six dynamometer-tested vehicles and of more than 1000 plumes from randomly selected

* "$PM_{2.5}$" refers to fine particles having an aerodynamic diameter smaller than 2.5 microns.
† Superscripts denote references provided in Section 6.

on-road vehicles of a wide range of sizes and types (vehicle plume measurement using a "sniffer"* vehicle).

A separate report ("CMAQ Report for Neighborhood Characterization Study") describes neighborhood ambient sampling by a sniffer vehicle (conducted before and after the plume following highlighted above and described further herein) and by a mobile (re-locatable) air monitoring system.

The remainder of this report provides background on vehicle contributions to the wintertime $PM_{2.5}$ problem in Fairbanks, summaries of how each of the study elements listed above was conducted and how the results improved understanding of the role of vehicle emissions, identification of how CMAQ support contributed to the current study, and the significance of the vehicle characterization study in supporting a technically sound and defensible $PM_{2.5}$ SIP for Alaska.

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* "Sniffer" refers to a vehicle that is instrumented to sample outside air while driving and is able to perform on-the-fly ambient pollutant measurements every few seconds.

2. BACKGROUND

Fairbanks has been collecting measurements of $PM_{2.5}$ at its downtown monitor for more than 20 years. Those measurements show a distinct seasonal pattern of elevated concentrations during both summer and winter months. Large uncontrolled wild fires are the principal cause of the elevated summer values. The causes of the elevated winter values are more complex and include severe meteorology (i.e., low wind speed, low mixing depth heights, and arctic winter temperatures), which limits dispersion potential; the combustion of large volumes of fuel for space heating (primarily high sulfur distillate fuel oil, wood and relatively low sulfur, low BTU coal); and poorly understood atmospheric chemistry that promotes secondary particulate formation. Collectively, these factors have caused the Borough to routinely exceed the more stringent 35 $\mu g/m^3$ National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ that EPA established in 2006, and resulted in Fairbanks being designated as a $PM_{2.5}$ nonattainment area that is required to develop a State Implementation Plan (SIP), which documents the control strategies that will be implemented to demonstrate attainment of the $PM_{2.5}$ standard.

The first step in developing a SIP strategy is to determine the relative contribution of the emission sources to the elevated concentrations. However, initial studies using Positive Matrix Factorization, UNMIX, instrumented vehicle measurements, and monitoring correlation, provided a wide-ranging and conflicting picture of the motor vehicle contribution to elevated $PM_{2.5}$ concentrations[*] and indicated that additional information was needed to resolve this issue.

Another approach that could be used to assess the relative contribution of motor vehicles to the level of directly emitted and related precursor emissions of $PM_{2.5}$ (which is a standard approach in air quality management) would be to construct an overall emissions inventory for Fairbanks. An examination of the available motor vehicle emission factor models, however, showed that they did not well represent winter conditions in Fairbanks. MOBILE6.2, the EPA-approved motor vehicle emission factor model at the time, did not include temperature correction factors for $PM_{2.5.}$ This finding conflicted with results of testing programs conducted in Fairbanks in the mid-1990s[4] and more recently by EPA for its Kansas City study,[3] which reported that directly emitted $PM_{2.5}$ emissions increased exponentially as ambient temperatures decreased (i.e., PM doubled for every 20ºF drop). Therefore, MOBILE6.2 as it was then configured could not be used reliably to quantify wintertime $PM_{2.5}$ levels in Fairbanks.

While this problem was addressed in MOVES (EPA's Motor Vehicle Emission Simulator), the successor model to MOBILE6.2, there is an additional concern that the logarithmic $PM_{2.5}$ temperature correction factor applied to gasoline vehicle $PM_{2.5}$ emissions may greatly overstate

[*] Contemporary estimates in 2008, for example, of the motor vehicle contribution to $PM_{2.5}$ during winter episodes varied from less than 5% (Sierra PMF study) to 35% or more (e.g., UAF correlation study).

the vehicular emissions because it does not account for the impacts of block heaters, which are universally employed in Fairbanks at ambient temperatures below -20ºF. Since block heaters impact several of the factors identified in the Kansas City study that influence the rate of $PM_{2.5}$ formation in gasoline vehicles (e.g., enrichment during cold start, time to catalyst light-off, etc.), it was expected (and later confirmed by the subject study) that use of block heaters would greatly diminish the impact of ambient temperature on directly emitted $PM_{2.5}$ levels. Furthermore, almost all of the winter testing conducted in the EPA's Kansas City test program, which served as the primary source for EPA's estimates of PM emissions for MOVES, was at ambient temperatures above 20°F, whereas most $PM_{2.5}$ exceedances in Fairbanks occur when temperatures are below 20°F. Discussions between Sierra and EPA staff in Ann Arbor, Michigan responsible for the development of MOVES confirmed these concerns and acknowledged that a precedent for addressing the impacts of Fairbanks-specific vehicle operating conditions (i.e., use of block heaters, extended cold start idle, and moderate winter driving) was established in the creation of AKMOBILE6 and needs to be addressed in MOVES.

Previous testing programs conducted in Fairbanks collected data quantifying the impact of block heater operation, extended idle, and diminished winter acceleration rates on hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxide (NOx) emissions. An analysis[5] of those data showed that block heaters reduced overall trip CO by 43.8%. It also showed the HC levels were reduced by 44.4% and NOx levels by 6.4%.

Recognizing that winter operating conditions in Fairbanks impact $PM_{2.5}$ emissions, the State sought to enlist EPA participation in vehicle testing programs to capture these effects, but efforts were unsuccessful. Therefore, to address the gaps in then-current knowledge and to provide a sound basis for estimating vehicular emissions in its Fairbanks $PM_{2.5}$ SIP, DEC issued a competitive procurement entitled "Characterize Vehicular Contributions to $PM_{2.5}$ in Fairbanks, AK."[6] The contract was awarded to and emission testing work was carried out by Sierra Research. The remainder of this report discusses that DEC-sponsored study and the critically important role of the Borough's CMAQ-sponsored FNSB staff support for elements of that study.

2.1 Characterizing Vehicular Contributions to $PM_{2.5}$ in Fairbanks

The main purposes of the vehicle emission characterization study were as follows:

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

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

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

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

5. To determine whether the U.S. EPA's MOVES emission model will properly represent emissions under wintertime conditions in Fairbanks, or whether it may need "adjustments."

The study consisted of four main elements: chassis dynamometer testing of more than 30 vehicles, on-road sampling of more than 1,000 vehicle plumes using an instrumented vehicle, sampling and recording of in-use engine coolant temperatures to document the state of engine warm-up, and an examination of MOVES in consideration of the possible need for low-temperature adjustments.

2.2 FNSB's CMAQ Contribution to the Vehicle Characterization Study

As specified in ADEC's RFP, FNSB provided 40-60 hours per week of FNSB assistance during the dynamometer study.

Details of the dynamometer study and on-road plume following, with particular emphasis on the CMAQ-sponsored staff support, are presented in the following section.

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3. DYNAMOMETER AND STATE OF ENGINE WARM-UP TESTING STUDY

This section documents the major FNSB staff contributions through CMAQ funding to DEC's vehicle characterization study. The dynamometer testing portion of the vehicle characterization study consisted of two winter seasons of measurements, a pilot study and a main study, as described below. The corresponding testing work—including preparation, execution, and analysis of results—is described in greater detail in separate report volumes by Sierra Research, as cited below.

3.1 Pilot Dynamometer Study

The first season of dynamometer testing, 2009–2010, may be characterized as a "pilot study" in the sense that only six carefully selected vehicles were tested. Details of the study design, equipment, procedures, analysis and results are provided in Volume 2 of the study report.[7]

3.1.1 Purposes

The main purposes of the pilot study were as follows:

1. To upgrade the Borough's 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 compared to emission estimates from the U.S. EPA's MOVES emissions model, with particular interest in ambient temperature effects and Alaska wintertime driving behavior.

3.1.2 CMAQ Support

Upgrading of the Fairbanks Cold Temperature Test Facility was carried out by Sierra Research, with assistance from Bob Wells and Dave Herring of the FNSB Heavy Duty Maintenance Shop, who provided expert support with dynamometer maintenance and other test cell support. (See Table 4-1 in the next section for a summary of FNSB staff support). Borough staffer Jeremy Bahr ably constructed a custom filter equilibration chamber to specifications provided by Sierra. Highly accurate filter weight measurements were required to accomplish vehicular PM emission tests in accordance with Federal Test Procedures, and the chamber was required in order to stabilize filters with respect to temperature and humidity prior to weighing them on a Sartorius tenth microgram balance. The balance was positioned on a high mass, low vibration pedestal in the environmentally controlled chamber, along with an electronic deionizer.

All test vehicles were registered in FNSB and recruited through an email inquiry to Borough employees. Vehicle recruitment was arranged by Borough staffers Kelly Shaw and Todd Thompson. Shaw, who is the former vehicle inspection and maintenance inspector for the Borough, also arranged for and prescreened all candidate vehicles (to ensure safe testability and to help ensure reasonably typical vehicles for the "normal" vehicle sample) prior to acceptance into the test program. Acceptance required that owners sign a participation agreement that was drafted by Sierra in consultation with the Borough, and coordination and collection of those agreements was done by Borough staff. Seven vehicles were accepted into the pilot study, with one of those serving as a standby (it was not needed).

Four of the seven vehicles were characterized *a priori* as "normals"—i.e., average mileage for their age (model years 1995 to 2007, and mileages ranging from 21,000 to 119,000), no fault codes set, and no known defects that might result in abnormal PM emissions. Two other vehicles were deliberately chosen as suspected high emitters having high mileage (>200,000 miles), known major defects, and visible smoke. Of the two high emitters, one was a relatively old (MY 1984) carbureted pickup having a strong smell of unburned gasoline and obviously incomplete fuel combustion. The second was a newer sedan (MY 1990) that had two defects induced (removal of the catalyst and enrichment of the fuel mixture).

The pilot testing program was conducted over 13 testing days in February 2010, during which the start of test ambient temperatures ranged from -24°F to +23°F. Each vehicle was tested with and without prior 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 but were specific DEC objectives for the test program). In addition, each vehicle was tested when ambient soak temperatures were in the range of +20 < T(ºF)< 0 and then again at 0º < T(ºF) < -20. Thus, each vehicle was tested (nominally) 12 days in all, and each vehicle-day of testing included one cold start and one hot start. As prescribed by DEC, driving followed the Alaska Drive Cycle,[*] which is designed to be representative of Alaska winter driving.

One additional element performed at the end of all the dynamometer testing was the on-road sampling of each of the dynamometer-tested vehicles. This was conducted by Sierra with the support of several Borough staff members, including drivers (Sierra researchers and other private individuals are not permitted to drive Borough vehicles), on-board record keepers, etc. This element was designed to test and demonstrate the capability of an on-road vehicle monitoring system to measure the in-plume emissions behind normal emitters and high emitters and distinguish the difference. This effort to sample both types of vehicles was, in fact, successful in that acceleration plumes from both types of vehicles could be distinguished from background and from each other, and in this way could be used to distinguish high and low emitters on road, as discussed further in the CMAQ saturation study report.

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

Testing was conducted six days per week. The dynamometer driving and other dynamometer test cell activities for the pilot study were shared by the four assigned Borough staff members with assistance from two DEC staff members (Missy Jensen and Joan Hardesty). Most of the test crew staff members had participated in one or more similar vehicle exhaust emission measurement campaigns in earlier years, and all test crew members alternated hours and days to provide the necessary support each day.

Following refresher training about test cell driving and safety, the test crew performed an assigned list of duties including the following:

- Receiving and checking out vehicles (fuel level, tire pressure, initial cosmetic damage, etc.);
- Positioning soak vehicles with plug-in as required;
- Moving (i.e., pushing) test vehicles into place and securing in the test cell;
- Assisting in vehicle alignment and cleaning tire treads to remove ice and snow;
- Positioning, attaching, and configuring testing equipment;
- Observing tests and assisting the driver as needed;
- Detaching and removing test vehicles and equipment after the test; and
- Completing documentation as needed.

For drivers, there was the additional step of reviewing the driving results with Sierra's test manager, reporting any false starts or stalls, and reviewing any drive trace speed violations.

When the testing portion of the study was completed, test data were analyzed by Sierra and Sierra's subcontractor Rincon Ranch Consulting.

3.1.3 Results

The main findings from the dynamometer pilot study are listed 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; 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 phase—between those times, test vehicles were returned to customer service, different fuels could have been used, and other changes may have occurred.

3. 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[*8]) 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.

4. 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.

5. 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 four normal emitters.

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[*] The use of radio-based remote start devices, locally referred to as "autostarts," is common 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.

[‡] Subsequent to the preparation of Sierra's report, EPA published an updated version of MOVES which more readily permits specification of drive cycles for light duty vehicles, thus allowing for the emissions effects of LDV extended warmup idles to be accounted for.

As a secondary objective of the dynamometer study, gaseous criteria pollutants were also measured. However, the data were limited due in part to IM240 system saturation during fuel enriched cold starts and HC analyzer malfunction.[*]

3.2 Main Dynamometer Study

The main dynamometer testing component of the vehicle characterization study, comprising multiple cold and hot start tests of more than 30 vehicles, was conducted in the winter of 2010–2011. Details of the study design, equipment, procedures, analysis and results are provided in Volume 1 of Sierra's study report.[9]

3.2.1 Purposes

The express purposes of this study were as follows:

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

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

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

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

5. To determine whether the U.S. EPA's MOVES emissions model will represent vehicle emissions properly under wintertime conditions in Fairbanks, or whether it may need "adjustments."

3.2.2 CMAQ Support

The study consisted of four main elements: multiple chassis dynamometer tests of each vehicle in a representative sample of more than 30 vehicles and analysis of results, on-road sampling and analysis of more than 1,000 vehicle plumes using an instrumented vehicle,[†] sampling and analysis of in-use engine coolant temperatures to document the state of engine warm-up, and an examination of MOVES in consideration of the possible need for low-temperature adjustments. Borough staff, through CMAQ support, had important roles in several of these elements, as described next.

[*] Both of these problems were addressed, but not until after the pilot study was completed. The problem of intermittent HC and CO analyzer saturation was eliminated by installing isolation amplifiers between the gas analyzer and the analog-to-digital conversion board of the Horiba IM240 system; the HC analyzer malfunction was traced to a plugged capillary tube, which was replaced.
[†] The "plume following" element of the main study is discussed in the Saturation Study CMAQ report.

The dynamometer testing in the main study was similar in many respects to the Pilot Study and was supported by a comparable Borough staff effort on a weekly basis. The main differences in the testing as related to Borough staff support are outlined below.

- More tests were conducted in the main study, with a sample of 32 vehicles (compared to just 6 in the Pilot Study), although the number of tests per vehicle was smaller (3 per vehicle in the main study vs. 12 in the pilot study). As a result, the main study required 19 days of dynamometer testing compared to 12 days for the pilot study, with a proportionally greater CMAQ staff commitment.

- In the main study, all of the dynamometer driving was done by a single staff person, Kelly Shaw (who was the most accurate driver). Shaw, with assistance from Ron Lovell, also screened all of the test vehicles and handled several unanticipated vehicle problems (e.g., minor vehicle damage and repairs).

- The main study was conducted in two test phases, consistent with the test plan of performing tests of each vehicle at both cold and warm temperatures. This design was used to deploy Carchip data loggers for the test vehicles and obtain information on state of engine warm-up at trip starts (discussed in Section 3.4, below).

As in the Pilot Study, DEC provided additional valuable support as test crew members.

Neither Borough staff nor DEC staff participated in the data analysis or reporting from the main study or other study elements. That portion was done by Sierra and its subcontractor Rincon Ranch Consulting. In addition, for the study of the state of engine warm-up, Sierra analyzed the results from data loggers installed for most of the dynamometer tests.

3.2.3 Results

Findings from the dynamometer-based testing are summarized below.

1. Use of block heaters ("plug-in"), heated garages, and extended warm-up idle for light-duty vehicles are all normal activities and/or practical necessities in Fairbanks in winter that can significantly affect $PM_{2.5}$ emissions. However, examination of these effects, which are critical in Fairbanks but less important in locations in the lower 48 states, was beyond the scope of EPA's Kansas City PM Emissions Characterization Study[10] and of (then current[*]) EPA guidance[11,†] for using MOVES. In addition, the PM emission factors

[*] The most recent release of MOVES allows for more readily specifying extended idle for light duty vehicles, as noted earlier.

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

in MOVES, including the temperature corrections of those emission factors, are derived from measurements made in Kansas City, where the minimum temperature for the testing was +12°F.* That Kansas City minimum temperature exceeds the long-term average monthly temperature in Fairbanks for the months of November through March[12] and is well above the -12°F average daily temperature for $PM_{2.5}$ design day episodes in Fairbanks.[13] Other "low temperature" vehicle PM emission studies used to support or help corroborate MOVES had only a limited number of vehicles and tests; conducted testing down to only about -20 or 0°F; and did not include analysis of plug-in, heated garaging, or warm-up idle. As a result of the above limitations, any modeling of Fairbanks PM emissions using MOVES must necessarily rely upon extrapolations of effects measured at higher temperatures, neglect the effects of plug-in, and/or neglect other real effects that significantly influence emissions. The results from emission testing in Fairbanks in the winter of 2011 (summarized below) confirm that such extrapolation and assumptions are not technically supportable and could result in overestimating the $PM_{2.5}$ emissions from light-duty gasoline vehicles by up to 680%.

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

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

4. Based on Fairbanks winter test results, block heater plug-in during overnight soak and 5-minute warm-up idle after engine start (which together are the common practice for

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of these factors." What the reviewer suggested as "options" are not, however, optional at Fairbanks winter temperatures, but instead are required for reliable daily vehicle starts.

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

vehicles parked out of doors overnight or for extended periods in Fairbanks in winter*[8]) reduced cold start $PM_{2.5}$ emissions by 74%. Neither plug-in nor warm-up idle of light duty gas vehicles is considered in MOVES, despite the fact that at temperatures below about -20°F, most gasoline vehicles will not start reliably without starting assist, and such starting is not routinely attempted in normal winter operation in Fairbanks.

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

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

3.3 State of Engine Warm-up in Fairbanks in Winter

For the Federal Test Procedure, the state of engine warm-up for a cold start test is generally adequately controlled by specifying the temperature range (68° to 86°F) and the duration of the prior vehicle soak. Testing of cold temperature certified vehicles (down to +20ºF) adds complexity to this simple picture, but soak time and temperature together still define the relatively simple implicit specification of the state of engine warm-up for vehicle certification testing. However, in Fairbanks, the widespread use of plugin block heaters and extended idle at low temperatures complicates the relationship of soak temperature and duration and the state of engine warm-up, and it raises significant questions about the applicability of the simple relationship which underlies the cold temperature emission estimates from MOVES.

3.3.1 Purpose

The purpose of this relatively low-cost add-on to the dynamometer test program was to better understand the state of engine warm-up at time of engine start for both the dynamometer-tested vehicles and vehicles in customer service.

3.3.2 CMAQ Support

The study of the state of engine coolant was based on installing five to six data loggers in test vehicles; returning those to customer service (typically for a week or more); and then retrieving the data loggers, uploading the data, and repeating the cycle, which lasted for some months. These data were then combined with similar in-use vehicle data from several years earlier. This entire data collection effort in 2010–2011, including vehicle owner contacts and coordination and signing of participation agreements and delivering compensation, was performed by

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

Borough staff with CMAQ support, as documented in Table 4-1. Study design, preparation of participation agreements, staff direction, data analysis, and reporting was done by Sierra.

The principal Borough staff members performing this work were Kelly Shaw and Todd Thompson, although test crew members all assisted with installing and retrieving data loggers before and after each dynamometer test.

3.3.3 Results

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

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

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

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

4. Instrumented vehicle data suggest that, except for very short soak periods (less than 2 hours), plug-in is used almost universally for engine starts at ambient temperatures below

-20°F. While it is possible to start some newer gasoline-powered vehicles at ambient temperatures below -20°F, this is neither recommended nor normal practice in Fairbanks.

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

3.4 Plume Following Study

In August 2009, as part of its Procurement for Characterizing Vehicle Contributions to $PM_{2.5}$ in Fairbanks, ADEC specified a scope of work[6] that included the following:

> *On-road Emission testing – a plume following study, where on road vehicles are followed by an instrumented vehicle to determine their emissions during on road use.*
>
> *The contractor will design and implement a vehicle plume following study, including quality control/assurance activities. The concept of the study is to capture and analyze on road vehicle emissions during on road use. Proposals should include methodology for the study, including study size, and demonstrate their understanding of the vehicle instrumentation required. The successful contractor will be required to set-up instrumentation, develop a quality assurance project plan, and conduct the study in Fairbanks. The contractor shall assume that some assistance will be provided by the Fairbanks North Star Borough staff. For purposes of the proposal, assume that FNSB will provide one driver and any vehicles needed to be instrumented. Final support assistance will be determined with the successful proposer.*

ADEC's procurement was awarded to Sierra Research, who devised and executed a plan to modify a Borough vehicle for plume sampling, train staff in its use, analyze the resulting data, and prepare a report. That report was provided to ADEC in July 2011.[14]

The main goal of the plume-following study was to gain a better understanding of emissions in Fairbanks winters from vehicles that cannot readily be tested on the Borough's light-duty chassis dynamometer (e.g., medium- and heavy-duty vehicles) and/or for which little information exists on the sensitivity of PM emissions to low temperature (e.g., Diesels).[*]

In the winter of 2009-2010, following the development and successful testing by Sierra Research of its prototype plume following instrumentation in Sonoma County, California, a Borough SUV

[*] Unlike the case for gasoline-powered vehicles, the USEPA's MOVES emission factor model currently has *no* provision for temperature adjustment of Diesel emissions. According to EPA, this is not because they believe there is no effect. Rather, they have insufficient data to quantify the effect.

was equipped with bumper- and roof-mounted cyclones to sample on-road plumes from followed vehicles. Real-time analyzers were installed and used to measure $PM_{2.5}$ and CO_2* concentrations; a GPS (satellite-based Geographical Positioning System) provided location; a computer logged and displayed data in real time; and supplemental manual, audio and video data were logged.

3.4.1 CMAQ Support for Vehicle Following in 2009-2010

Following training by Sierra, and under CMAQ funding support, Borough staff operated the sampling vehicle on-road, conducting "plume following" operations over a period of 15 days in February and March 2010, consulting with Sierra on issues that arose, and uploading data regularly. Borough staff also prepared contemporaneous audio notes (necessary for efficient capture of license plates) which they later transcribed and, with the aid of the State's registration database, used to characterize vehicle types. This allowed for Sierra to conduct detailed analyses and comparisons across vehicle and engine types, the results of which are summarized below along with results from on-road plume following of the six dynamometer-tested light duty vehicles from the pilot study.

3.4.2 Results of Vehicle Following Study in 2009-2010

Based upon on-road measurements of $PM_{2.5}/CO_2$ ratios in the exhaust plumes of six vehicles previously tested on a dynamometer and upon a sampling of more than 1,000 plumes from pseudo-randomly selected on-road target vehicles of all types in Fairbanks, several conclusions were reached, as summarized below.

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

2. Based on the above threshold ratio and the results from sampling acceleration plumes from a pseudo-randomly selected sample of 630‡ on-road vehicle plumes, 7.5% of the on-road fleet in Fairbanks would be classified as high emitters.

3. The highest average emission ratio was for heavy-duty Diesel trucks (0.408), closely followed by heavy-duty gasoline-powered trucks (0.326); plume ratios for these two categories were statistically indistinguishable from each other.§

4. The second-highest emissions ratio was for Diesel-powered vehicles (0.245), which was about three times that for gasoline-powered vehicles (0.080), ($p \sim 0.00\%$).

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* Carbon dioxide concentrations provided a "tracer" for combustion plumes.
† Five-second ratio of vehicle-emitted $PM_{2.5}$ and CO_2 concentrations after subtracting estimated background
‡ This represents the subsample whose license plates could be read, thereby permitting exclusion of duplicate counts of the same vehicle.
§ For heavy-duty Diesel and gasoline-powered trucks, and Diesel buses, fewer than 15 vehicles were sampled; as a result, error bands on the estimated means are wide and the power to discern significant differences was reduced.

5. The average emission ratio for light-duty Diesel trucks (0.202) was about three times that for light-duty gasoline-powered trucks (0.071), ($p \sim 0.00\%$).

6. The average emission ratio for heavy-duty gasoline-powered trucks (0.326) was about 4.5 times greater than that for light-duty gasoline-powered trucks (0.071) ($p \sim 0.00\%$).

7. The average emission ratio for light-duty gasoline-powered trucks was comparable to that for (gasoline-powered) cars and Diesel buses.

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4. SUMMARY OF CMAQ SUPPORT

As described earlier and shown in Table 4-1 (below), Borough staff under CMAQ funding supported the subject multi-year study in a variety of ways. Neither the table nor descriptions are intended to be comprehensive; instead, they are intended to highlight the major functions, which encompass many other duties.

Table 4-1
Summary of Major Activities of FNSB Staff
in Support of the Vehicle Characterization Study

Pilot Dynamometer and Plume Following Studies, 2009–2010		Main Dynamometer and Engine Warm-up Studies 2010–2011	
Staff	Duties	Staff	Duties
Bahr	Constructed filter equilibration chamber; served as test crew and driver; on-road driver for Plume Following	Bahr, Falk, Gano, Govoni, Remick, Simpson	Served as test cell crew
Gano	Served as test crew and driver; on-road driver for Plume Following	Lovell,	Served as test cell crew; assisted with vehicle inspections and minor vehicle repairs
Shaw	Assisted in vehicle recruitment; inspected all test vehicles; modified one high-emitting vehicle; test cell manager and driver; assisted with lab maintenance	Shaw	Assisted in vehicle recruitment; inspected all test vehicles; test cell manager; drove for all dyno tests; performed minor vehicle repairs; installed and retrieved data loggers; transferred data
Thompson	Coordinated staff; test crew and driver; assisted in vehicle recruitment; on-road driver for Plume Following	Thompson	Assisted in vehicle recruitment; coordinated staff; served as test cell crew; assisted with data loggers and data transferal
Wells, Herring	Provided dyno and lab maintenance support	Wells, Herring	Provided dyno maintenance support

CMAQ funding from fiscal years 2008 and 2009 supported the winter 2009–2010 dynamometer testing program, which was approximately 2.5 weeks in duration, and the on-road Plume Following, which was about 2 weeks on-road and 2 weeks post-processing. CMAQ fiscal year 2009 and 2010 funding supported the winter 2010–2011 dynamometer testing program, which was approximately 4 weeks in duration.

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5. SIGNIFICANCE OF THE SUBJECT STUDY

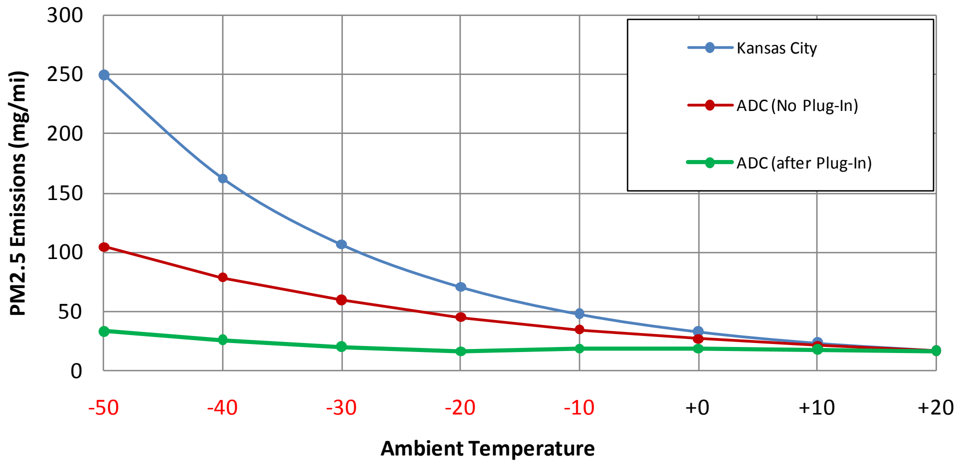
The current study provided DEC and FNSB with a rational basis for the assessing and documenting the contribution of motor vehicles to the Fairbanks winter $PM_{2.5}$ emissions inventory and, thereby, enabled the preparation of an effective and a cost-effective SIP. Absent this research, Alaska would have been forced to rely on highly questionable assumptions about motor vehicle PM emissions and the effects of ambient temperature and block heater plugin upon them. It is not clear whether such an approach could produce a technically sound and defensible SIP. It is particularly informative to note that EPA's MOVES model, which is a critical part of EPA-recommended guidance for estimating vehicular PM emissions for State Implementation Planning, makes no provision for block heater plugin, which is used in Fairbanks in winter almost universally during $PM_{2.5}$ episodic conditions.

Plugin was found in the Sierra dynamometer study to reduce cold start $PM_{2.5}$ emissions by 74%. Even more significantly, the results from emission testing in Fairbanks confirm that extrapolation of MOVES results to Fairbanks temperatures (perhaps the only EPA approvable option for DEC absent the current study) could have resulted in an overestimation of $PM_{2.5}$ from light-duty gasoline vehicles by up to 680%. The effect of both of these default assumptions is shown in Figure 5-1, which is taken from Sierra's report to ADEC.[9] The figure compares $PM_{2.5}$ emission vs. temperature trends as predicted by the Kansas City study[15*] to trends based on the Alaska Drive Cycle (ADC) testing, a driving cycle that is typical of Alaska winter driving. Two ADC lines are shown: no plug-in, and a simple plug-in scenario (0% plug-in at +20°F, 100% at -20°F, and linear interpolation between). In all cases here, the basis for comparison is a 43/57 weighted (Cold ADC/Hot ADC) composite trip of 4.74 mi length.

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

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

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



Source: "Characterizing Vehicular Contributions to PM2.5 in Fairbanks, Alaska, Volume 1: Dynamometer-Based Emissions Measurements, Vehicle Keep-warm Activities, and MOVES Analysis," Sierra Research, July 2011.

Thus, the use of unadjusted MOVES emissions estimates would likely have resulted in motor vehicle emissions being substantially overestimated. Furthermore, subsequent emission inventory analysis by Sierra indicates that the resulting error from using unadjusted MOVES emission estimates could have falsely indicated motor vehicles as the major source of $PM_{2.5}$. That conclusion would have radically undermined any attempt to mitigate the true major source category, which is residential space heating. Most likely, it would have also resulted in years of both unmitigated, potentially harmful population exposure to excessive ambient $PM_{2.5}$ concentrations and costly, unnecessary, and ineffective control measures for vehicles.

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6. REFERENCES

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