Report No. SR2006-09-01

Tier 2 Gasoline Emission Benefits in Alaska

prepared for:

Alaska Department of Environmental Conservation

September 2006

prepared by:

Sierra Research, Inc.
1801 J Street
Sacramento, California 95814
(916) 444-6666

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Principal authors:

Frank Di Genova
Robert Dulla
Tom Carlson

Sierra Research, Inc.
1801 J Street
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Acknowledgement and Disclaimer

This work was sponsored by the Alaska Department of Environmental Conservation (ADEC), and we would like to particularly acknowledge the contributions of former Air Program Manager Ron King, who conceived of the project along with then Project Manager, and now Acting Air Program Manager, Alice Edwards. We would also like to acknowledge the continued excellent support and assistance that we received from the Fairbanks North Star Borough, particularly Glenn Miller, Director of the Department of Transportation; Jim Conner, Director of the I/M Program; Bob Wells, who provided essential facilities' support; and both mechanic Dave Herring and Referee and Master Technician Kelly Shaw, who ably and efficiently performed all fuel changes and assisted with myriad vehicle and testing issues.

Special recognition is due to John Hargesheimer and Peter Beardsley, who managed and led the Nortech team; Senior Consultant Nadine Hargesheimer, who recruited and coordinated participants; and Nortech's dedicated and hard-working on-site test team consisting of Dennis Boyce, Tony Digatono, Andi Hunter, Ronald Pratt, and Dennis Shepard, all of whom performed commendably for long hours under challenging testing conditions.

The statistical analysis was performed with major support from our subcontractor Robert W. Crawford.[*]

Finally, despite the excellent support that we have received, any opinions or errors in this report are our own and not the responsibility of our sponsor ADEC or of any other contributors.

[*] Rincon Ranch Consulting, Tucson, AZ.

Tier 2 Gasoline Emission Benefits in Alaska

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1. EXECUTIVE SUMMARY

In January and February of 2006, an exhaust emissions measurement study of 60 vehicles was conducted at the Fairbanks Cold Temperature Test Facility in Fairbanks, Alaska, to determine the effect of implementing the U.S. Environmental Protection Agency's (U.S. EPA's) Tier 2 (low sulfur) gasoline regulations upon exhaust emissions of carbon monoxide (CO) and other pollutants in Alaska. Reliable quantification of the benefits of low-sulfur gasoline is critically important because the estimated benefits from the regulation constitute a major portion of the current Air Quality Maintenance Plan for CO in Fairbanks.

The testing used randomly recruited and mostly privately owned vehicles, and measured their emissions before and after switching from commercially available high-sulfur gasoline to low-sulfur test fuel. Testing was conducted at ambient temperatures using a chassis dynamometer and was designed to simulate actual wintertime operation in Fairbanks. A brief but aggressive "conditioning" cycle was performed on each vehicle immediately after fuel change in an attempt to mimic the effect of normal, intermittent high-load driving events that would be expected to purge pre-existing sulfur deposits from vehicle catalysts, thereby enhancing catalyst activity.

Replicate cold start and hot start tests were performed on each fuel. As used here, "cold start test" means an exhaust emissions test performed on the chassis dynamometer in which the vehicle was soaked outside overnight with a plug-in engine heater, started cold (using battery assist if needed), idled for five minutes to simulate normal engine warmup, and then driven over the 4.7-mile, 13.6-minute Alaskan Drive Cycle (described later). "Hot start test" means an engine start and drive of the ADC immediately after another cold or hot start test, i.e., with a warmed up engine. Average mass emissions, expressed as grams of CO per mile, are reported for each test and were analyzed to test for the effects of low-sulfur fuel and other factors. In addition, cold start test results were analyzed separately for the start plus warmup idle portion of the test (first five minutes) and the "cold drive" that immediately followed.

Conclusions from the study are divided into those that derive from the measurement portion of the study and those from the analysis of emissions inventory.

Summarized below are our main conclusions from the measurement of exhaust emissions test data and that pertain to changing from 164 ppm sulfur commercial gasoline in Fairbanks in the winter of 2005-06 to low- (1.9 ppm) sulfur test fuel.

1. Changing to low-sulfur test fuel reduced vehicular exhaust CO emissions during cold drive and hot start operation by average amounts that ranged from 20% to as much as 67%, depending upon the operating mode and model year group.

2. The CO and other emissions benefits were greatest (in percentage terms) for the newer model year groups that will account for the large majority of fleetwide travel in coming years. For model year 1996 and later vehicles, low-sulfur test fuel was estimated to reduce cold drive CO emissions by 45% to 64% and hot start CO emissions by 67%.

3. Significant emissions benefits on the above cycles were also observed for total hydrocarbons (THC) and oxides of nitrogen (NOx) and were greatest (on a percentage basis) for the newer vehicles. As with CO, the emission benefits for older vehicles were smaller and, in some instances, not statistically significant.

4. During the start plus five-minute warmup idle portion of the test cycle, CO emissions were significantly increased (by 30%) for 1996 and newer model year vehicles. This CO disbenefit was concentrated in the initial 60 seconds of the cold-start idle period—there was no net increase or decrease in CO emissions during the remaining 240 seconds of the idle period.

5. The presence of the CO disbenefit (and a correlated NOx benefit) was unexpected and is likely due to inadequate vehicle conditioning after the fuel change and either the unusually aggressive driving during the sulfur reduction drive or some unidentified change in fuel property.

6. The most conservative estimate, which is presented by the study, is that the observed CO disbenefit will also occur in the real world after the low-sulfur fuel is introduced. Alternatively, the apparent disbenefit may be an artifact of inadequate vehicle conditioning after fuel change, in which case the observed disbenefit may be expected to disappear with additional mileage accumulation.

7. All of the aforementioned percentage changes in emissions apply to the switch from commercial fuel to low- (1.9 ppm) sulfur <u>test</u> fuel. We estimate that switching from commercial fuel to 30 ppm "<u>compliance</u>" fuel (as required by the USEPA) would reduce all of the projected changes by about 17% (i.e., hot start CO emissions for 2001 and newer model year vehicles that were reduced by 66.7% on low-sulfur test fuel are estimated to be reduced by 55% [66.7 × (1-0.17)] when using average 30 ppm sulfur compliance fuel).

8. Measured emissions benefits (percentage reductions in emissions) were not significantly different for cars and trucks.

Our main conclusions as related to the calculation of tons per day of CO emission reductions from using low-sulfur (30 ppm average "compliance") fuel in Fairbanks in the winter of 2005-06 and in the future are as follows:

1. The overall emission reduction benefits observed in the test program for CO generally tend to confirm the emission reductions projected for light-duty gasoline-powered vehicles in Fairbanks in 2005 using the U.S. EPA's MOBILE6 model together with Alaska's version, AKMOBILE6. As shown in Figure 1-1, percentage emission benefits in 2005 were calculated as 11.3% using the AKMOBILE6 and MOBILE6 models and 13.4% based on the test measurements. (As described later in the report, these results are in reasonable agreement in light of uncertainties in the analysis.)

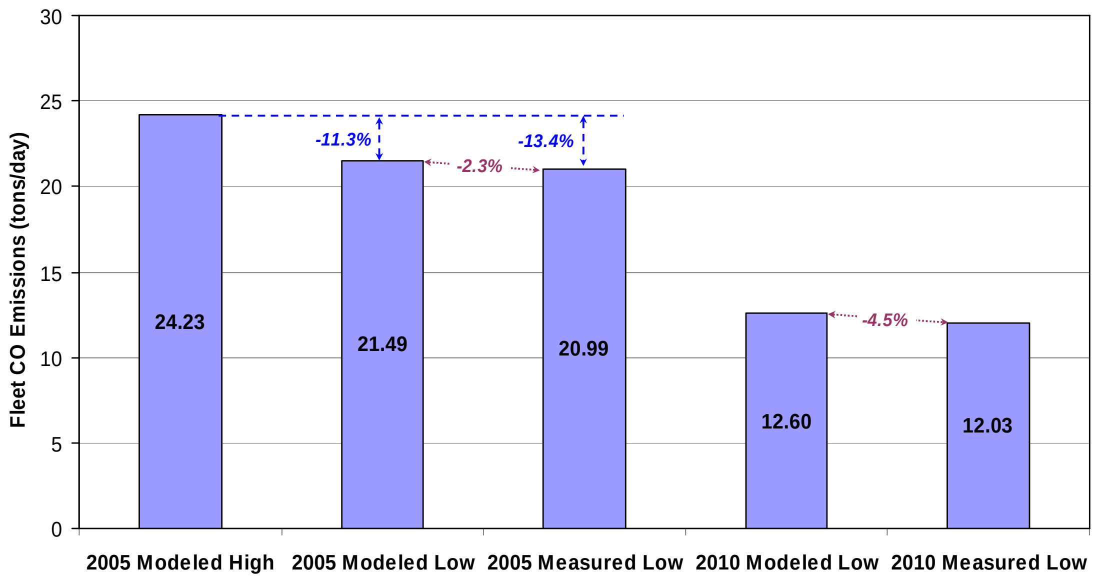
2. Projecting emissions to 2010 is much more uncertain, but if a similar relationship to AKMOBILE6 exists in 2010 as in 2005, CO emissions will continue to be reduced significantly by low-sulfur gasoline. These results are also summarized in Figure 1-1.

3. If the observed CO emissions disbenefit is an artifact of the lack of adequate conditioning after fuel change and conditioning in the test program, the idle emissions shown in the figure would not increase in the measurement-based projections but would be the same as in the MOBILE-based low-sulfur cases (or possibly even lower), resulting in measurement-based projections of CO emissions that are lower than shown by about one ton per day or more.

1.1 Organization of the Report

Section 2 of this report provides an introduction and background for the test program. Details of the testing are documented in Section 3. Section 4 describes test results, quality assurance, analysis of the "idle disbenefit," and data organization. Section 5 presents the data analysis and results, including comparison with results from other studies. The vehicle fleet emissions benefits for CO in Fairbanks in 2005 and 2010 are quantified in Section 6. References cited throughout the report are listed in Section 7. A series of technical appendices support the analysis and provide details of the statistical analysis of the test data. Lab notes and results from individual emissions tests are listed in separate volumes 2 and 3, respectively. Detailed test results are provided in a separate computer-readable data volume.

Figure 1-1
Comparison of Low-Sulfur Fuel Impacts on
Fairbanks Light-Duty Fleet CO Emissions (tons/day)



Notes: Vertical arrows show percentage LSG fleet reductions from the "high" sulfur 2005 baseline.
Slanted arrows show relative differences in model- and measurement-based low-sulfur emission estimates for each year.

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2. INTRODUCTION AND BACKGROUND

Both the Municipality of Anchorage (Anchorage) and the Fairbanks North Star Borough (Borough) have experienced dramatic improvements in air quality in recent years. Anchorage has not experienced a violation of the 8-hour carbon monoxide (CO) standard since 1996 (when the second maximum recorded value was 10.5 ppm) and Fairbanks has not experienced a violation of the 8-hour CO standard since 1999 (when the second maximum recorded value was 10.3 ppm). In light of these improvements, each community was redesignated to attainment of the CO standard in 2004 with the approval of its Carbon Monoxide Maintenance Plan. Despite these improvements, both communities remain vulnerable to strong inversions, particularly Fairbanks.[1*] Analysis incorporated in the Fairbanks Maintenance Plan shows that if the weather patterns of the 1990s and earlier years return, it is possible and even likely that the Borough will record a violation of the ambient CO standard. In light of these findings, the Borough has made commitments to implement an array of local controls to enhance prospects for continued attainment. But the single largest source of CO reduction derives from the implementation of EPA's Tier 2 low-sulfur gasoline requirements. Given the magnitude of the reductions associated with this program, concerns about growth (particularly from the construction of a gas pipeline), and a commitment to consider eliminating the I/M program in the next few years, it is critical that the benefits of implementing the low-sulfur gasoline requirements be verified under wintertime Alaska operating conditions.

Previous studies conducted or sponsored by ADEC, the Borough, and the Municipality have confirmed that EPA's mobile source emission factor models do a poor job of predicting emission levels and related control measure benefits under wintertime operating conditions in Alaska. Similar concerns apply to the MOBILE-predicted CO benefits of Tier 2 gasoline sulfur reductions. Tier 2 regulations have required refiners to steadily decrease the average and maximum sulfur levels in gasoline marketed in different areas of the U.S. These regulations require refiners to decrease average sulfur levels from approximately 150 ppm (with a maximum value of 300 ppm) in 2004–2005 to an average of 30 ppm (with a maximum value of 80 ppm) in 2006, with a one-year extension for Geographic Phase-In Areas (GPA) in parts of the western U.S. and in Alaska (40 CFR 80.215).

Data obtained from gasoline surveys conducted by the Alliance of Automobile Manufacturers[2] show that average winter gasoline sulfur levels in Fairbanks have not declined since the Tier 2 requirements were implemented in calendar year 2000. A

[*] Superscripts denote references provided in Section 7.

summary of the results is shown below in Table 2-1. Unfortunately, no comparable survey has been conducted for Anchorage.

Table 2-1
Alliance Survey Data
Winter Gasoline Sulfur Levels
Fairbanks, Alaska

Calendar Year	Regular wt %	Premium Wt %	Regular ppm	Premium ppm
1995	0.033	0.002	330	20
1999	0.016	0.018	160	180
2000	0.011	0.014	110	140
2001	0.013	0.016	130	160
2002	0.016	0.019	160	190
2003	0.015	0.019	150	190
2004	0.015	0.018	150	180
2005	0.015	0.022	150	220

While these trends may seem surprising, it must be remembered that the values shown represent the average across all brands marketed within Fairbanks. Since there are only two refiners in Alaska that produce motor gasoline and they are known to have dramatically different sulfur levels (Tesoro has advertised levels below 10 ppm and Flint Hills Resources, formerly MAPCO, has produced gasolines at the upper end of the Tier 2 requirements), it is possible that the trends presented in Table 2-1 reflect shifts in distributor purchasing patterns from the refiners (i.e., a shift away from marketing Tesoro gasoline in Fairbanks).[1]

EPA's Tier 2 regulations will require Alaskan refiners to start producing gasoline meeting the 30-ppm average limit in January 2007. This means that the higher sulfur gasoline will start to disappear from the market in the fall of 2006. Thus, (baseline) testing of the cold temperature benefits from these reductions was sought by ADEC in the winter of 2005-06, while the higher sulfur gasoline was still being sold in the marketplace and commercial low-sulfur gasoline was still available in selected areas.

2.1 Objectives and Constraints upon the Current Study

On October 14, 2005, ADEC issued a Request for Proposals, soliciting support for dynamometer testing under cold temperature conditions. The overall objective of the study was "to determine the emissions reduction benefits from low-sulfur gasoline at cold temperatures."[3] The RFP further specified that the contractor must start work no sooner than November 22, 2005, and provide deliverables by the dates shown for the seven defined tasks that are summarized below.

1. Quality Assurance Plan, to be delivered by December 9, 2005.

2. Determination of gasoline consumption patterns through the use of a questionnaire of specified sample size, to be completed by December 23, 2005.

3. A matrix of sampling size choices based upon relative error and confidence limits needed to quantify expected CO benefits, to be completed by December 23, 2005.

4. Design of a Testing Program considering specified factors by December 23, 2005.

5. Conduct of a Testing Program, including the procurement of a representative sample of test vehicles. Testing was to begin "no later than January 17, 2006 and to be completed no later than February 28, 2006."

6. Quantification of the Emission Benefits of Low-Sulfur Gasoline for individual vehicles, and organized into "common age and emission control categories" and fleet averages, by April 19, 2006.

7. Reports (monthly status reports, a draft report by May 1, 2006, and a final report by June 30, 2006).

Sierra's successful response to ADEC's RFP outlined a plan for six consecutive 6-day weeks of testing of 60 vehicles to complete all tasks, but also identified a need for replicate cold start tests beyond what was feasible under the original budget, in order to discern meaningful differences in emissions when using the two fuels. Specifically, Sierra's analysis, which is presented later in this report, quantified and examined the historical, relatively large variability of exhaust emissions test results in Fairbanks when cold vehicles are started (as compared to starting of warmed up vehicles, which is repeatable with much higher precision) and identified the sample sizes needed in order to meet ADEC's objectives for testing under cold start conditions. As a result of that determination and subsequent discussions, ADEC supplemented testing resources and imposed the additional contract requirement that at least 200 "cold start" tests and 400 "hot start" tests[*] must be performed. Finally, while not explicitly listed in the RFP, ADEC's description of its needs and a knowledge of EPA policies made it clear that ADEC would require MOBILE-based emission inventory estimates of average winter day CO emissions in Fairbanks with and without EPA compliant low-sulfur gasoline.

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[*] As used here, a "cold start test" means an exhaust emissions test conducted using a chassis dynamometer in which the vehicle is soaked overnight out of doors with a plug-in engine heater, started cold (using battery assist if needed), idled for 5 minutes, and then driven over the 4.7-mile, 13.6-minute Alaskan Drive Cycle (described later). "Hot start test" means an engine start and drive of the ADC immediately after another cold or hot start test, i.e., with a warmed up engine.

3. TESTING PROGRAM

3.1 Overview

A dynamometer-based exhaust emissions testing program was conducted in the winter of 2005-06 in Fairbanks for the purpose of evaluating the effectiveness of federal Tier 2 low-sulfur gasoline in reducing exhaust emissions under winter operating conditions in Alaska. The study design provided for six consecutive six-day weeks of testing of a total of 60 gasoline-fueled vehicles within the January-February 2006 time window defined in ADEC's RFP, and for providing at least 200 cold start and 400 hot start tests. As detailed below, recruited vehicles were emission-tested on "as-received" (high sulfur) fuel, conditioned on low-sulfur (1.9 ppm, by weight) fuel using an aggressive driving protocol that was intended to remove sulfur from the catalyst, and then emission tested again on low-sulfur fuel. Exhaust mass emissions of carbon monoxide (CO), total hydrocarbons (THC), oxides of nitrogen (NOx), and carbon dioxide (CO_2) were measured using a chassis-dynamometer-based constant volume sampling system (CVS) and were compared before and after the fuel switch, for both cold and hot start drives of the Alaska Drive Cycle (ADC).[4] For cold starts, vehicles were plugged in overnight and idled for 5 minutes to emulate common practice for engine startup in Fairbanks in the winter.

The remainder of this chapter presents details of the high- and low-sulfur fuels that were used, the sample fleet and its recruitment, the equipment that was used for testing, and the test procedures that were followed.

3.2 Fuels Used in Evaluating the Emission Benefits of Tier 2 Gasoline

All vehicles accepted into the test program were first subjected to baseline emissions testing using "as-received" fuel.[*] The "as-received" fuel in the test vehicles was not sampled or analyzed in this program, but a telephone survey conducted as a part of this study by Hays Research Group[†] showed that 91.3% of households tend to use regular gasoline "more often" as compared to 8.7% that use premium gasoline more often.[5] Further, during the period of vehicle testing, only one fuel provider—Flint Hills Resources (FHR)—supplied gasoline in the Fairbanks area.[‡] Information regarding the

[*] As described later, this could be either the fuel received in each vehicle or a mix of the as-received fuels from several vehicles.
[†] A summary of Hays Research Group's phone survey results, which addresses a number of other issues in addition to the regular/premium fuel split, may be found in Appendix A.
[‡] Personal communication with ADEC.

physical and chemical properties of in-use gasoline during the testing period are available both from FHR[*] as well as the Winter 2006 fuel survey published by the Alliance of Automobile Manufacturers (Alliance). Fuel property data from these sources for regular and premium unleaded gasoline are summarized in Table 3-1. As shown, there is reasonable agreement between the fuel property data provided by FHR and those reported by the Alliance fuel survey.

After testing with high-sulfur fuel, each vehicle either was drained of remaining fuel by a Borough mechanic or, if draining was not practical, was run on the dynamometer until fuel was exhausted. In practice, almost all of the test vehicles were able to be drained using the vehicle's own fuel pump. In one case (vehicle number 24), fuel draining apparently led to the failure of the fuel pump, probably due to pumping of residue from the bottom of the tank, and resulted in having to replace the fuel pump and retest the next day. The vehicle was then refueled with the Tier 2 gasoline used in the program and subjected to preconditioning and another round of emissions testing.

The low-sulfur test fuel used in the emissions measurement program was a regular grade unleaded gasoline produced by Tesoro[†] and purchased from Inlet Petroleum Company.[‡] Eleven 55-gallon drums were procured in December 2005 and shipped to the test site in Fairbanks for use in January and February. Available fuel property data from the batch of test fuel used in the program are summarized in Table 3-1. As shown in the table, the most notable difference between the test fuel and the in-use gasoline available in the Fairbanks area is in sulfur content, where the test fuel was essentially sulfur-free[§] while the in-use fuels had sulfur contents in the range of 160 to 215 ppm. Although complete chemical composition data for the test fuel are not available, the lower specific gravity, higher benzene content, and substantially lower T90 temperature suggest differences in the chemical composition of the fuel relative to the in-use fuels. While differences in chemical composition other than sulfur content are also known to affect exhaust emissions, the lack of data precludes assessment here. Furthermore, it should be noted that there has been very little study of fuel composition effects on emissions at low temperatures other than for oxygenate impacts, which were not a factor here. Finally, the use of a test fuel that is a regular-grade gasoline in vehicles designed for or customarily operated on premium in-use gasolines could have also resulted in some effects on exhaust emission levels, although these effects would be expected to be minor.

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[*] Flint Hills Resources, 1100 H&H Lane, North Pole, Alaska, 99705.
[†] Tesoro Corporation, 300 Concord Plaza Drive, San Antonio, Texas, 78216-6999.
[‡] Inlet Petroleum Company, 459 West Bluff Drive, Anchorage, Alaska, 99501.
[§] Analyses of additional (earlier) fuel samples by Tesoro, shown in Appendix B, showed similar sulfur levels (1-2 ppm) to the batch used for testing.

Table 3-1
Properties* of In-Use Regular and Premium Gasoline in Fairbanks During Winter 2006 and Tier 2 Test Fuel

Property	Regular Grade FHR	Regular Grade Alliance	Regular Grade Low S Test Fuel	Premium Grade FHR	Premium Grade Alliance
Sulfur (ppm)	161	170	1.9	192	215
Relative Density (60/60ºF)	0.7428	0.7441	0.7347	0.7599	0.7607
Vapor Pressure (psi)	14.4	14.7	14.4	14.0	13.7
Distillation (ºF)					
IBP	76	82	82	77	84
T10	94	100	100	96	105
T50	192	200	195	218	223
T90	303	304	278	309	310
EP	344	342	338	348	347
RON	91.0	91.0	90.9	95.1	94.9
MON	83.3	83.5	84.0	85.3	85.4
(R+M)/2	87.1	87.2	87.5	90.2	90.1
Benzene (vol.%)	3.3	2.8	4.4	2.9	2.6
Aromatics (vol.%)	N/A	34.4	N/A	N/A	42.0
Olefins (vol.%)	N/A	0.9	N/A	N/A	1.3
Saturates (vol.%)	N/A	64.7	N/A	N/A	56.7
Oxygen (wt.%)	0	0	0	0	0

3.3 Vehicles Tested

Candidate vehicles for testing were recruited primarily through a random phone survey of households located in Fairbanks North Star Borough. Hays Research Group† conducted the survey in December 2005, which resulted in successful contact with 402 households and identification of 142 respondents who expressed interest in allowing the use of their vehicles for testing in return for a rental vehicle and/or a monetary consideration. The phone survey was also used to help ascertain what monetary consideration would be needed to induce participation and to determine the fraction of households using premium fuel.

When selecting from the list of available candidates, our original goal was to test a representative distribution of vehicles from the three model year groups (pre-1990,

* In some cases, standard estimating methods for converting between different metrics used to characterize the same fuel properties have been applied in order to allow for better comparison of fuel properties.
† Hays Research Group, PO Box 110183, Anchorage, Alaska, 99511-0183.

1990-95, and 1996+) and to try for a 50/50 split between cars and trucks. As testing proceeded, we planned to follow an approach for vehicle selection as follows:

- 1st - fill in gaps of the original target range;
- 2nd - target newer vehicles since they account for the majority of travel; and
- 3rd - take whatever we could get if we have trouble meeting recruitment targets (a common problem).

A total of about 90 vehicles were targeted for recruitment in the program, with the assumption that about one-third would fail on-site inspections or initial starts. This resulted in about 60 usable vehicles, or 10 per week over the 6-week testing period. Most vehicles had to be retained on site for five to seven consecutive days. Because of this relatively long retention period and other testing requirements (discussed below), the initial list of positive respondents to the phone survey was exhausted before the end of the program. To complete the recruitment, Sierra's subcontractor Nortech Environmental & Engineering Consultants[*] ultimately resorted to soliciting volunteers from personal and business contacts and several local used car dealers.

Nortech pre-screened all vehicles by telephone, eliminating from further consideration any vehicles that could not be safely tested. These included vehicles that, according to information provided by their owners, had bald or otherwise unsuitable tires[†] that could not be temporarily replaced (with owner-provided summer tires) or had fluid leaks, vehicles that were prone to overheat or had non-working gauges, and vehicles with a "check engine" or "service engine soon" light illuminated.[‡]

All vehicles that appeared to meet testing criteria based on owners' descriptions were brought to the test site on the day before their planned testing, typically at a rate of 10-13 vehicles per week, and were physically screened by Nortech for testability. A copy of the screening criteria used by Nortech is provided in Appendix C. The most common problem uncovered by the on-site inspections was the presence of a previously unknown exhaust leak or leaks. Because such leaks could present a safety hazard in testing, leaking vehicles were excluded from the test program. Owners of such vehicles were paid a small consideration for their trouble but were rejected from the test program.

The resulting sample fleet for testing consisted of 20 cars and 40 trucks, ranging from model years 1985 to 2005. The average age (based on model year) of the cars tested was 6.5 years and of the trucks 10 years. These respective ages are somewhat younger for cars and older for trucks, compared to the national on-road fleet.[6] Table 3-2 summarizes the model year breakdown of the sample fleet compared to the targeted fleet.

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[*] Nortech Environmental & Engineering Consultants, 2400 College Rd, Fairbanks, Alaska, 99709.
[†] Other problematic tire types included studded tires, which can damage the dynamometer rolls; and soft compound winter tires, which can be seriously damaged by operation on the dynamometer.
[‡] This was to avoid the potential difficulties, including safety concerns, associated with vehicles experiencing engine or emission control problems during testing that would not be revealed by illumination of a check engine light.

Table 3-2 **Model Year Distribution of the Sample Fleet**			
Model year range	Cars # tested (# targeted)	Trucks # tested (# targeted)	Cars + Trucks # tested (#targeted)
Pre-1990	1 (10)	7 (10)	8 (20)
1990-95	3 (10)	10 (10)	13 (20)
1996 and later	16 (10)	23 (10)	39 (20)
Totals	20 (30)	40 (30)	60 (60)

As Table 3-2 shows, the sampling targets were generally met for trucks and newer cars but were not met for older cars.* However, as discussed later in this report, the differences in emissions between cars and trucks of the same model year groups were generally found to be insignificant. Furthermore, the secondary objective of targeting newer vehicles because they make up a majority of the major travel fraction (and become increasingly important in future years) was exceeded by a wide margin.

Most of the cars sampled were model year 2001 and newer vehicles that had been certified to national low-emitting vehicle standards with second generation onboard diagnostics ("OBD II"). Trucks covered a broader range of ages and included thirteen pre-1993 Tier 0 vehicles that were not certified to cold temperature CO standards, four 1993-95 vehicles that were certified pursuant to the phase-in of Tier 1 with OBD, thirteen 1996 to 2000 OBDII vehicles, and ten 2001 and newer NLEV vehicles.

Seventy-five percent (75%) of the test fleet had automatic transmissions, and the distribution of 4-, 6-, and 8-cylinder engines was 30%, 42%, and 28%, respectively. The average engine displacement was 3.7 liters (range 1.5 to 7.5 liters), and the average odometer reading was 84,895 miles (range 2,508† to 200,843 miles‡). A list of the test fleet, including a more detailed description of each of the vehicles, is provided in Appendix D.

3.4 Equipment Used for Testing

All emission testing was performed in Fairbanks, Alaska, at the Fairbanks Cold Temperature Test Facility, which was built with ADEC support and in cooperation with

* The main reason for not matching sampling targets more closely was the relatively large number of older cars sought and the limited time available to recruit them under the deadlines imposed.

† Vehicle number 35, a relatively low mileage 2003 model year vehicle, was accepted into the program to fill a spot need when a late testing vacancy occurred. However, vehicles with mileages below 4,000 miles were generally excluded from testing, following EPA's common practice of avoiding testing of vehicles with "green" or not fully broken-in catalysts.

‡ Odometer readings were not available from three of the vehicles, and odometer readings for four other vehicles (vehicle numbers 22, 32, 51, and 74), all of which were 1990 or earlier model years, were adjusted (subjectively) for likely odometer rollover.

Fairbanks North Star Borough. Details of the facility are presented elsewhere.[7] The facility has been used by ADEC and FNSB in a number of wintertime vehicle emissions studies.[8,9,10]

Briefly, the testing facility consists of a Real Time* 8.5 inch diameter, dual, split-roll electric chassis dynamometer with Baldor power controller, and a modified Horiba IMVETS sampling system, with custom Sierra drivers aid, bench control, and data logging software. As provided by Real Time, the dynamometer rolls were coated with an abrasive finish to minimize tire slip and the dynamometer was configured to operate without an inter-roll drive belt (normally used for roll warm up), in accordance with advice provided by Real Time.†

In order to allow cold temperature operation, the system was modified in several ways. In Fairbanks, the sampling system is normally configured for direct connection to the vehicle exhaust system with heated dilution air taken from inside the building. An adjustable blast gate has been installed to permit control of the amount of dilution air. Water traps have been placed in the raw exhaust sample line and the continuous dilute sample line. To help ensure consistent operation and to prevent freezing, heaters have been installed in the dynamometer motor containment (to warm the drive belt), around the optical encoder that is used to measure motor speed and, as required, beside the drivers aid monitor.

The flow control system includes a computer-controlled 15 hp, nominal 700 SCFM Spencer Turbo-blower and a Horiba critical flow venturi (CFV), which are located in a van that is situated in the garage of the Borough's bus maintenance facility. The dynamometer rolls and motor are located near the van, inside the adjacent test cell. Prior to and during testing, an exterior roll-up door can be opened to expose the vehicle to outside ambient temperatures (vehicles are pre-soaked outside overnight in preparation for testing and then pushed onto the dynamometer). Additional details about the test facility have been documented elsewhere.

Only a few minor modifications were made to the test facility prior to the start of the current test program. These are outlined below.

- The main drive belt connecting the 40-hp electric motor and dynamometer rolls had, in previous weeks of testing (for another project), experienced a few occasions of slippage, which was apparent from the loud percussive sound it generated during hard accelerations of heavier test vehicles. This was a potential concern for the current program because we anticipated using the dynamometer, albeit briefly, near its maximum loading in order to help ensure sufficient engine load to require hydrocarbon enrichment in the exhaust in order to effect sulfur removal during the planned sulfur removal cycle (discussed further in the next section). To avoid repeated belt tooth slippage that could damage the belt or

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* Real Time Instruments, 24972 Hon Avenue, Laguna Hills, CA 92653.

† This configuration avoided excessive inter-roll belt slippage during hard accelerations and decelerations, which had been experienced when the dynamometer was first installed and tested.

bearings, the drive belt was tightened slightly above specification. This additional precaution was taken after consultation with Real Time, at the advice of the manufacturer,* and with assistance from Borough maintenance staff.

- A manual drum pump† was brought by Sierra Research personnel from Sacramento and set up for dispensing low-sulfur gasoline to portable containers that could then be emptied into vehicles.

- Prior to testing, a ten-point calibration was performed on the four gas analyzers, and a strobotachometer‡ was used to confirm the dynamometer roll speed.

Several modifications were required during the course of the six-week test program as a result of equipment failure or other problems encountered, in most cases as a result of the extremely low temperatures encountered in January 2006 (as low as -51ºF). A few of these are highlighted below.

- During the coldest period of testing, the drivers aid monitor, which used a cathode ray tube, began to operate erratically. A 1,500 watt space heater was placed next to it on the drivers aid cart, but the power cord to the heater embrittled due to the cold and broke. The heater was removed and the monitor was replaced with a newer one; a blanket placed over the monitor helped to retain heat and prevent a repeat of the problem.

- The original drum pump experienced minor seal leakage when used outside and had to be replaced, along with its conventional (non-arctic grade) dispensing hose that stiffened to the point of being unusable. The hose was replaced with one of arctic grade.

- The multi-conductor cable to the drivers aid pendant stiffened, then several wires shorted together, resulting in destruction of two solid-state isolation relays in the test van and the loss of indicator lights on the drivers pendant. A new twisted pair to the pendant was installed and a work-around for the relays and lights was found using the on-screen display.

- One compressed air hose stiffened, blistered, and then leaked; it was replaced.

- One bumper that was apparently embrittled by cold was broken and pulled off the vehicle while attempting to tow it to the dynamometer; the bumper was replaced.

- One solenoid valve for controlling the lift-brake failed (this may have been related to cold and/or contamination of the air supply); it was replaced.

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* KLC Enterprises Inc, 4765 Holland Rd, Saginaw, MI 48601.
† Fill Rite 112, Rotary Hand Pump, www.benfordfueling.com.
‡ Extech Instruments, Model 461830/461831, 335 Bear Hill Rd., Waltham, MA 02154

- At an ambient temperature below -40ºF, the rollup garage door froze and became stuck in the "up" position. Supplemental tension applied to the rollers helped to free it.*

3.5 Test Procedures

A vehicle emissions test plan was developed to better quantify the expected effects upon emissions of CO, THC, and NOx from reducing the sulfur content of gasoline in FNSB's nonattainment area from then-current levels of about 160 ppm to under 30 ppm.

Test Program Design – ADEC's requirements specified performing 200 cold start tests and 400 hot start tests on a representative sample of vehicles within a six-week testing window. These targets for replicate testing were based upon an analysis conducted by Sierra of the variability of both hot and cold start exhaust emissions from light-duty, gasoline-powered vehicles in Fairbanks, and a determination of the number of hot and cold start tests that would be required in order to detect a statistically significant difference in those respective average emissions from the sample fleet after switching to low-sulfur gasoline (see Appendix E, "Task 3 Report").

In order to meet ADEC's targets for replicate testing of a representative sample of vehicles, Sierra designed a test program based upon the testing of ten different vehicles per week for ten weeks, with a schedule that was designed to maximize the number of cold starts possible. This approach was necessary because practical limitations dictated that most vehicles could be cold-started only once per day (in order to allow for an 8-hour "soak" period between cold starts), after which repeated hot starts could be performed in succession. Because ADEC further specified that all testing be performed in replicate and using a representative sample fleet, the number of vehicles to be tested each week was set at the maximum number (i.e. ten vehicles) that could be supported by six 10- to 11-hour test days per week (no testing on Sundays), while giving each vehicle at least two cold starts (with preceding overnight soak) and four hot starts both before and after fuel change.

Before deciding on a 60-vehicle sample size, Sierra considered the option of using a test fleet of just 30 vehicles over the six-week test period and doubling the number of replicate tests. Although such an approach could also have been used to meet the stated sampling requirements for the study, we concluded that the selected sample size of 60 vehicles, which required roughly double the recruitment effort and double the labor for moving vehicles, would likely provide more accurate representation of the on-road fleet. Sample sizes larger than 60 were not considered because we did not believe that all of ADEC's requirements for cold and hot start replicate testing before and after fuel change

* Although emissions testing has been conducted successfully in Fairbanks at this facility for about a decade, the subject test program was the first at this facility to attempt and conduct testing at temperatures below -40º (which is within the normal winter temperature range for Fairbanks).

(and other testing requirements, discussed later) could be met for more than ten vehicles per week.

As required by ADEC, a draft Test Plan (Appendix F) and Quality Control/Quality Assurance plan (Appendix G) were prepared. In addition, written procedures were prepared for the Sierra's van operator (Appendix H). The next section summarizes the test plan.

Summary Description of the Test Plan - The Test Plan was based on the receipt, screening and testing of weekly batches of vehicles. Briefly, the test protocol consisted of the steps described below.

1. Test vehicles were brought to the test site with requested near-empty fuel tanks – Typically, on Sunday afternoons or early evenings, 10 to 13 vehicles were driven to the test site and physically screened by Nortech. Upon successful screening, each vehicle was assigned a letter designation, A through J, which automatically assigned its days of the week for pre-fuel change testing, fuel change and conditioning, and post-fuel change testing. At least two vehicles having low (but not critically low) fuel levels were selected for fuel change on Monday, when they were drained of fuel by a Borough mechanic. The remaining vehicles, after initial tests on as-received fuel, were also drained of as-received (high sulfur) fuel, but on a schedule that depended upon the test schedule, mechanic availability, and other factors.

2. Measured amounts of high-sulfur fuel were added – Using calibrated five-gallon fuel jugs, just enough of the drained high-sulfur fuel was added back to each vehicle to complete high-sulfur testing (approximately one to two gallons in most vehicles, depending upon residual fuel level and expected fuel economy). The amount of fuel needed was estimated from vehicle fuel economy certification data and from previous estimates of fuel consumption during warmup idle.

3. Extended soak (minimum of 8-hours) with plug-in – Preliminary telephone survey data from Fairbanks* suggested that most morning starts by household vehicles are of warmed engines, either by heated garages or by plug-in. The survey data also confirmed previous studies showing that warmup idles tend to be five to ten minutes in duration. To mimic these behaviors, we used plug-in for all "cold" starts (after extended soak) and a warmup idle duration of five minutes. Except in unusual circumstances, the extended soak occurred overnight.

4. High-sulfur (baseline) testing – After overnight soak with plug-in, vehicles were pushed onto the dynamometer and subjected to the following test sequence:

    - A cold start;
    - A five-minute (300-second) warmup idle;

* Unpublished survey data.

- Two-bag, 4.7-mile, 13.6-minute Alaska Drive Cycle or ADC (see Figure 3-1); and
- Four to six consecutive hot ADCs. (The exact number of replicate tests performed, both cold and hot start, depended upon the amount of fuel remaining in the tank and where the vehicle fit in the test schedule, as discussed later.)

In configuring the dynamometer for each vehicle that was tested, Sierra used a version of its "I/M Lookup Table" that was customized for use with the modified Real Time IM240 Dynamometer in Fairbanks.

5. <u>Dispensing low-sulfur fuel into the tank</u> – To minimize the risk of residual high-sulfur fuel contaminating the newly added low-sulfur fuel, ten gallons of low-sulfur fuel were, in almost all cases, added to the tank of each test vehicle (see "Adjustments to the test plan" later in this section). Fuel was first dispensed from the drums into five-gallon storage jugs and then into the test vehicles. Two different vehicles received a fuel change each day, Monday through Friday (thus allowing a more predictable schedule for the mechanics who performed fuel changes).

6. <u>Vehicle operation on the dynamometer to clean up the catalyst and condition the vehicle</u> – Previous studies[11,12] have suggested that vehicle operation on low-sulfur fuel under a relatively aggressive driving cycle can remove sulfur from the catalyst. Accordingly, a brief but aggressive "sulfur reduction driving cycle" was devised and used in the current program. The cycle originally used a 5-minute, 60 mph cruise followed by five wide open throttle accelerations, but was later modified to conform to the limitations of the dynamometer and power controller (see Figure 3-2, below and item 5, "Adjustments to the Test Plan" later in this section). For this portion of the testing only, and after consultation with Real Time, the dynamometer inertia test weight was set to the maximum level (regardless of vehicle weight), which still permitted setting the road load horsepower to 20 hp at 50 mph with assumed tire/roll loss of 0 hp.[*] This approach ensured a relatively high horsepower loading at all steady-state speeds in addition to accelerations, but avoided overloading the power controller or dynamometer.

7. <u>Second minimum 8-hour soak</u> – Following its sulfur reduction cycle, each vehicle was again soaked overnight with plug-in.

8. <u>Low-sulfur fuel (treatment) testing</u> – This step repeats the testing procedure in step 4, but with the low-sulfur fuel.

[*] In practice, this meant setting the inertia weight of the dynamometer exactly equal to the physical or "base" inertia of the system. As a result, no electrical inertia simulation was used, and dynamometer's full 30 hp power absorption capacity was available to simulate road load, which permitted controlled high loadings at speeds up to about 55 mph.

Figure 3-1
Alaska Drive Cycle
13.6 minutes, 4.74 miles

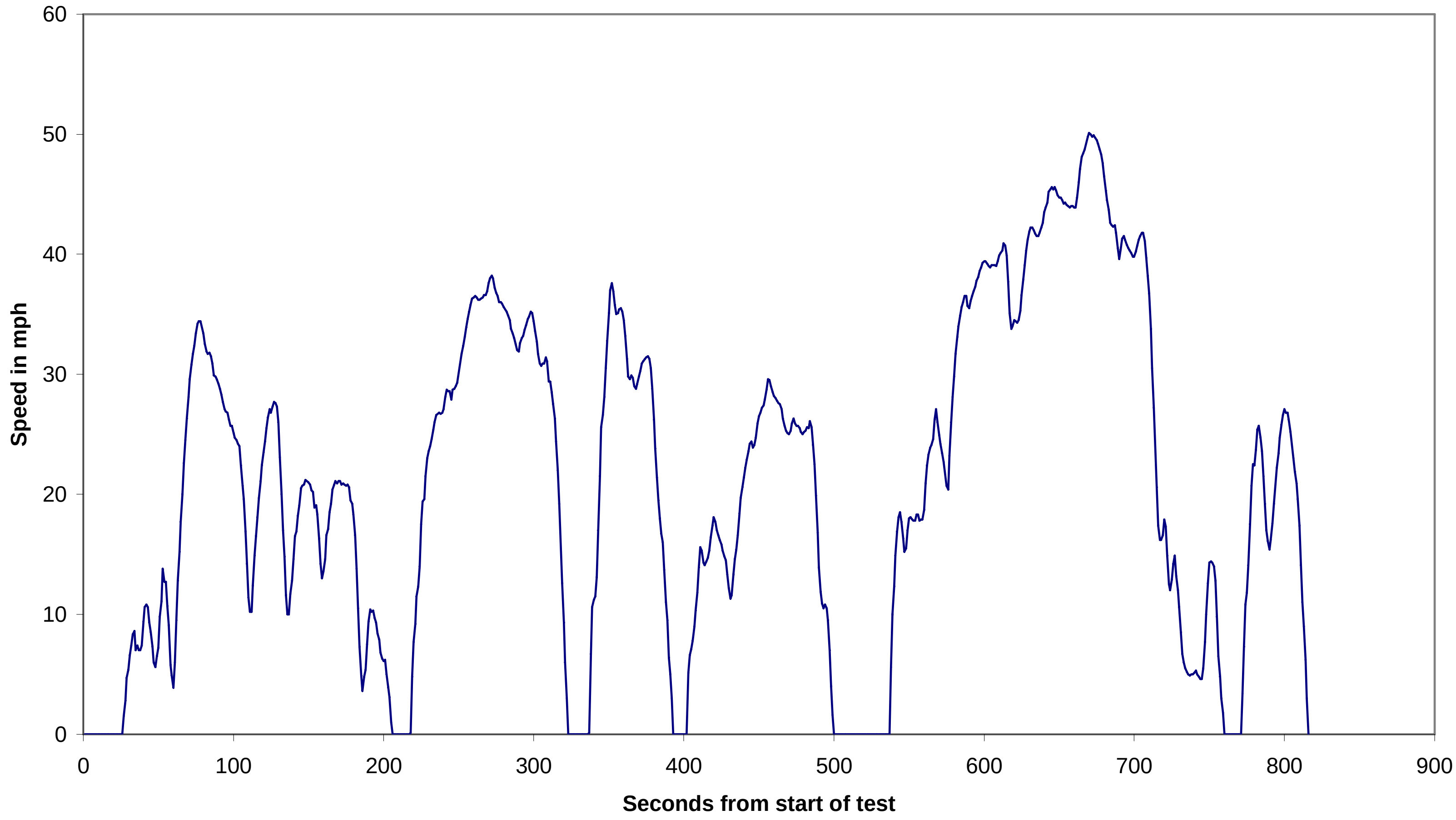
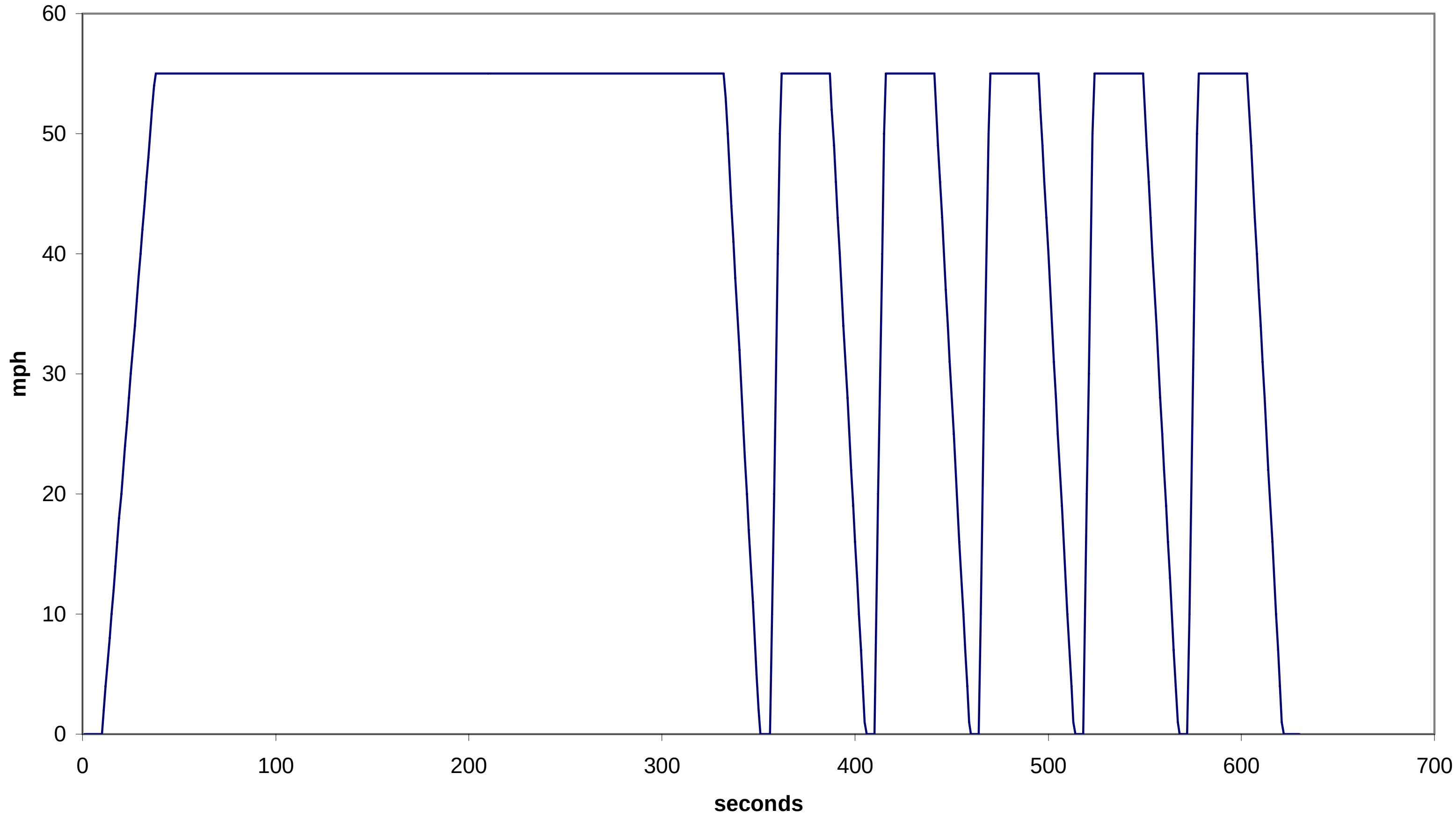


Figure 3-2
Sulfur Reduction Cycle for FNSB Dynamometer
Warmup drive followed by 5 successive wide open throttle accelerations



Although it may not be obvious from the above list of the steps involved in testing each vehicle, meeting ADEC's targets for numbers of tests required a Test Plan that maximized the number of hot and cold starts each week. The Plan, in turn, required testing most of the vehicles in the 10-vehicle weekly sample on every day of the week, Monday through Saturday. The weekly test schedule for all vehicles and an illustrative sample test schedule for one of those vehicles are shown in Tables 3-3 and 3-4.

Table 3-3 shows the order of testing for all the vehicles in one week. The vehicles are labeled A through F (in the test log shown later, the designation vehicle "A1" refers to a vehicle that was assigned to slot A in the test schedule during week 1 of testing). The first column shows, day by day, which vehicles received the pre-fuel change "full test sequence" (i.e., a cold start, warmup idle, cold ADC, and then 4-6 hot ADCs). The second column shows which vehicles received the more abbreviated pre-fuel change "cold start" (i.e., a cold start, warmup idle, and cold ADC with no hot ADCs to follow[*]). The third column shows each vehicle's scheduled change from as-received (high sulfur) fuel to low-sulfur fuel. Each such fuel change was followed immediately by the sulfur reduction cycle. Finally, columns 3 and 4 are analogous to columns 1 and 2, except that they occur after the fuel change rather than prior to it.

The test schedule can be further understood by considering an individual vehicle, such as Vehicle A, whose schedule is shown in Table 3-4. Vehicle A, like all vehicles (nominally), is received on Sunday, screened, plugged in and soaked overnight. On Monday, it receives the pre-fuel change full test sequence, after which its fuel is changed and it is subjected to the sulfur reduction cycle. On Tuesday, it receives the post-fuel change full test sequence, and on Wednesday it receives a (supplemental) post-fuel change test and is finished testing, after which it may be returned to its owner.

The example of vehicle A illustrates one feature of the test design (which is later shown to be important for the data analysis), namely, that vehicles that received a fuel change early in the week received more tests after the fuel change than before it. The converse is, of course, also true, i.e., vehicles that received a fuel change late in the week, received more tests prior to fuel change than after it. However, no fuel changes were performed on Saturday because (1) cold start testing after the fuel change first required an overnight soak, and it was decided not to test on Sundays (to allow a break for the testing staff and for routine maintenance); and (2) Borough staff members, who usually performed the fuel changes interspersed among their normal duties, were generally not asked to work on weekends.

[*] Note that no additional hot start ADCs are needed on this second day of testing each vehicle because all the needed hot starts were obtained on the first day. All that is needed on the second day is a cold start ADC following the overnight soak.

Table 3-3
Weekly Test Schedule

	Pre Fuel Change Full Test Sequence	Pre Fuel Change Cold Start	Change Fuel S Drive Off Cycle	Post Fuel Change Cold Start and Hot Start	Post Fuel Change Cold Start
Monday	A, B	C, D, E, F,G,H,I	A, B		
Tuesday	C, D	E, F, G, H	C, D	A, B	
Wednesday	E, F	G, H	E, F	C, D	A, B
Thursday	G, H	I, J	G, H	E, F	C, D
Friday	I, J		I, J	G, H	C, D, E, F
Saturday				I, J	C, D, E, F, G, H

Table 3-4
Sample Test Schedule For One Vehicle (Vehicle A)

	Pre Fuel Change Full Test Sequence	Pre Fuel Change Cold Start	Change Fuel S Drive Off Cycle	Post Fuel Change Cold Start and Hot Start	Post Fuel Change Cold Start
Monday	X		X		
Tuesday				X	
Wednesday					X
Thursday					
Friday					
Saturday					

Finally, it should be noted that the detailed schedule shown, which did bring order to a relatively large testing program, was not considered immutable in its day-to-day implementation. Vehicles or individual tests unavoidably were dropped as a result of vehicle or equipment malfunctions, errors in test setup or operation, etc. When test slots became available as a result, other vehicles already in the program had their testing expanded, which was accomplished most simply by adding hot start tests at the end of a sequence of other tests. Typically, if pre-fuel change tests were added in this way, an attempt was made to add post-fuel change tests for the same vehicle so that the overall balance of pre- and post-fuel change tests could be reasonably preserved for each week and for the entire test program.

<u>Adjustments to the Test Plan</u> - As in most studies, commencement of work in the field resulted in changes to the test plan, as highlighted below.

1. Although specified in the original plan, in most cases it was not necessary to have 13 vehicles delivered on Sunday in order to ensure that 10 vehicles could be successfully fuel-changed and tested during the week. Thus, the number of vehicles and days for delivery at the margin were tailored to information about the condition of vehicles, which reduced the expense, and owner frustration, of returning extra vehicles untested.

2. It was learned early in the test program that the Borough's experienced mechanic and referee were able to quickly empty the fuel tanks of almost all vehicles on which it was attempted, thus avoiding the time, expense, and uncertainty introduced into the schedule from having to exhaust remaining fuel by driving the dynamometer.

3. The daily order of vehicle testing was rearranged several times in order to take maximum advantage of the availability of support from Borough staff for making fuel changes. Thus, vehicles scheduled for fuel change on a particular day were sometimes tested first thing in the morning, and on other days were tested near the end of the day. In all cases, however, the conditioning drive on low-sulfur fuel was performed on the same day as fuel change.

4. Just as quickly as it was learned that fuel could be emptied and refilled with measured amounts, it was confirmed (as originally expected) that the amounts of fuel needed to be added back could be estimated only very crudely, in part due to (1) uncertainty about how much residual high-sulfur fuel remained in each tank after "emptying" by pump out, (2) likely variations in certification fuel economy on the EPA city cycle vs. the ADC driving as adjusted roughly for additional fuel use during warmup idle, and (3) emptying of fuel tanks while the vehicles were level in the mechanic's bay but operating on the dynamometer with rear wheels generally higher than front wheels (thus, the amount of fuel left in the tank when emptied would also depend on where the fuel intake line to the engine was positioned in the fuel tank). As a result of all of these uncontrolled variables, a few vehicles ended up receiving too much fuel, which then had to be burned off in

dynamometer driving,* and a few ran out of fuel while undergoing needed tests. The latter problem was addressed by refueling and providing additional tests. (Hot start tests were run immediately after adding a small amount of fuel, but any additional cold start tests were run after a supplemental 8-hour soak period with plug-in.)

5. The sulfur reduction cycle was originally based on a five-minute, steady-state 55 mph drive that was intended to warm up the dynamometer and all drive train components, followed by 5 successive wide open throttle (WOT) accelerations up to 65 mph against the maximum inertia weight of the dynamometer. However, it was quickly determined that the dynamometer's power controller was configured for a maximum speed of only 60 mph in order to protect the dynamometer and power controller. Accordingly, the maximum speed of the test cycle was reduced to 55 mph (allowing a safety margin). A second change was also required for the sulfur reduction cycle due to a very small amount of residual belt slip that could still be observed upon launch for several of the more powerful vehicles. This belt slip was avoided by having drivers "ease into" the start of the WOT acceleration for the first second or two before going to full WOT. Thus, the resulting sulfur reduction target trace, which was shown earlier in Figure 3-2, was used only as a guide to help ensure equipment warmup and sufficient time at WOT for sulfur removal. This modified approach virtually eliminated belt slippage, while still providing a sufficiently rich exhaust mixture to ensure sulfur reduction.

6. Several vehicles were forced to drop out of the program due to overheating during testing, exhaust leaks, or for other reasons. To help compensate for these lost tests, and to fill out the testing schedule, several of the existing vehicles were subjected to additional replicate tests beyond those listed in the original test plan.

7. Because of the aborted vehicles and because one vehicle received a charge (10 gallons) of low-sulfur fuel in a dual tank, there was insufficient fuel in the last week of the program for every vehicle to receive the full 10-gallon allotment. Accordingly, the last week's per-vehicle allotment was reduced to 5 gallons, which did not provide the same level of assurance about diluting any residual amount of high-sulfur fuel that might be remaining in the tank, but which was enough to complete testing of every vehicle.

8. January is, on average, the coldest month in Fairbanks, but January 2006 was one of the coldest on record,† and continued testing operations required not only great care to avoid personal injuries and property damage, but also an unusual amount of maintenance and repair, as noted earlier. Despite these problems, the testing

* On-road fuel burn-off was also considered, but was judged to be inappropriate due to the additional risks imposed by on-road driving under typically icy or otherwise dangerous conditions and the limitations of the supplemental insurance coverage obtained for the test fleet.

†The period of testing had near record low temperatures in January, but also included several days of record high temperatures in Fairbanks. Copies of the National Oceanic and Atmospheric Administration's Local Climate Data for January and February 2006 are provided in Appendix L.

schedule was interrupted only once (January 27), by the on-site manager, who canceled testing for the day for reasons of crew safety, when the forecast temperature was below -50ºF.

Staffing - Throughout the period of testing, the test van and on-site operations were managed by Frank Di Genova, QEP; Dr. Michael St. Denis; and Mssrs. Joe Roeschen and Tony Ashby, all of whom rotated through that duty. Laboratory notes, as recorded by the van operators for all of the testing, are provided as a separate volume of this report.[13]

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4. RESULTS FROM EMISSIONS TESTING

Following a brief overview, this section describes quality assurance/quality control checks that were performed on the emissions testing data, with detailed discussion of several 'outlier' results and documentation of an apparent "idle disbenefit" (i.e., CO emissions increase during initial idle after a cold start) that was observed with low-sulfur fuel. The section ends with a description of data organization in the report.

4.1 Overview

Quality assurance and quality control of data were key elements of the current study. Emissions test parameters and test results were examined individually and compared to each other and to results from prior testing of other vehicles, to help identify and screen out or flag questionable or faulty data. These and other checks identified several test misclassifications that were corrected, several tests that lacked preceding start of day calibrations and had to be invalidated,[*] and several vehicles that exhibited unusual features in their measured CO emissions, as discussed in more detail later. These and related elements are discussed in Section 4.2.

Preliminary analysis of the hot-start test data collected in this program demonstrated that exhaust emissions of THC, CO, and NOx were substantially reduced on low-sulfur fuel, in accordance with the expectations for warmed-up vehicle operation. However, the cold-start test data showed the surprising trend that CO emissions were *increased* on low-sulfur fuel compared to the cold-start testing on high-sulfur fuel. Considerable effort was made to investigate this effect, both to assess the reliability of the evidence for it and to identify hypotheses regarding its origin to the extent possible with present data. Details on the analysis of idle disbenefit are presented in Section 4.3.

The emission testing phase of the study resulted in 827 attempted tests (meaning cold start, hot start, and sulfur reduction tests[†]) in all and 702 successful cold and hot start tests, between January 16 and February 25, 2006, on a total of 60 gasoline-fueled, light-

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[*] All of these invalidated or flagged tests were in addition to those tests that were aborted and/or identified as invalid contemporaneously by the on-site test manager (due to engine overheating, exhaust leaks, etc.).
[†] As used here, "cold start test" means an exhaust emissions test of an engine start following overnight soak with plug-in, a 5-minute warmup idle, and an Alaska Drive Cycle (ADC). A "hot start test" means an engine start immediately following another drive, plus an ADC drive. A "sulfur reduction test" means a drive of the sulfur reduction cycle that was described earlier in this report.

duty vehicles. Organization of the test sequences,* average emissions results from individual tests, and second-by-second emissions measurements are described in Section 4.4.

4.2 Quality Assurance/Quality Control

To help ensure rigorous test procedures and high-quality data, Sierra has developed and relies upon standard operating procedures[14] (SOPs) for the operation of the facility's dynamometer and analytical bench, for its dynamometer-based driving, and for daily service and diagnostic activities by the project's on-site test manager. Deviations from written test procedures are recorded by the on-site manager. Accordingly, quality assurance checks of the dataset began with a review of the on-site manager's test logs. Additional steps in the review are listed here.

- Emissions test parameters and test results were examined individually and compared to each other and to results from prior testing of other vehicles, to identify and screen out questionable or faulty data.

- Average CO emissions (g/mi) from all tests were plotted in the order that testing was performed by vehicle (discussed further below), to show test-to-test variability and the potential effects of several factors, including fuel change.

- Background CO levels were examined for reasonableness compared to the normal range of concentrations expected in a garage environment.

- A Sierra custom FORTRAN program was used to process the logged second-by-second data files and generate diagnostic files which were, in turn, reviewed in order to flag any questionable data,

- Any flagged or suspicious data were subjected to further more detailed investigation (in some cases to the level of examining second by second data) and either corrected or discarded.

These and other checks identified several vehicles that exhibited unusual features in their measured CO emissions. Several tests were found to be misclassified, which was corrected. Several other tests were found to lack preceding start of day calibrations and had to be invalidated. Finally, two vehicles were found to have high and/or variable emissions that merited further examination. Specifically, the low-sulfur fuel cold start test results from vehicle 14 and the hot start test results from vehicle 50, both of which were suspect, were given particular scrutiny (described below), as were several other emissions trends, including the apparent idle disbenefit, which is discussed later.

* As used here, "test sequence" means a test or collection of tests whose drive cycles are combined (for the efficiency of analysis) to yield a single composite drive cycle (see Appendix J-1 for more detail).

Vehicle 14, a 5.7 liter 1992 Chevrolet Silverado with a relatively high odometer reading of 174,945 miles,* was notable in that it exhibited the highest cold start emissions of any vehicle tested: 199 and 268 g/mi in two tests with low-sulfur fuel, representing a large and unexplained increase not only from one cold start test to the next, but also between the high-sulfur test results, which showed smaller variation (145, 154, and 127 g/mi), and the low-sulfur test results (see Figure 4-1). Similar figures, showing all apparently valid tests for all other vehicles, can be found in Appendix I. In all of these figures, the height of each bar indicates the grams per mile of CO emissions for a test, and the labels on the abscissa indicate a Cold start test (i.e., cold start, five-minute warmup idle, and cold ADC), Hot start (ADC), or Sulfur Reduction test. With the exception of SR tests and certain tests of vehicles 14 and 50 (discussed below) that are suspect, only valid tests are shown. In the case of sulfur reduction tests, results are shown whether valid or not, in order to show where in the test sequence the change occurred from high- to low-sulfur gasoline (all SR tests shown as zero g/mi are invalid). Finally, it should be noted that while tests were conducted in the order shown, they were not, in all cases, conducted consecutively. Cold starts, for example, always occurred immediately after a suitable soak period. On the other hand, the sequences of four hot start tests were usually conducted back to back and immediately following a cold start test, as per the testing protocol.

As mentioned earlier, variability in cold start emissions is neither unusual nor unexpected for wintertime operation of vehicles in Fairbanks, but the magnitude, direction, and variation between tests was large enough in the case of vehicle 14 to raise a serious question about the validity of the test results. Furthermore, inspection of individual tests showed that the speed trace for the final (highest) cold start test of vehicle 14 "missed" about the first 50 seconds of its drive, i.e., its drive appeared to begin at about second 370, rather than at about second 320. That is, the vehicle appeared to be idle during the first three accelerations of the ADC for unexplained reasons† and, as a result, was not fully warmed up when subjected to relatively high power acceleration at second 370. For all of these reasons, we consider the validity of the low-sulfur cold start tests for vehicle 14 to be suspect.

Another vehicle (number 50, a 1986 Chevrolet K10 pickup) was noteworthy in that it was the only vehicle that showed a very substantial CO emissions disbenefit for hot start—it had significantly greater CO emissions on low-sulfur gasoline than on high-sulfur gasoline during warmed-up operation on the Alaska Drive Cycle (other vehicles showed a CO disbenefit only for cold start and only for the first minute of warmup idle). The CO emissions disbenefit for hot starts for all vehicles can be seen in Figure 4-2, which is a histogram of the low-sulfur CO benefit for hot start CO emissions from all test vehicles.

* In the test sample, only vehicle 37, with 200,843 miles, had accumulated more miles than vehicle 14, but a number of trucks were older than vehicle 14.

† This could have occurred if the driver was late in getting back into the vehicle after the five-minute warmup (which we think is the most likely cause, although no such fact was recorded by the test cell operator), if severe tire slip occurred on the roll (possibly due to the presence of excessive snow and ice), or if an unexplained equipment malfunction or other operating error occurred. We are not aware of any evidence supporting one vs. another of these hypotheses in this case.

Figure 4-1
Average Cold Start, Hot Start, and Sulfur Reduction Test Results for CO Emissions from Vehicle 14 (low S cold starts are considered suspect, see text)

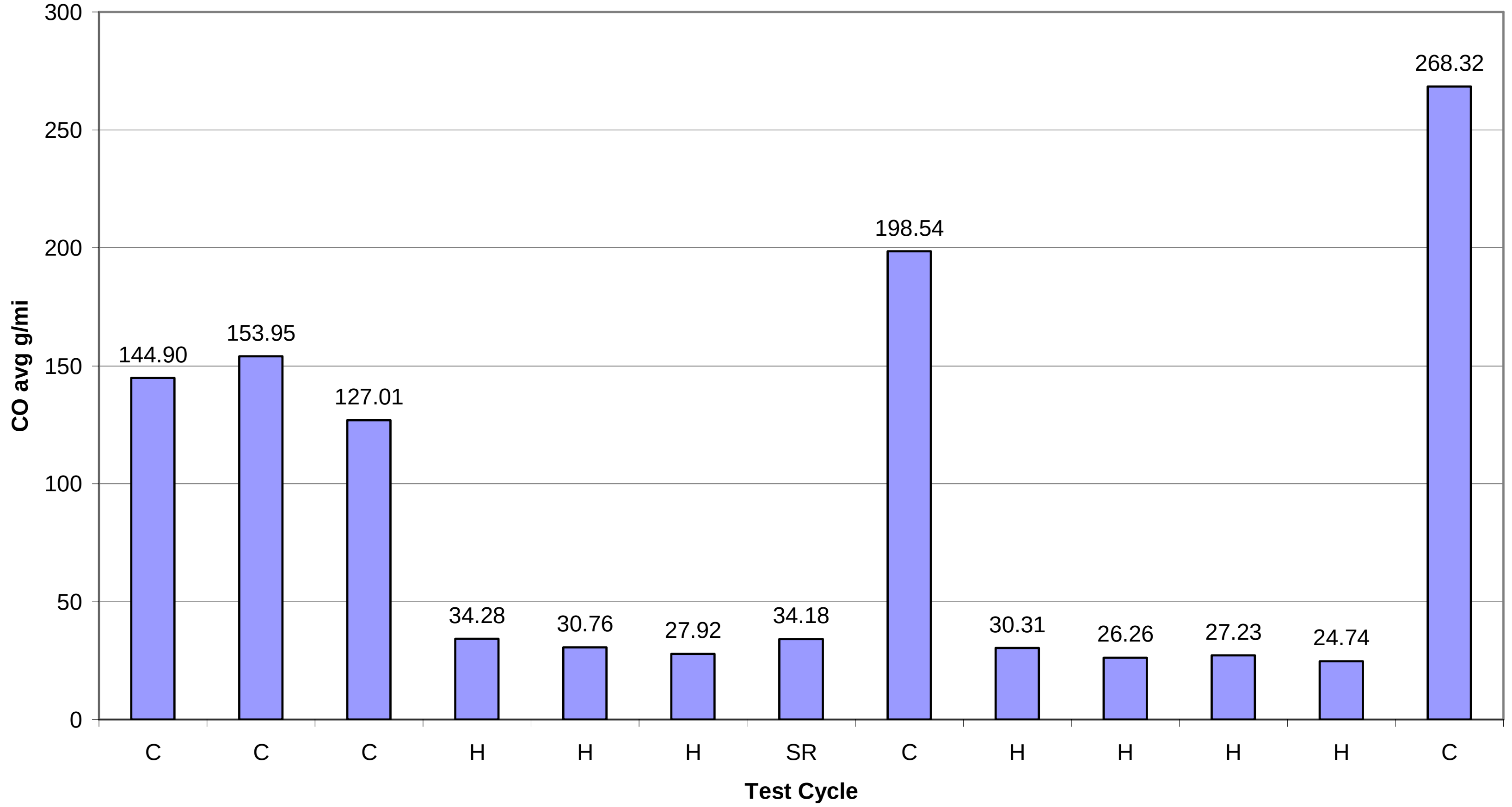
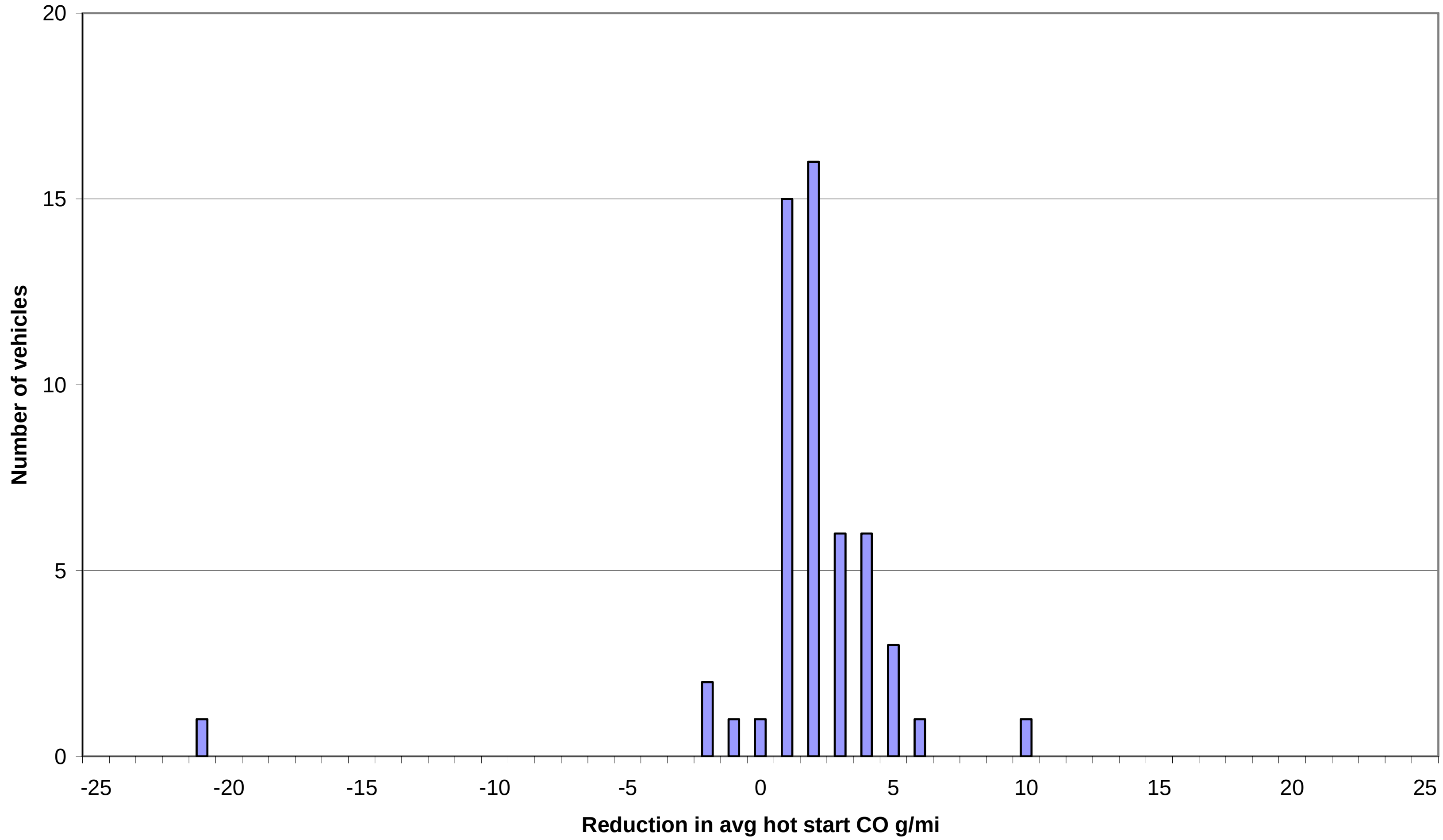


Figure 4-2
Distribution of Vehicles by Change in Hot Start CO Emissions with Fuel S Change



Vehicle 50, which is shown on the far left side of the figure, is clearly an outlier for this sample fleet.

The entire sequence of cold and hot start tests for vehicle 50 may be seen in Figure 4-3, and serves to illustrate three points. First, vehicle 50 showed substantial increase in average hot start CO emissions after fuel change. Secondly, the figure shows that vehicle 50, the second oldest vehicle in the sample fleet, had extraordinarily high hot start emissions. And finally, it showed that after fuel change, those emissions were continually decreasing and apparently had not yet stabilized even after four ADCs (a total of over 18.8 miles and 54 minutes of engine operation). In this regard, it is worth noting that at least one prior fuel sulfur change study[15] found that 10 miles of driving was generally sufficient to stabilize emissions, as we also observed in most cases here. However, that prior study examined only six vehicles—all of which, unlike vehicle 50, were California LEVs (low emission vehicles)—and it found marked vehicle-to-vehicle differences in response to sulfur change, as were found in the current study as well.

Figure 4-4 shows, separately for each vehicle, the average emissions, computed using Microsoft Excel, from all valid high- and low-sulfur hot start tests. A comparison of the individual test points confirms that of all the test vehicles, only four exhibited average hot start emissions that were greater when low-sulfur fuel was used, and of those, only vehicle number 50 showed a significant difference. Vehicle 50 was also the only truck that showed greater hot start emissions when using low-sulfur fuel. We are not aware of any technical reason for CO emissions from this or any other catalyst-equipped vehicle to increase significantly when switched to low-sulfur fuel.

For all of the reasons stated above, and even though the post fuel change cold start emissions measured for vehicle 14 and the hot start emissions from vehicle 50 may be valid, we believe it is not reasonable to attach to them the same level of confidence that applies to the rest of the dataset. That would, in our view, likely distort the overall results when applied to estimate longer-term emissions (where emissions stabilization is presumed to occur). For this reason, we performed statistical analyses both with and without these two elements. While the results do not differ dramatically, we consider them to be most credible without the suspect data. In addition, we used a log-transformation of data (primarily for other reasons, as discussed later in this section), which tends to discount the effects of higher emission values, including the suspect values noted above (which are relatively high for cold and hot starts, respectively).

Figure 4-3
Average Cold Start, Hot Start, and Sulfur Reduction Test Results for CO Emissions from Vehicle 50
(low S hot starts are considered suspect, see text)

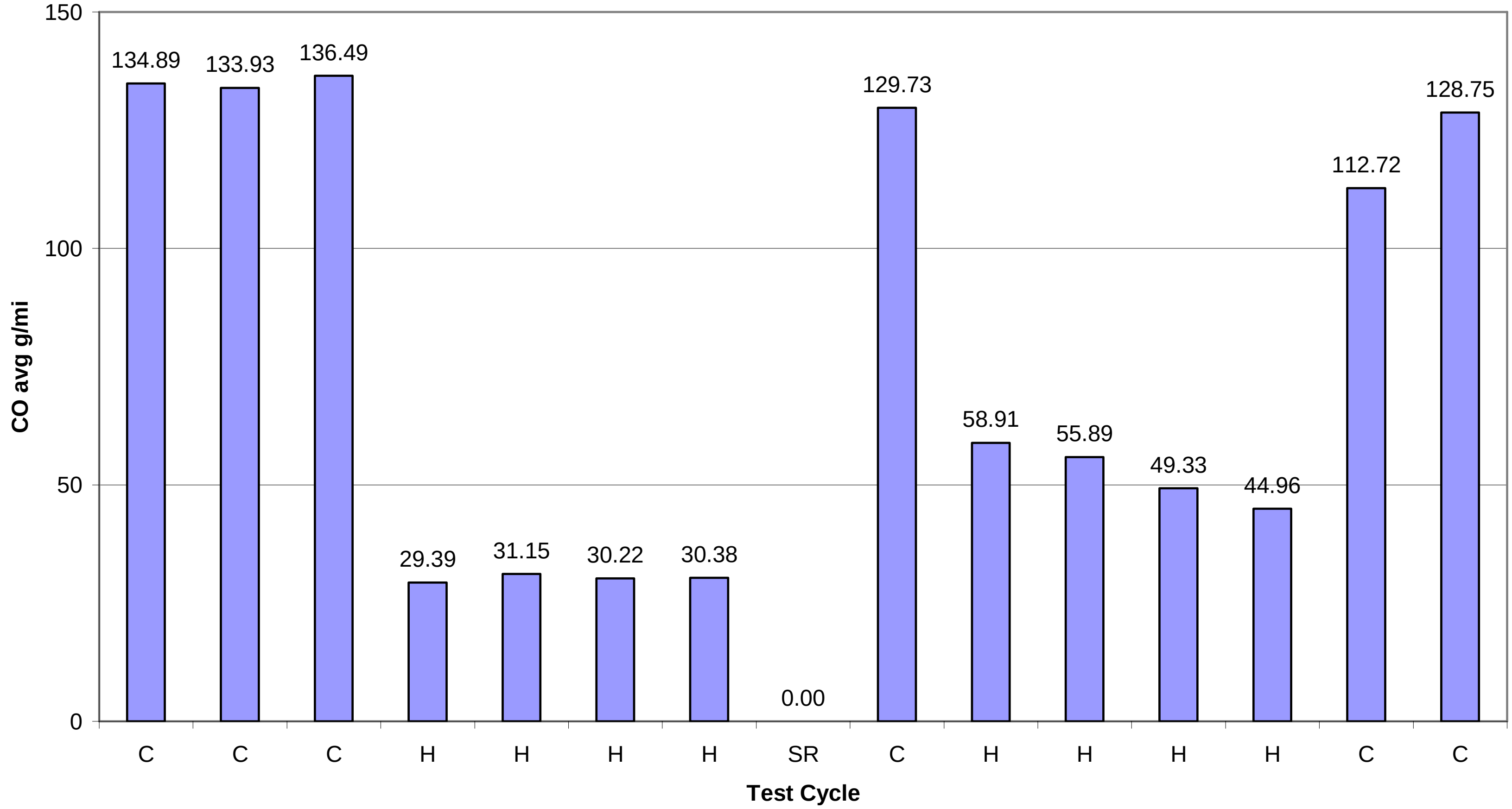
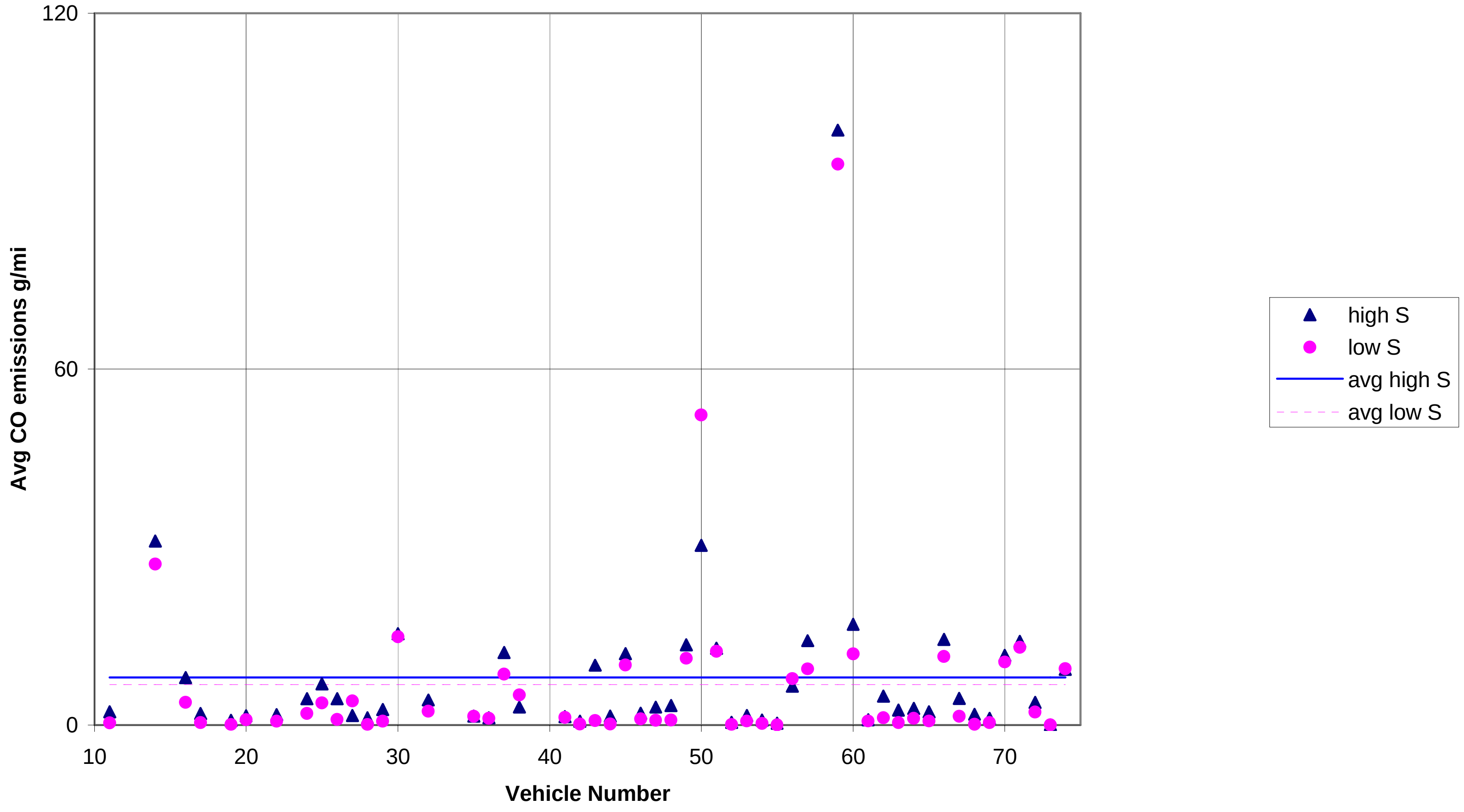


Figure 4-4
Avg CO Emissions for Hot Start ADCs with High and Low Sulfur Fuel, by Vehicle Number



4.3 Idle Disbenefit

The expectation in this study, based on engineering considerations, was that low-sulfur gasoline would have little or no effect on exhaust emissions until such time as vehicle warmup had brought the catalyst to operating temperature, i.e., after catalyst "light off." It was further supposed that low-sulfur fuel might hasten light-off,* and that increased catalyst activity after that point would reduce exhaust emissions. Because catalyst light-off will be reached more slowly following a cold start, it was thought likely that the average low-sulfur fuel benefit would be smaller (in percentage terms) for cold-start tests than for hot-start tests, and even possibly be statistically insignificant. Contrary to this logic, however, the cold-start test data showed the surprising trend that start plus initial idle CO emissions were *increased* on low-sulfur fuel compared to the cold-start testing on high-sulfur fuel. Considerable effort was made to investigate this effect, both to assess the reliability of the evidence for it and to identify hypotheses regarding its origin to the extent possible with present data.

Investigation of the cold-start effect began with the determination that CO emissions were increased *only* during the 5-minute idle period that begins the cold-start test, while CO emissions were reduced during the remainder of the test, during which the vehicle is driven to simulate a 4.7-mile trip. Further, it was found that the CO effect was actually confined to the first 60 seconds of the idle period.

While the main focus of the current study was CO, our next step was to examine all of the measured pollutants to try to gain insight into the cause of the observed CO disbenefit. As shown in Figure 4-5, using data for all vehicles in the test program, CO emissions on low-sulfur fuel increased by 19% on average during the first 60 seconds of the cold idle period, while NOx emissions decreased by 16%, compared to the emissions on high-sulfur fuel. THC emissions increased only slightly. During the remainder of the five-minute idle period, emissions of all pollutants were found to be relatively unaffected by the use of low-sulfur fuel—CO emissions increased by 4%, while THC emissions decreased by 6%, and NOx emissions were essentially unchanged, compared to the comparable idle period on high-sulfur fuel. In this latter period, the observed emission changes were not statistically significant. While not definitive, these trends—specifically the increase in CO and decrease in NOx—suggest that the air-fuel mixture was being enriched more† during the first 60 seconds of the idle on low-sulfur fuel than it was with the baseline, high-sulfur (as-received) fuel. Furthermore, the effect was strongest in MY 1996 and later vehicles, suggesting that it may be associated with the computer control of engine operation.‡

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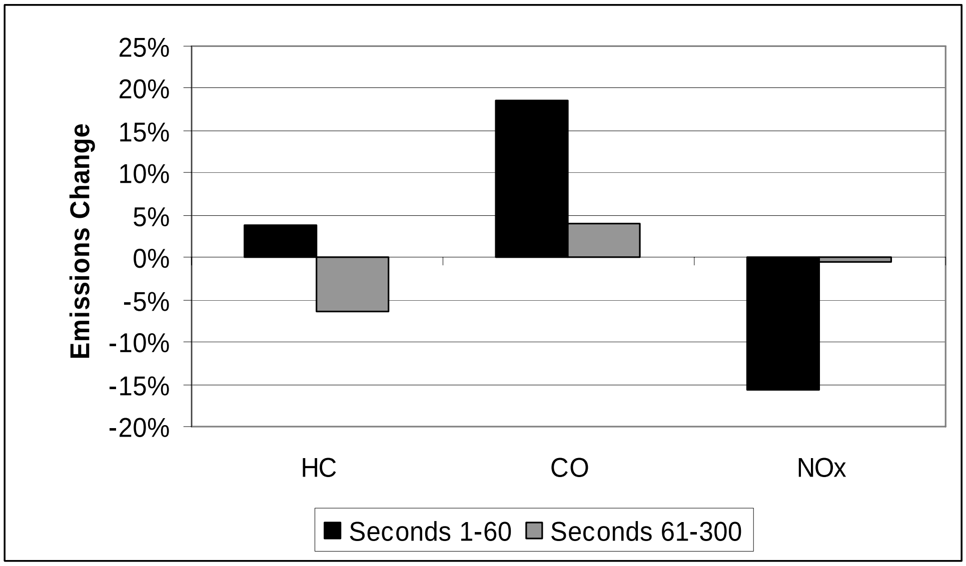
* Light-off normally occurs within the first one to two minutes after engine start, but it can be delayed by colder temperatures, an inefficient catalyst, or catalyst placement far downstream of the engine (common with older vehicles that were certified to less stringent emission standards and not requiring close catalyst coupling for quick light-off).

† Air-fuel ratio enrichment is required for engine start and smooth idle, especially at low temperatures. We are suggesting here an additional apparent enrichment on startup with the low-sulfur fuel due to the fuel change.

‡ 1996 and later model year vehicles use second generation on-board diagnostic controls and, generally, more computer-intensive engine and emission control systems than older models.

Figure 4-5
CO Emissions Change for Low-Sulfur Fuel
(positive % change is an emissions disbenefit)



For three-way catalytic converter-equipped vehicles,* the air-fuel ratio at time of engine start and prior to the onset of closed loop operation under feedback control from the oxygen sensor(s) is determined by the open-loop fuel metering that can, in turn, be affected by a variety of factors including fuel characteristics and the engine's previous operating history. The open-loop fuel metering rate itself is controlled by so-called "block learn" algorithms that, over time,† adapt the air fuel ratio to account for the operating activity of the engine and the characteristics of the fuel. A step change in fuel characteristics, such as a switch to a fuel of different density, would require a period of time in closed-loop operation for the block learn algorithms to adjust the default open-loop fuel metering. It is also possible (at least theoretically) that the default open-loop calibration could be adversely, but temporarily, affected by extreme or atypical modes of engine operation. Therefore, it could be that the intense, high-load nature of the sulfur reduction driving cycle, which was deliberately designed to provide power enrichment of the engine in order to effect the chemically reducing environment needed to purge sulfur deposits from the catalyst, resulted in an unusually lean stored correction of the air-fuel mixture, which was used for open-loop operation during the immediately following cold-start test on low-sulfur fuel.

As a result, there are two hypotheses for the cause of the observed cold-start effects, and particularly the CO disbenefit, with low-sulfur fuel:

* This includes almost all 1985 model year and later light-duty gasoline-powered vehicles.
† Block learn systems monitor and may adjust air fuel ratio both during a single drive ("short term") and from drive to drive ("long term").

1. The process of vehicle conditioning on low-sulfur fuel, specifically the aggressive, high-load operation during the sulfur removal drive, affected the open-loop air fuel ratio for cold startup, presumably through block learning on the sulfur conditioning drive; or

2. Some physical or chemical property of the low-sulfur fuel led to alteration of the air fuel ratio during the period of open-loop operation at and immediately following engine start-up.

As discussed earlier in this report, some differences in properties were observed between high- and low-sulfur fuels, but it was also noted that complete chemical composition data for the Tier 2 gasoline were not available. Thus, our ability to evaluate the second hypothesis was limited.

One set of fuel properties that could potentially be important in helping to understand emissions differences is front-end volatility. Front-end volatility can be represented by the temperatures T5, T10, and T20, which indicate the points along a distillation curve at which 5, 10, and 20%, respectively, of the fuel has boiled off under specified test conditions. Front-end volatility is an important parameter that is adjusted by refiners to match conditions for optimal cold starting.[16] If reduced front-end volatility of low-sulfur fuel were to give rise to harder starting, with concomitantly longer engine cranking and/or more engine stalls and restarts, CO emissions would be expected to increase. However, we did not see a correlation between high CO emissions and those cold starts that were noted in the operator's log as requiring starting assist (i.e., battery boost).

In order to define the CO disbenefit more precisely, the data were examined for evidence that emissions differed in a systematic way as additional testing on low-sulfur fuel, and additional engine operating experience, was accumulated. A sample of 15 vehicles was examined for which 3 or more valid cold-start tests had been completed.[*] A CO emissions baseline was established for the 5-minute idle period by averaging CO emissions measured during the cold-start tests on high-sulfur fuel. The cold-start tests on low-sulfur fuel were then placed in the order conducted, and the trends in CO emissions during the 5-minute cold idle period were examined.

As Figure 4-6 shows, each vehicle displayed its own trend in emissions during the idle period of the cold-start tests, although common trends can be observed. Notably, of the 15 vehicles, all but one showed an increase in CO emissions on the first cold-start test, compared to the emissions baseline on high-sulfur fuel. Some vehicles showed this effect only on the first cold-start test, with their subsequent cold-start tests falling back to the baseline level. Other vehicles showed a sustained increase in emissions on all cold-start tests, or even a trend of increasing emissions with subsequent testing.

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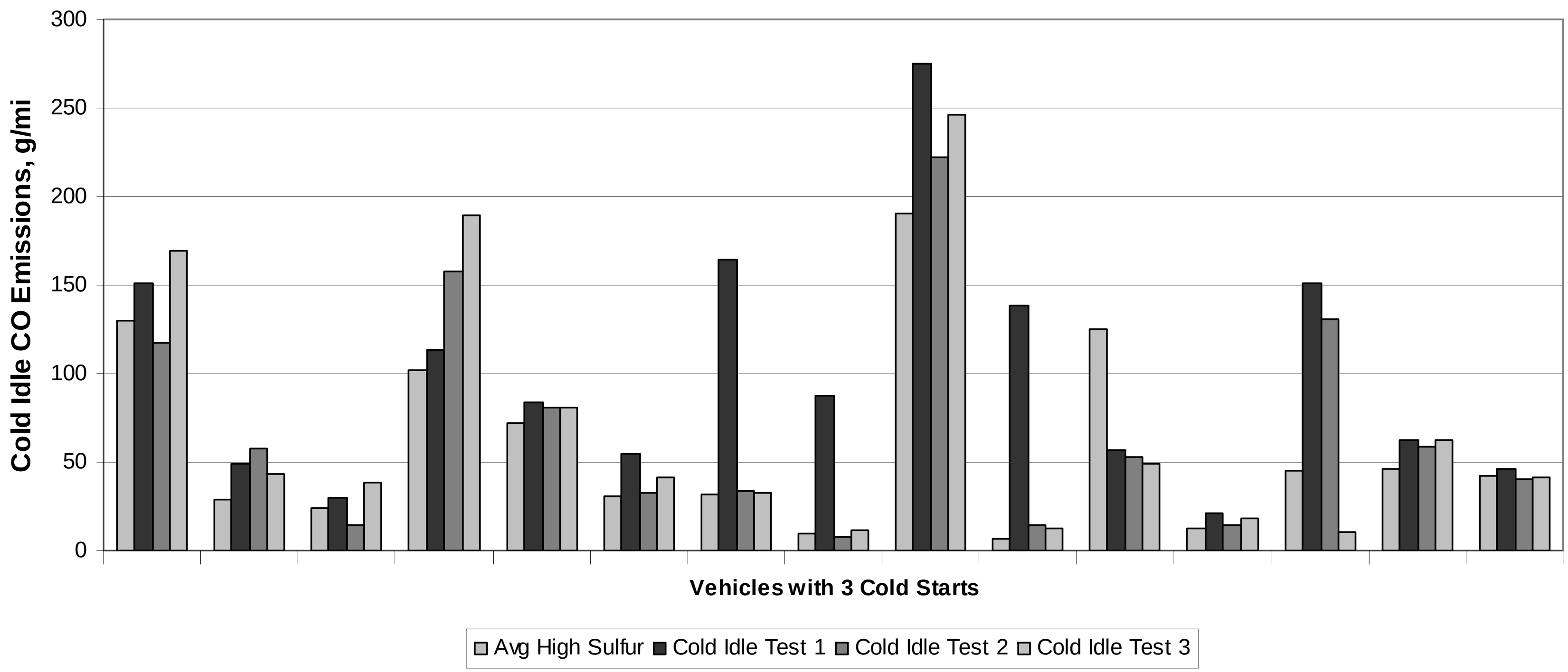
[*] These tend to be the vehicles that received fuel changes early in the week and had more cold starts after fuel change.

Figure 4-6
Avg Cold Start CO Emissions on High Sulfur Fuel and Successive Cold Start CO Emissions for Vehicles with 3 Cold Starts after Fuel Change



On average across all 15 vehicles, we found that CO emissions during the 5-minute idle period increased from a baseline of 60 g/test on high-sulfur fuel to 99 g/test on the first low-sulfur cold-start, 69 g/test on the second cold-start, and 70 g/test on the third cold-start. Thus, cold idle CO emissions are greatly increased on the initial cold-start test, but thereafter fall back to, and appear to stabilize at, a level still higher than the baseline level on high-sulfur fuel.

The test sequence specified conducting a sulfur-removal drive after the fuel change, followed by an overnight cold soak and initial cold-start test on low-sulfur fuel. The complete series of hot-start tests was then conducted on each vehicle, before returning it for a second overnight-cold soak and later cold-start test. In most cases, all hot-start tests were conducted immediately following the initial cold-start test, and no further hot-starts occurred between subsequent cold-start tests.

Based on the emissions change between first and second cold-start tests, it appears that the vehicles were only partially conditioned to low-sulfur fuel at the first cold-start test, but their conditioning was improved by the series of hot-start tests conducted after it. In most cases, no testing was conducted between the second and third cold-start tests, so that only 4.7 miles of driving (during the second cold-start test) would be added to the vehicle conditioning by the time of the third cold-start test. Therefore, the similarity of CO emissions between the second and third cold-start tests is not surprising.

Given these findings, it is probable that the initial cold-start test on each vehicle is subject to a bias associated with incomplete vehicle conditioning. To remove this bias, the first cold-start test for each vehicle was deleted from the database, reducing the size of the cold-start sample to 39 vehicles (compared to 53 vehicles for the hot-start testing). However, an increase in CO emissions, and a corresponding decrease in NOx emissions, compared to the hot-start baseline, was still present in the data for the second and later cold start tests. Because of the length of time that may be required to fully reset "block learn" algorithms, vehicle conditioning could remain incomplete even after the second and third tests, so that the test data may not fully reflect the emissions levels that would be measured after several months of operation on low-sulfur fuel.

Although its cause cannot be conclusively identified, it is clear that the CO emissions increase during the cold-start idle is a real effect present in the data collected in the test program. It appears to be the result of insufficient conditioning to stabilize emissions, and is most pronounced in model year 1996 and later vehicles, during the period of open-loop operation immediately following engine start up. Further, the effect appears to be diminished by the accumulation of operating time on low-sulfur fuel. Whether this effect would continue to diminish over time and eventually disappear cannot be determined from the testing conducted in this program. Additional testing, conducted over a longer period of operation on low-sulfur fuel, would be needed to resolve that issue.

4.4 Data Organization

In all, 330 test sequences were attempted over the course of the six-week emissions study. Each of these test sequences was comprised of one or more cold or hot start tests that were run consecutively. Table 4-1 summarizes the numbers of hot and cold start tests that were completed successfully, by model year group.

Table 4-1
Numbers of Tests Completed Successfully by Model Year Group and Test Type

Model year range	Hot Start Tests	Cold Start Tests	Hot & Cold Start Tests
Pre-1990	56	36	92
1990-95	86	55	141
1996 and later	313	156	469
Totals	455	247	702

Following an introductory explanation of format, Appendices J-1 and J-2 provide descriptive listings of all test sequences, in the order performed, including those tests that were in whole or in part incomplete, aborted, or otherwise invalid. Emission results for each test individually are summarized in Appendix K, expressed in grams per mile for each test phase. Summary test results are also reported in greater detail in Volume 3 of this report, which is a separately bound data volume. Second-by-second emissions, a tabulation of which is too voluminous to print, are provided in a separate, computer-readable data volume. Analysis and discussion of results is presented in the next section.

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5. ANALYSIS AND RESULTS

This section explains the methodologies used to analyze test data and the results of that analysis, describing the effects of low-sulfur gasoline upon emissions; and compares the results with those from other studies. Findings are summarized at the end of the section.

The methodologies used for data analysis were guided by (1) ADEC's requirements for the project (as described earlier), (2) the structure of the data that were obtained, and (3) the emissions measurements. Included were the following elements:

- Aggregation of emissions data for cars and trucks;
- Aggregation of vehicles by model year groups depending upon the response to low-sulfur fuels by pollutant;
- Consideration of not only hot and cold start average emissions, but also separate analysis of cold start emissions from the first minute of operation, from the five-minute warmup idle period, and from the "cold start driving" portion of each cold start test; and
- Consideration of the heteroskedacity* of the data and the log-transformation of emissions variables.

Despite the transient CO disbenefit observed after cold start, the overall measurement results showed low-sulfur gasoline to have large and robust net emissions benefits, which tended to corroborate or exceed the emissions benefits projected using EPA's MOBILE6 and Alaska's AKMOBILE6 emissions models. Analysis of the average per-vehicle emission benefits from the measurement program are discussed in Section 5.2.

Related studies by EPA and others provide some basis for checking the reliability of the emission measurements collected here. Section 5.3 presents the available information for such comparisons and explains its limitations, including a discussion of the low and record high ambient and test cell temperatures observed during the current study.

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* Heteroskedacity refers to the tendency of the error variance to change systematically across the range of the data.

The most important finding from our analysis is, of course, the significant reduction of CO emissions observed with low-sulfur gasoline. This and other findings are documented in the summary of results that is presented in Section 5.4.

5.1 Methodology

One of the principal objectives of the study (Task 6 of ADEC's RFP) was to determine emissions in "common age and emission control categories" as well as "fleet averages." To meet these objectives, a series of questions was first considered, which helped determine how to structure the statistical analysis. Based on the presence of the CO emissions disbenefit, it was clear that the statistical analysis should be structured to consider each of three emissions segments separately:

- Cold Idle – engine start followed by five minutes of idle at the beginning of the cold-start test;

- Cold Drive* – the simulated 4.7-mile trip driven during the cold start test after the initial 5-minute idle is concluded; and

- Hot Start – the complete hot-start test, including emissions generated during engine start and the simulated 4.7-mile trip.

As discussed later in this report, this segmentation of emissions also supported the application of emissions benefits to the inventories estimated by the AKMOBILE model. In addition, while the primary focus of both the measurement and analysis portions of the study has been on CO, emissions were also measured and analyzed separately for THC and NOx.

Emissions performance is frequently found to differ among vehicles on the basis of model year, age, technology, and, in some cases, vehicle type (car versus light truck). For purpose of this analysis, vehicles were grouped by model year as follows to conform to the categorizations used in the MOBILE and AKMOBILE models:

- Pre-1996 vehicles (all vehicles of model year 1995 or older);
- Model year 1996 to 2000 vehicles; and
- Model year 2001 and later vehicles.

These divisions reflect the introduction of OBD-II technologies in model year 1996 and of national low-emitting vehicles (NLEVs) in model year 2001, and they generally match the model year groupings used for emissions characterizations in the MOBILE6 and AKMOBILE6 emission inventory models. Accordingly, the analysis was designed to

* The "cold idle" plus the "cold drive" together comprise what is usually termed a "cold start."

allow the estimated emissions benefit of low-sulfur fuel to be different for each of these model year groups where the empirical evidence so warranted, but to combine (pool) the model year groups when no differences by model year could be detected.

Over the past 20-25 years, passenger cars and light trucks have increasingly been used as interchangeable substitutes for personal transportation and have been subject to increasingly stringent (and similar) emissions certification standards. There has been a tendency over time toward convergence of emission control technology and in-use emissions performance for car and light trucks. Early stages of the statistical analysis tested whether there was any evidence for differences in the effect of low-sulfur fuel on cars and trucks of comparable model year group, and in no instance were statistically significance differences found. As a result, a decision was made to aggregate cars and light trucks in the analysis to improve the statistical power of the data for estimating emission effects by model year.

<u>Effect of Ambient Temperature upon CO Emissions</u> - Ambient temperature has a systematic and uncontrollable effect on emissions measured during cold-start testing. In principle, the colder the temperatures during the overnight soak period and the cold-start test, the greater will be (1) the viscosity of engine oil and the internal engine friction to be overcome, (2) the enrichment of the air-fuel mixture required to start and idle the engine, and (3) the CO emissions.* Once the vehicle is fully warmed, the temperature history of the overnight soak is largely erased and the effect of ambient temperature during the test is greatly diminished. Therefore, we must anticipate the potential for ambient temperatures to affect cold-start emissions, in at least two different ways.

First, it is possible for ambient temperatures to change during the period that emissions testing is performed on each vehicle. For each vehicle, the baseline testing on high-sulfur gasoline was conducted first, over a period of one to several days (to allow for multiple overnight soaks between cold starts). After the change to low-sulfur fuel and vehicle conditioning on the sulfur removal cycle, a series of cold-start tests was conducted, again over a period of one to several days. If ambient temperatures changed substantially during the period required to complete testing, it is possible for the temperature change to measurably affect the low-sulfur fuel benefit observed for the vehicle. Thus, in the statistical analysis it becomes important to control for the potential biasing effect of ambient temperature differences that occur during testing for each vehicle.

Second, ambient temperatures varied markedly during the six-week period over which testing was conducted. Figure 5-1 shows the variation in ambient temperatures during the program. The lower data points and curve in the figure show minimum daily ambient temperatures as reported by the National Weather Service for Fairbanks International

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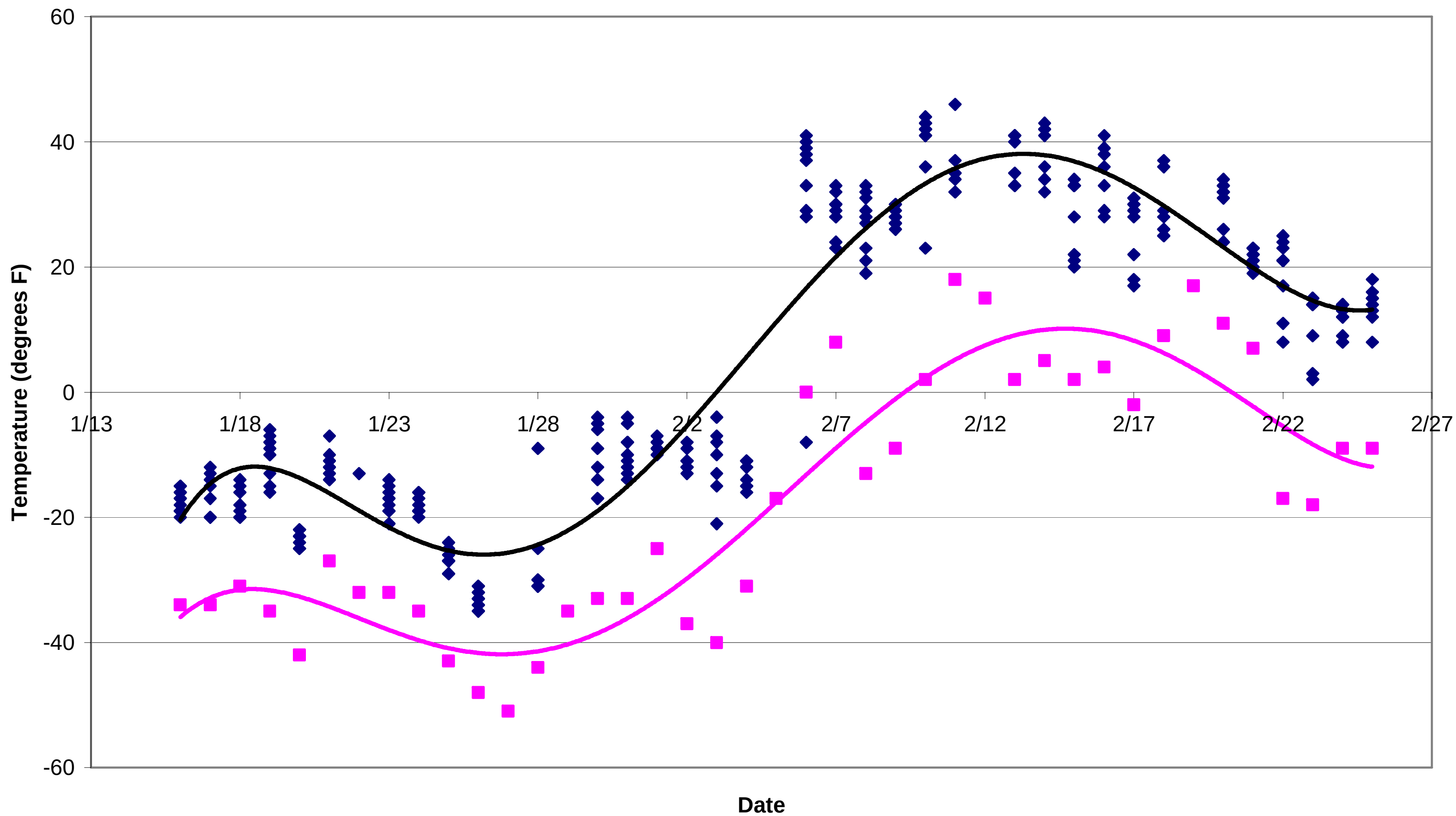
* This brief conceptual description is not intended to capture all the important aspects of the emissions/ambient temperature relationship, many of which are discussed elsewhere in this report. For example, most vehicle operators in Fairbanks tend to either garage their vehicles or use plug-in engine heaters when parking vehicles for extended periods at ambient temperatures around 20°F or colder, and virtually all operators do so at temperatures below about 0°F. Also, an important step change in emissions normally occurs when the catalyst ‘lights-off’ and the emission control system commences closed loop operation, i.e., under feedback control from the exhaust oxygen sensor.

Figure 5-1
Test Cell Temperatures for Emission Tests (upper symbols and trend line) and Fairbanks International Airport Daily Minimum Temperatures (lower symbols and trend line)



Airport. The upper data points show test cell temperatures at the start of each test, and a smooth curve shows their general trend. Typically, and for a variety of reasons,* test cell temperatures were seen to be about 15-25°F higher than the minimum daily ambient temperatures and increasing over the course of each test day.

Testing conducted in January and early February 2006 was subject to unusually cold temperatures that fell to as low as –35º F in the test cell. Weather conditions changed abruptly after the first week in February to become much milder, with test cell temperatures rising as high as 45º F and minimum daily ambient temperatures as high as 18º. The average ambient temperature for the test program overall was close to the 20º F† temperature used in AKMOBILE to reflect an average winter day, although the minimum daily ambient temperatures (shown in the figure), which are probably more representative of average soak temperatures, were either slightly below or far below the 20º F specified in AKMOBILE.

If the emissions effect of low-sulfur fuel depends upon the average temperature under which a vehicle is operated, then the variation in temperature during the testing has further potential to bias the estimated benefits. For example, if low-sulfur fuel can be thought of as having a constant percentage effect on emissions, then a vehicle tested early in the program would be likely to show higher baseline emissions and a larger emissions change in grams, than a similar vehicle tested later in the program. In this instance, a statistical analysis of mass emissions data (grams) would tend to find larger emissions benefits for those vehicles that happened to be tested earlier in the program.

The potential for a biasing effect depends on the day-to-day variation in temperature during the program, the strength of the corresponding effect on emissions, and the choice of independent variable. An analysis of data measuring the percentage benefit directly would tend to be much less affected than an analysis measuring the change in mass emissions (grams). For this analysis, we have applied a logarithmic transform to the emissions data for the purpose of variance stabilization. In log-space, the regression model is naturally interpreted as estimating a percentage emissions benefit for low-sulfur fuel and should therefore be less susceptible to bias due to day-to-day temperature trends. Nevertheless, two different variables were employed to test and control for the potential biasing effects of day-to-day temperature changes.

Computational Methodologies - The statistical analysis was performed using SAS‡ and MATLAB.§ Several alternatives were considered for the statistical methodology to be used in estimating the emissions benefits of low-sulfur fuel from the dataset. One approach, used previously by EPA,[17] involves regressing the emissions measurements of individual tests in a SAS GLM model that employs the ABSORB statement to remove

* Test cell temperatures were measured on an internal wall of the test cell. With the rollup door up (the normal position throughout the test day), the test cell was exposed to afternoon solar heating, if any. Also, test cell temperatures usually increased over the course of a test day due to vehicle and testing operations.
† MOBILE6 permits temperatures lower than 20ºF to be specified, however, 20ºF is the lowest temperature used in the model's calculations.
‡ SAS Institute, Cary, N.C.
§ Mathworks, Inc., Nattick, MA.

the effects associated with individual vehicles. In essence, this method differentiates the data to express each emissions test as a deviation from the overall average for each vehicle. This method does not directly compute an observed emissions change with low-sulfur fuel, but infers this from the regression analysis.

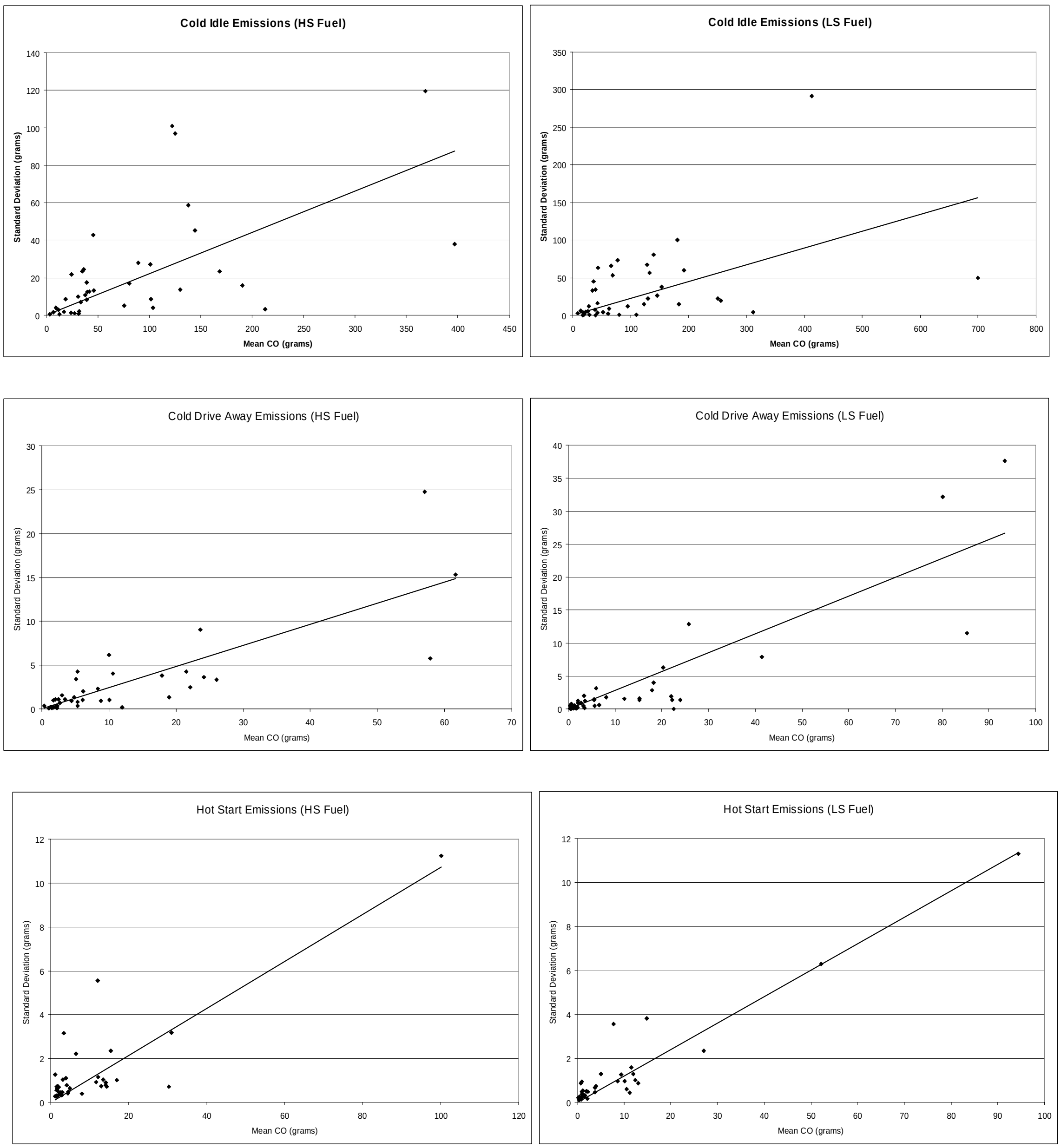
After using the SAS GLM approach in the initial data analysis, we concluded that our understanding of the data would be increased if we could work directly with the emissions changes observed for each vehicle. However, the data collected in the program are not paired data in which a low-sulfur emissions test value can be subtracted from a corresponding high-sulfur emissions value. Further, the number of tests varies from vehicle to vehicle and between high- and low-sulfur testing for each vehicle. Therefore, choices must be made regarding how mean emissions differences will be computed for each vehicle and then combined in the analysis of emissions impacts. These choices are discussed below.

Heteroskedacity and the Need for Variance Stabilization - The common assumption in statistical analysis, and specifically in regression analysis, is that data points share a common error variance. This means that the fluctuation of individual data points above and below a regression line can be characterized by a distribution with zero mean and constant variance σ^2 for all data points. If some data points are measured with greater accuracy, and some with lesser accuracy, the regression line can be unduly influenced by the points with greater variance, and the coefficients estimated by the regression may be subject to bias. The emissions testing conducted for this program included replicate testing on each fuel for most vehicles. In general, a total of two or three cold-start tests were conducted for each vehicle on each fuel, while typically four hot-start tests were conducted on each fuel. Repeat test variability is a measure of the extent to which successive tests of a vehicle on the same fuel will give different values and is therefore a direct measure of the accuracy with which emissions data can be collected in the test program. Using the data on replicated testing, it is possible to determine the magnitude of repeat-test variability, by fuel and test cycle, and to display its trend with emission levels.

Figure 5-2 shows a series of graphs demonstrating the repeat-test variability of CO emissions on the three emissions cycles and two fuels encountered in this analysis. The leftmost column pertains to testing on high-sulfur fuel, and the rightmost to testing on low-sulfur fuel. The top, middle, and lower graphs in each column pertain to the cold idle, cold drive, and hot-start testing, respectively. Each graph shows the standard deviation of CO emissions, estimated from the variation of repeated tests around the mean value for each vehicle, plotted on the vertical axis against the mean emission level for the vehicle on the horizontal axis.

From these plots, one can easily deduce that the standard deviation of emissions measurements increases in nearly direct proportion to the mean emission level for the vehicle. Given this, the data can be closely approximated by a model of constant coefficient of variation (also plotted in each graph). Because the repeat test variability increases with mean emission level, the accuracy with which mean emissions can be

Figure 5-2
Heteroskedacity in CO Emissions Data



measured (in g or g/mi terms) will decrease at higher emission levels. In these circumstances, an analysis of the data conducted in terms of mass emissions (g or g/mi) will be affected by heteroskedacity—i.e., the tendency of the error variance to change systematically across the range of the data.

Some method of weighting or transforming the data must be employed to stabilize the variance with respect to vehicle emission levels. For this purpose, we have chosen to transform emission values using the natural logarithm. After transformation to log values, the plots of repeat test variability comparable to Figure 4-8 show little or no apparent trend in standard deviation with log emission level.

Therefore, the individual emission measures $E_{i,j}$ for vehicle i on fuel j for test k are transformed to $\ln(E_{i,j,k})$. Mean values are then computed to give the vehicle's mean log emissions on each fuel:

$$\ln E_{i,1} = \text{mean}(\ln(E_{i,1,k})) \text{ for high-sulfur fuel } j=1 \qquad (1)$$

$$\ln E_{i,2} = \text{mean}(\ln(E_{i,2,k})) \text{ for low-sulfur fuel } j=2 \qquad (2)$$

A logarithmic dependent variable is then formed that estimates the change in log emissions for each vehicle i:

$$Y_i = \ln E_{i,2} - \ln E_{i,1} \qquad (3)$$

The dependent variable can be interpreted as the logarithm of a ratio between (a properly defined) mean emissions on low-sulfur fuel and mean emissions on high-sulfur fuel. From this one can compute the implied emissions ratio R_{LS-HS} as:

$$R_{LS-HS} = \exp(Y_i) - 1 \qquad (4)$$

Negative values for the dependent variable Y_i and for the emissions ratio R_{LS-HS} imply that emissions are reduced on low-sulfur fuel, while positive values imply that emissions are increased.

Weighted Regression Analysis - Having defined a dependent variable that measures the emissions change observed for each vehicle, we must address the fact that the data points for different vehicles are subject to different uncertainties of measurement. The variance associated with repeat-test variability has been stabilized by the log transformation, but the mean values for different vehicles are based on differing numbers of tests on each fuel. Therefore, some data points (computed from more tests) are likely to be more reliable than other data points (computed from fewer tests). A weighted regression approach was used to account for the varying reliability of the data.

A formal standard error was estimated for each data point based on the repeat-test variability observed in testing on high- and low-sulfur fuels and the number of tests conducted on each fuel. If σ^2_{HS} is the population variance for repeated high-sulfur tests,

N_{HS} the number of high-sulfur tests conducted on a vehicle, σ^2_{LS} is the population variance for repeated low-sulfur tests, and N_{LS} the number of low-sulfur tests conducted, then the expected variance of the mean is given by:

$$\sigma^2_{SE} = \sigma^2_{HS} / N_{HS} + \sigma^2_{LS} / N_{LS} \qquad (5)$$

where the number of tests N, and not N-1, appears in the denominator because we are using the population standard deviations. This is termed a formal error because it is the standard error that we would expect each data point to have based on our knowledge of the population; it is not computed from the test data for each vehicle individually.

Weighted regression analysis is a well-known statistical methodology and has been fully implemented in the SAS GLM procedure. For weighted regression, each data point is assigned a weight that is inversely proportional to its variance given by Equation 5. Data points with larger variance are given reduced weight in the regression, while points with smaller variance are given increased weight.

Statistical Controls for Ambient Temperature Differences - As noted in a prior section, ambient temperatures varied during the testing and may have had an effect on the measured emissions change, particularly during cold-start testing. Control variables were introduced into the regression analysis to account for temperature effects. Temperature differences between the high- and low-sulfur testing for each vehicle were measured by the variable deltaT, which is defined as:

$$\text{deltaT} = T_{LS} - T_{HS} \qquad (6)$$

using the overnight minimum temperatures recorded at the airport as a measure of the temperature encountered during the overnight cold-soak that preceded each cold-start test. If the ambient temperature increases on average between high- and low-sulfur testing for the vehicle, deltaT will be positive and should be expected to reduce emissions on low-sulfur fuel, leading to a negative sign for the associated coefficient. The deltaT variable was included in each regression model to control for the potential effect of varying ambient temperature.

A second temperature effect is potentially present, related to ambient temperature trends over the test program— i.e., the occurrence of very cold temperatures early in the test program and much milder temperatures at the end. The choice of the log transform has the effect of measuring the low-sulfur fuel effect in terms of a percentage change in emissions, and this approach is much less likely to be biased by day-to-day temperature trends. Nevertheless, the analysis developed two measures of this effect and evaluated their usefulness as controls:

$$\text{absT} = (T_{LS} + T_{HS}) / 2 = \text{average temperature during vehicle's testing} \qquad (7)$$

$$\begin{aligned} \text{tempGroup} &= 0 \ \text{ for early testing (cold temperature)} \\ &= 1 \ \text{ for late testing (mild temperature)} \end{aligned} \qquad (8)$$

The variables were introduced in the regression models as alternative forms of control, but no instance was found in which either variable was statistically significant or its introduction had a material effect on other coefficient values. Given that the dataset overall was judged to be closely representative of the temperature for an average winter day, the decision was made to drop the absT and tempGroup variables from further consideration and to base the benefit estimates on the pool testing.

The final regression models were estimated using deltaT as the sole control for temperature variations. The deltaT terms were found to be statistically significant in only a few instances, but have been retained in all models to act as a control. The SAS ESTIMATE statement was then employed to estimate emissions effects for each model year group controlled to a zero temperature difference. To the extent that temperature differences are present in the data and influence the measured emissions, these effects have been removed from the estimates presented here.

Summary of Data Preparation and Variables Used in the Analysis – Summarized below are the key steps in data preparation and the definition of the primary variables used in the analysis.

- All valid hot start tests were retained. A total of 53 different vehicles were represented in the hot-start dataset

- All valid cold-start tests were retained, except that the initial low-sulfur cold-start test on each vehicle was deleted. A total of 39 different vehicles were presented in the final cold-start database.

- Test data for Vehicles 14 and 50 were provisionally deleted for the reasons given elsewhere in this report. The vehicles were reintroduced as a sensitivity study to determine if their exclusion had a material effect.

- The analysis was conducted for three different emissions cycles, including the Cold Idle and Cold Drive portions of the cold-start test and the complete Hot-Start test.

Variables used in the analysis include those listed below.

- Early MY Vehicles – a dummy variable having the value 1 for vehicles in the first two model year groups (built prior to MY 2001), and a value 0 otherwise

- Late MY Vehicles – a dummy variable having the value 1 for vehicles in the latter two model year groups (built in MY 1996 and later), and a value 0 otherwise

- MY 1996-2000 Vehicles – a dummy variable having the value 1 for vehicles in the second model year group, and a value 0 otherwise

- MY 2001 and Later – a dummy variable having the value 1 for vehicles in the third model year group, and a value 0 otherwise

- deltaT – a continuous variable representing the ambient temperature difference between the testing on low- and high-sulfur fuels.

Where a regression model includes one or more dummy variables representing model year groups, the intercept term should be interpreted as representing the model year group(s) excluded by the dummy variable(s).

5.2 Effects of Low-Sulfur Gasoline upon Emissions

Results of the analysis of emission measurements are summarized in Table 5-1 and discussed in this section. The data shown in the table represent the average emission benefits of changing from winter 2005-06 commercial gasoline in Fairbanks to the 1.9 ppm sulfur test fuel that was used in the test program, and the resulting percentage reductions in emissions are presented by pollutant, by vehicle model year group, and, separately, for the cold idle, cold drive, and hot start* modes of operation. Detailed results and their discussion may be found in Appendix L.

The main finding from our analysis of emissions measurements, as reflected in the table, is that changing to low (1.9 ppm) sulfur test fuel reduced vehicular exhaust CO emissions during cold drive and hot start operation by amounts that ranged from 20% to as much as 67%, depending upon the operating mode and model year group. The CO and other emissions benefits were greatest (in percentage terms) for the newer model year groups that will account for the large majority of fleetwide travel in coming years. For model year 1996 and later vehicles, low-sulfur test fuel was estimated to reduce cold drive CO emissions by 45% to 64% and hot start CO emissions by 67%. Significant emissions benefits on these cycles were observed for all measured pollutants (THC, CO, and NOx) and were greatest for the newer vehicles. The emission benefits for older vehicles were smaller and, in some instances, not statistically significant.

During the five-minute warmup idle portion of the test cycle, CO emissions were significantly increased (by 30%) for MY 1996 and later vehicles, and NOx emissions were significantly decreased (by 24%) in all model year groups. Although THC emissions increased on average, the effect was small and failed to reach the level of statistical significance. This CO disbenefit is likely due to inadequate vehicle

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* As in the analysis, "cold idle" refers to emissions from a cold engine start (after overnight plug-in) plus those emissions resulting from five minutes of warmup idle. "Cold drive" refers to the emissions during dynamometer operation while driving the Alaska Drive Cycle after warmup idle. "Hot start" refers to the emissions of a warmed up vehicle from the start and driving of an Alaska Drive Cycle on the dynamometer.

Table 5-1 **Average Emission Benefits of Changing from Winter 2005-06 Commercial Gasoline in Fairbanks to Low-Sulfur (1.9 ppm)* Test Fuel**			
	Total Hydrocarbons (THC)	Carbon Monoxide (CO)	Nitrogen Oxides (NOx)
Cold Idle Emissions			
Pre 1996 Vehicles	-5.4% ± 9.4%	0.4% ± 9.5%	**24.1% ± 5.3%**
MY 1996-2000 Vehicles	-5.4% ± 9.4%	**-29.7% ± 9.7%**	**24.1% ± 5.3%**
MY 2001 and Later	-5.4% ± 9.4%	**-29.7% ± 9.7%**	**24.1% ± 5.3%**
Cold Drive Emissions			
Pre 1996 Vehicles	**22.8% ± 10.7%**	13.6% ± 15.1%	**26.2% ± 9.1%**
MY 1996-2000 Vehicles	**22.8% ± 10.7%**	**44.6% ± 29.2%**	**26.2% ± 9.1%**
MY 2001 and Later	**53.8% ± 8.5%**	**64.0% ± 6.4%**	**73.4% ± 4.4%**
Hot Start Emissions			
Pre 1996 Vehicles	**49.2% ± 9.5%**	**20.3% ± 10.9%**	13.7% ± 21.3%
MY 1996-2000 Vehicles	**49.2% ± 9.5%**	**66.7% ± 2.9%**	**60.3% ± 6.3%**
MY 2001 and Later	**49.2% ± 9.5%**	**66.7% ± 2.9%**	**60.3% ± 6.3%**

Notes: Positive benefit values indicate that emissions decrease for low-sulfur fuel.
Benefit estimates achieving at least the 90% confidence level are shown in bold.

conditioning after the fuel change and either the unusually aggressive driving during the sulfur reduction drive or some unidentified change in fuel property.

For CO emissions, it is clear that the disbenefit was present only in the later model year groups (MY 1996 and later vehicles), which tends to suggest an association with the high levels of engine computerization on these later OBD II vehicles. For NOx, there was only slight evidence that the observed benefit may have been larger in the later model year groups. To the extent that the NOx benefit that was coincident with the CO disbenefit was suggestive of an altered air-fuel ratio, this appears to have been true for all vehicles. However, it is possible that this apparent change occurred only for the model year 1996 and later vehicles, and the present dataset provided insufficient power to detect the difference among model year groups.

For the cold drive portion of the cold-start test, emission benefits were observed across the board for all pollutants and all model year groups. The observed benefits were large and statistically significant (with one exception), ranging from 23–54% for THC, from 14–64% for CO, and from 26–73% for NOx. The magnitude of the benefits indicates

* Note that this table summarizes the effect of switching to 1.9 ppm sulfur test fuel and, unless adjusted, should not be construed to represent the effect of switching to 30 ppm sulfur complying fuel (see narrative).

clearly that the vehicles' catalysts were lit off early in the cold drive and that catalyst activity benefited from the reduced sulfur burden using low-sulfur fuel.

Only for CO emissions in the oldest model year group did the estimated emissions benefit fail to reach at least the 90% confidence level. However, the observed CO benefit in that group was comparable in size to the statistically significant benefits that were observed for HC and NOx. Given the clear evidence for a beneficial effect of low-sulfur fuel on the other pollutants, it should be acceptable to retain the small CO benefit in later inventory calculations, in spite of the failure to reach statistical significance. The small weight[*] (low travel fraction) given to this vehicle group should reduce any concern regarding a decision to retain the observed benefit.

Emission benefits were also observed across the board for all pollutants and vehicle groups in the hot-start testing. The observed benefits were comparable to, or somewhat larger than, the benefits observed during the cold drive, and were statistically significant at the 90% confidence level (or better) in all but one instance. The similarity of percentage benefits for the cold drive and hot-start portions of the testing is not surprising if the engine catalysts were lit off early in the cold drive. In the one instance where the observed benefits failed to reach statistical significance (NOx emissions for pre-1996 vehicles), the similar and statistically significant effects on other pollutants would support retaining the observed benefit in inventory calculations.

Other notable facts from the table and other data provided in the appendices are summarized below.

- For cold starts, most vehicles were relatively high CO emitters on either fuel. Average measured CO emission rates for cold start tests were about ten times higher than the intermediate useful life 50,000 mile certification standard of 3.4 g/mi and, for 1994 and later vehicles, they were about twice the 10-12.5 g/mi cold temperature CO standard.[†18]

- Average cold start emissions (which included five-minute warmup idle) were, not unexpectedly, five to six times higher than hot start emissions and were much more variable.

<u>Adjustment to Account for 30 ppm Complying Fuel Rather than 1.9 ppm S Test Fuel</u> – Prior to applying the foregoing results for low-sulfur test fuel to project emission inventory changes for Fairbanks (see Section 5) or trying to compare the results above with other studies (Section 5.3), all measurement-based percentage changes in emissions

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[*] Weightings that are assigned to each vehicle group are discussed in Section 6, which describes the use of the MOBILE6 and AKMOBILE6 emission factor models to compute tons per day emissions using the emission reduction percentages for low-sulfur fuel that are described in this section.

[†] Beginning with model year 1994, new vehicles were subject to cold temperature certification standards for CO emissions of either 10 or 12.5 g/mi, phased in over three years (40% for 1994, 80% for 1995, and 100% thereafter).

were adjusted by an assumed linear sulfur adjustment factor,[*] which is intended to account for the fact that the current test program was conducted and the effects were observed for a test fuel that contained 1.9 ppm[†] sulfur rather than the assumed average 30 ppm sulfur "compliance" fuel mandated by EPA. The adjustment assumes a baseline sulfur level of 164 ppm, resulting in a sulfur adjustment factor calculated as follows:

$$\text{30 ppm S adjustment factor} = \frac{\text{(ppm baseline – ppm compliance)}}{\text{(ppm baseline – ppm test fuel)}}$$

$$= \frac{(164 - 30)}{(164 - 1.9)}$$

$$= 0.83$$

Thus, for example, for MY 2001+ vehicles that showed a 66.7% reduction in hot running emissions when switching from 164 ppm sulfur gasoline to 1.9 ppm sulfur in the test program, the adjusted percent reduction was estimated to be 55.1% (0.83 X 66.7%) after application of the above adjustment factor. The results of adjusting all of the test results shown in Table 5-1 in this way are shown in Table 5-2, and represent the projected emission benefits (as a percent reduction compared to commercial gasoline in Fairbanks in the winter of 2005-06) of compliant 30 ppm sulfur fuel for each of the stated pollutants by model year group and operating mode.

<u>Sensitivity of Results to Vehicle Exclusion</u> - Earlier portions of the report discussed at length issues with the low-sulfur cold start test results for vehicle 14 and the hot start results for vehicle 50. While the preferred approach was to delete these vehicles from the sample for the reasons given earlier, it may be important to demonstrate that the conclusions drawn from the data are not materially affected by this decision. Table 5-3 (which may be compared with Table 5-1) therefore summarizes the emissions benefits that would be estimated for low-sulfur test fuel if Vehicles 14 and 50 were included in the sample.

Vehicles 14 and 50 are older vehicles that fall into the pre-1996 model year group, so that the decision to retain or exclude them from the dataset naturally has greatest effect on the estimates for this group. By comparing Table 5-3 with Table 5-1, one can see that a decision to retain vehicles 14 and 50 changes the emissions benefit estimates for pre-1996 vehicles only marginally:

- In most instances, the estimated emissions benefit or disbenefit changes by no more than 2 to 4 percentage points, with the largest change (a reduction from 13.6% benefit to 6.0% benefit) occurring for CO, where the estimated benefit fails to achieve statistical significance anyway.

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[*] Although there are few emissions data available at sulfur concentrations as low as 1.9 ppm, the assumption of a linear adjustment factor at least down to the range of 30 ppm sulfur for all three pollutants appears to be justified based on comparison with Auto/Oil study results.

[†] As used here, "ppm" refers to the average sulfur concentration by weight in parts per million.

Table 5-2
Average Emission Benefits of Changing from Winter 2005-06 Commercial Gasoline in Fairbanks to Low-Sulfur (30 ppm)* "Compliance" Fuel

	Total Hydrocarbons (THC)	Carbon Monoxide (CO)	Nitrogen Oxides (NOx)
Cold Idle Emissions			
Pre 1996 Vehicles	-4.5% ± 7.8%	0.3% ± 7.9%	**20.0% ± 4.4%**
MY 1996-2000 Vehicles	-4.5% ± 7.8%	**-24.7% ± 8.1%**	**20.0% ± 4.4%**
MY 2001 and Later	-4.5% ± 7.8%	**-24.7% ± 8.1%**	**20.0% ± 4.4%**
Cold Drive Emissions			
Pre 1996 Vehicles	**18.9% ± 8.9%**	11.3% ± 12.5%	**21.7% ± 7.6%**
MY 1996-2000 Vehicles	**18.9% ± 8.9%**	**37.0% ± 24.2%**	**21.7% ± 7.6%**
MY 2001 and Later	**44.7% ±7.1%**	**53.1% ± 5.3%**	**60.9% ± 3.7%**
Hot Start Emissions			
Pre 1996 Vehicles	**40.8% ± 7.9%**	**16.8% ± 9.0%**	11.4% ± 17.7%
MY 1996-2000 Vehicles	**40.8% ± 7.9%**	**55.4% ± 2.4%**	**50.0% ± 5.2%**
MY 2001 and Later	**40.8% ± 7.9%**	**55.4% ± 2.4%**	**50.0% ± 5.2%**

Notes: Positive benefit values indicate that emissions decrease for low-sulfur fuel.
Benefit estimates achieving at least the 90% confidence level are shown in bold.

Table 5-3
Summary of Emission Benefits for Low-sulfur Test Fuel When Vehicles 14 and 50 are Retained in the Dataset

	Total Hydrocarbons (THC)	Carbon Monoxide (CO)	Nitrogen Oxides (NOx)
Cold Idle Emissions			
Pre 1996 Vehicles	-7.8% ± 10.1%	4.5% ± 10.0%	**24.5% ± 5.9%**
MY 1996-2000 Vehicles	-7.8% ± 10.1%	**-28.3% ± 11.0%**	**24.5% ± 5.9%**
MY 2001 and Later	-7.8% ± 10.1%	**-28.3% ± 11.0%**	**24.5% ± 5.9%**
Cold Drive Emissions			
Pre 1996 Vehicles	**18.8% ± 10.6%**	6.0% ± 15.2%	**26.0% ± 8.4%**
MY 1996-2000 Vehicles	**18.8% ± 10.6%**	**43.7% ± 11.6%**	**26.0% ± 8.4%**
MY 2001 and Later	**53.3% ± 8.5%**	**63.6% ± 6.4%**	**73.4% ± 4.3%**
Hot Start Emissions			
Pre 1996 Vehicles	**49.2% ± 9.5%**	**16.6% ± 10.8%**	13.1% ± 19.8%
MY 1996-2000 Vehicles	**49.2% ± 9.5%**	**66.6% ± 2.9%**	**60.3% ± 6.1%**
MY 2001 and Later	**49.2% ± 9.5%**	**66.6% ± 2.9%**	**60.3% ± 6.1%**

Notes: Positive benefit values indicate that emissions decrease on low-sulfur fuel.
Benefit estimates achieving at least the 90 percent confidence level are shown in bold.

* Note that this table summarizes the estimated effect of switching to 30 ppm sulfur compliance fuel (see narrative).

- In no instance is the statistical significance changed to a material degree. Where the previous analysis reports statistically significant benefits or disbenefits, the alternative analysis, in which Vehicles 14 and 50 are retained, would report similar and statistically significance benefits or disbenefits.

- The benefits estimated for other model year groups are affected in only minor ways and only in instances where vehicles of all model years have been pooled for analysis.

5.3 Comparison with Other Studies

Previous studies of the effects upon emissions of changes in gasoline sulfur level, following the lead of the Auto/Oil Air Quality Improvement Research Program (AQIRP), have shown significant CO, HC, and NOx benefits for low-sulfur gasoline. A sampling of these studies is summarized here.

In 1991, the Society of Automotive Engineers published results from Phase 1 of the AQIRP cooperative research study.[19] The test fleet consisted of ten (then current) 1989 model year vehicles that were each tested on two fuels having sulfur levels of 466 ppm and 49 ppm, and overall reductions were reported of 13% for CO, 16% for HC and 9% for NOx.

In studies that were used to support EPA's "Complex model," Mayotte et al. reported in 1994 on the effects upon exhaust emissions of various constituents in reformulated gasoline, including sulfur content. Phase I[20] of the program focused on high emitting vehicles and oxygenated fuels, examining, among other factors, the effect of fuel sulfur change upon emissions. Eight blended fuels were used, with sulfur levels varying from 58 to 371 ppm (and other parameters varying as well). The Phase I test fleet included 36 vehicles of model year 1986 to 1990 (20 "normals" and 16 "higher than normal" emitters). Compared to "industry average" (324 ppm) gasoline, low (58 ppm) sulfur gasoline yielded CO emission reductions of 13.4% for the normal emitters, 14.2% for the higher emitters, and 13.8% for the 36-vehicle fleet; emissions benefits were also seen for HC, NOx, and other pollutants.

In Phase II, Mayotte et al. [21]reported on testing of 40 vehicles using 8 fuels that varied in several properties, including sulfur content. Vehicle selection was intended to represent the in-use fleet in 1995, with 20 "normal" emitters and 12 "higher than normal" emitters (one participant withdrew his vehicle before the end of testing). Test results showed that, compared to industry average baseline fuel having a sulfur content of 295 ppm, the low olefin and low (59 ppm) sulfur fuel yielded CO reductions of 16.7% for normal emitters, 11.9% for higher emitters, and 14% for the 39-vehicle fleet. By comparison, the low olefin fuel alone (with sulfur content of 327 ppm, roughly matching the baseline fuel) yielded CO emission reductions of 8.4%, 8.3%, and 8.3%, for the respective fleet vehicles, which appears to suggest that roughly half of the observed benefit for low-sulfur and low-olefin fuel was associated with the low sulfur. Mayotte et al. concluded that the Phase II test results support the conclusions of the Phase I study.

In a third phase, Korotney et al.[22] reported further on interactive effects of various fuel constituents, including sulfur, on emissions from 19 light-duty vehicles. The purpose of the program was to determine fuel effects on exhaust emissions that were outside the range of the fuel parameters used in EPA's Complex model, in order to determine if the model's extrapolations were reasonable. "Raw emissions measurements" shown in the Korotney et al.'s appendix suggest (with one apparent outlier vehicle removed) a reduction (calculated by method of linear least squares) of 11% for switching from 315 ppm sulfur (fuel 4) to low-sulfur fuel (9.3 ppm, fuel 6).

In a 1995 SAE paper, [23] Rutherford et al. reported updated emissions benefit measurements for low sulfur and other selected fuel parameters for a fleet consisting of half of the original AQIRP fleet and two newer fleets (model year 1994 and later) of six vehicles each. A set of six fuels was tested, including fuels of 35 ppm and 320 ppm nominal sulfur content with other properties systematically varied. Results were primarily reported graphically, and show CO reductions on the Federal Test Procedure (FTP) of about 10-16% (depending on the fleet) with the change to low-sulfur fuel.

In a 1998 SAE paper,[24] Schleyer et al. reported testing 12 vehicles (two vehicles each of six popular models of 1997 model year California Low Emission Vehicles) with seven test fuels ranging in sulfur content from 30 to 630 ppm. The base fuels included a conventional (non-reformulated, non-oxygenated) Federal fuel and California Phase 2 reformulated gasoline, and each was blended with a "sulfur-doping mixture" to obtain the targeted sulfurs for blend fuel. Vehicles were conditioned after fuel change using a back-to-back repeated aggressive and high-speed cycle that included ten wide open throttle accelerations. Vehicles were tested both with their "as-received" (nominally 10,000 mile) catalysts and with 100,000-mile aged catalysts. With 100,000-mile catalysts and the "conventional fuel set," reductions of 46% for CO, 61% for NOx, and 32% for NMHC (non-methane hydrocarbons) were reported. Emission reductions on low-sulfur fuel occurred in all three phases of the FTP and for both catalyst ages but were smallest percentage-wise[*] (but largest in absolute g/mi reductions) for Bag 1, where the engine and catalyst started at test cell temperature.

In a 1999 SAE paper, [15] Schleyer et al. reported testing six popular models of 1997 model year California Low Emission Vehicles for sulfur reversibility with 100,000-mile aged catalysts. Four fuel changes were performed on each vehicle, with fuel alternating between 30 ppm and 630 ppm sulfur non-oxygenated conventional Federal gasolines. Conditioning drives included multiple wide open throttle accelerations, LA4 drive cycles, and the US06 drive cycle.[†] The Federal Test Procedure was used for emissions evaluation; in all, 720 miles were accumulated on each test vehicle. Thus, compared to

[*] For the 100,000-mile catalyst, CO emissions were reduced 25%, 74%, and 65% for Bags 1, 2, and 3, respectively.

[†] The US06 is intended to represent the more aggressive high-acceleration and high-speed cruise fraction of driving that is not included in the LA4 driving cycle.

the current study for ADEC, Schleyer et al. tested about one-tenth the number of vehicles, accumulated about ten times more mileage per vehicle, and used different test cycles and very different test conditions.* In a pertinent part, Schleyer et al. reported that (1) there was usually a step change in emissions in response to a fuel sulfur or driving cycle change, (2) stabilization to the new emissions level usually occurred within ten miles of driving, and (3) the fleet average effect of reducing sulfur level from 630 ppm to 30 ppm was 57% for CO, 63% for NOx, and 46% for NMHC.

In July 2001, the USEPA published a report[17] on fuel sulfur effects on exhaust emissions, which was presented as a "first-cut approach" to modeling the effects of exhaust emissions but which, in fact, served as much of the basis for treatment of fuel sulfur effects in its MOBILE6 (empirical) emission factor model. EPA's approach entailed the following elements: categorization of vehicles by emitter class; regression using the SAS "ABSORB" procedure; logarithmic transformation of g/mi emission values; computation of "start," "running," and "FTP-composite" emissions; analysis by technology groups (Tier 0, Tier 1, LEV, ULEV, and cleaner, and analysis for light-duty trucks); and treatments for long-term and irreversibility effects.

In 2002, EPA's report was reviewed by Sierra Research in a technical memorandum[25] that highlighted some of the shortcomings of EPA's proposed modeling approach.

Generally, the percentage emissions reductions estimated for 30 ppm sulfur "compliance fuel" from the current test program were of the same order or greater than the (percentage) reductions reported in other studies. However, more quantitative comparisons of results are complicated by differences in uncontrolled factors, temperature probably being foremost among them. As mentioned earlier, the temperatures in Fairbanks over the course of the current study ranged from near-record lows during the month of January to several record daily highs in February. Local climatological data for Fairbanks International Airport (elevation 461 feet) during the study months of January and February 2006 can be found in Appendix M-1 and M-2, respectively.†

In addition to having substantially lower temperatures than other published studies of fuel sulfur effects, the current study differed with respect to the following:

- An Alaska-specific winter driving cycle rather than the LA4 driving cycle that is used in the FTP;

- Overnight plug-in prior to cold start‡;

** The FTP used by Schleyer et al. specifies a test temperature of 68-86ºF and the LA4 drive cycle, whereas ADEC's test program was conducted around 0ºF and used the Alaska Drive Cycle with overnight plugin.
† We are not aware of any other major low-sulfur gasoline emission measurement studies conducted at temperatures comparable to those in Fairbanks.
‡ A rule of thumb is that about half of the fleet will not start cold at 0ºF without starting assist, such as plug-in, battery boost, or spray-in ether, and almost no gasoline vehicles will start cold at -20ºF without some form of starting assist.

- Five-minute warmup idle*;
- Fleet age, condition, and vehicle mix†; and
- 1.9 ppm sulfur test fuel, which is much lower than the 30+ ppm gasoline sulfur levels for which MOBILE6 was designed and well below the sulfur levels of fuels used in all of the other studies reported.

In addition to the factors listed above, comparisons may be complicated by differences in vehicle conditioning between sulfur evaluation tests. Interestingly, Schleyer et al,[15] who tested only six vehicles of model year 1997 but over longer periods, reported a rapid stabilization in emissions (within ten miles) when test conditions change. That finding seems to be consistent with the finding from the current study that the first cold start after fuel change in the current program did not appear to fully reflect stabilization of emissions.

5.4 Summary of Findings from the Analysis of Measurement Data

Our findings from the measurement and analysis of exhaust emissions test data, which pertain to changing from 164 ppm sulfur commercial gasoline in Fairbanks in the winter of 2005-06 to low (1.9 ppm) sulfur test fuel, are summarized below.

- Changing to low-sulfur test fuel reduced vehicular exhaust CO emissions during cold drive and hot start operation by amounts that ranged from 20% to as much as 67%, depending upon the operating mode and model year group.
- The CO and other emissions benefits were greatest (in percentage terms) for the newer model year groups that will account for the large majority of fleetwide travel in coming years. For model year 1996 and later vehicles, low-sulfur test fuel was estimated to reduce cold drive CO emissions by 45% to 64% and hot start CO emissions by 67%.
- Significant emissions benefits on the above cycles were also observed for THC and NOx and were greatest for the newer vehicles. As with CO, the emission

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* In Fairbanks, 5-10 minute warmup idle after prolonged soak is the rule rather than the exception, even with plug-in. Plug-in allows the engine to start. Other warmup idle activity may have more to do with allowing time for clearing windows, unplugging and stowing extension cord, and increasing the cabin temperature for passenger comfort.

† None of the other studies cited were Alaska specific, and it is reasonable to suppose (and has been confirmed in previous studies for FNSB and ADEC) that vehicles subjected over their lifetimes to extreme cold temperatures, extended idle, and other conditions in Alaska may have different emissions from vehicles that have not been subjected to such conditions.

benefits for older vehicles were smaller and, in some instances, not statistically significant.

- During the start plus five-minute warmup idle portion of the test cycle, CO emissions were significantly increased (by 30%) for MY 1996 and later vehicles. This CO disbenefit was concentrated in the initial 60 seconds of the cold-start idle period. There was no net increase or decrease in CO emissions during the remaining 240 seconds of the idle period.

- CO emissions tended to fall on subsequent cold-start tests, but appeared to stabilize at levels still higher than the average on high-sulfur fuel. For most vehicles, the series of hot-start tests on low-sulfur fuel were conducted immediately after the initial cold-start test and may have contributed to improving the vehicle conditioning to low-sulfur fuel.

- The presence of the CO disbenefit (and a correlated NOx benefit) was unexpected because technical considerations suggest little or no potential for catalyst activity to influence emissions during the cold engine startup and five-minute idle period.

- The CO disbenefit is likely due to inadequate vehicle conditioning after the fuel change and either the unusually aggressive driving during the sulfur reduction drive or some unidentified change in fuel property.

- All of the aforementioned percentage changes in emissions apply to the switch from commercial fuel to low (1.9 ppm) sulfur test fuel. We estimate that switching from commercial fuel to 30 ppm "compliance" fuel (as required by the USEPA) would reduce all of the projected changes by about 17% (i.e., hot start CO emissions for MY 2001 and later vehicles that were reduced by 66.7% on low-sulfur test fuel would be reduced by 55% [66.7x(1-0.17)] when using average 30 ppm sulfur compliance fuel).

- Measured emissions benefits (percentage reductions in emissions) were not significantly different for cars and trucks.

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6. QUANTIFYING EMISSION BENEFITS IN ALASKA

While the previous chapter documented average results from emission testing, an additional objective (Task 6) of the current study, and the subject of this section, is to quantify the fleet emission benefits, i.e., to determine the effect of low-sulfur gasoline upon the emission inventory (i.e., change in tons of emissions per winter day). The focus here is on the Fairbanks on-road vehicle emissions inventory for CO in calendar years 2005 and 2010. (CO is the primary pollutant of interest in Alaska; thus, vehicle fleet emission impacts were determined only for CO under this effort.) The section begins by reviewing MOBILE6 and AKMOBILE6 methodologies for computing emissions, and then discusses integration of the current measurement-based study results into MOBILE and the outcome from that integration.

6.1 MOBILE6 and AKMOBILE6 Methodologies and Outputs

MOBILE6 – MOBILE6 allocates vehicle exhaust emissions to either the "extra" emissions associated with an engine start (i.e., start emissions) or the "base" emissions associated with travel (i.e., running emissions). The distinction between start and running emissions is important because start emissions are sensitive to the "soak time" (i.e., the period of time a vehicle is at rest prior to the start), while running emissions are not. The split between running and starting emissions also provides a basis to separately account for the effects of other variables such as ambient temperature and changes in fuel composition. EPA's federal test procedure (FTP) brackets the range of start emissions that can be expected in customer service by measuring start emissions from a full "cold" start (i.e., after a 12-hour soak that is representative of a vehicle parked overnight) and from a full "hot" start (i.e., after a 10-minute soak that is representative of chained trips where the vehicle is fully warmed up). Separate characterizations of cold and hot starts and running emissions provide the basis for representing exhaust emissions under different operating conditions (e.g., morning commute, freeway operation, mid-day trips, etc.).

To understand how MOBILE6 quantifies start and running emissions, it is first necessary to understand how EPA collects the test data used to calculate those estimates. All vehicles are certified to the FTP, which is a test procedure that represents a driving pattern in Los Angeles (referred to as the "LA4" drivecycle) in 1975. The LA4 is a 7.5-mile trip that includes two segments: the start segment, which includes the start (either cold or hot), lasts 505 seconds, and is 3.59 miles long; and the running segment (i.e., the second half of the trip), which lasts 867 seconds and is 3.91 miles long. EPA typically collects bag measurements in the following sequence: the first trip is a cold start after a 12-hour soak, which captures Bag 1 and Bag 2 emissions over the entire LA4; at the end of the first trip the engine is turned off and the vehicle soaks for 10 minutes and is then restarted and the vehicle is driven for the first 505 seconds/3.59 miles of the LA4 and Bag 3 emissions are collected. This second trip is commonly referred to as the "hot 505."

To save resources, emissions from the running portion of the second trip (the hot start trip) were not collected. This is because the engine is considered to be fully warmed up at the end of either a cold start or a hot start; thus, the running emissions from the cold start trip can be weighted together with the hot start test to represent emissions from a full hot start LA4 trip. The procedure used to weight the three bags to create an average of cold and hot start tests is as follows:

- Data collected by EPA indicate that, on average, 43% of trips are cold starts and 57% are hot starts.
- FTP Bag 1 weighting = 43% * (3.59 miles / 7.5 miles) = .206
- FTP Bag 3 weighting = 57% * (3.59 miles / 7.5 miles) = .273
- FTP Bag 2 weighting = (43% + 57%) * (3.91 miles / 7.5 miles) = 0.521

Using the above weighting factors, the following is the standard weighting of the 3 bags, reported in grams per mile, for the full FTP:

- FTP = (Bag 1 * 0.206) + (Bag 2 * 0.521) + (Bag 3 * 0.273)

In developing MOBILE6, EPA recognized that FTP data do not allow a precise separation of start and running emissions since Bags 1 and 3 contain a mixture of both start and running emissions. Bag 2 provides no insight into start emissions, as it does not contain an engine start and its driving cycle is considerably different from the cycle used for Bags 1 and 3. Therefore, to estimate the amount of FTP emissions that can be allocated to an engine start, EPA determined that emissions from a new cycle would be needed. That cycle is referred to as the Hot Running 505 (HR505). It is an extra 505-second cycle performed immediately after Bag 3 of the FTP. It uses an identical driving cycle as the first and third bags of the FTP, but does not include an engine start. Emissions collected/estimated for this cycle can be subtracted from Bags 1 and 3 of the FTP to quantify the start increment following a 12-hour soak and a 10-minute soak. The approach EPA used to develop this increment was to collect data for a sample of 77 vehicles and extrapolate the results to a larger data set. For some of the FTP tests, the predicted HR505 emissions were higher than the Bag 1 and/or Bag 3 emissions. This caused the start increment to be negative for these vehicles. EPA retained the negative values for all technology categories except those with small sample sizes.

Thus, the start emission increment following a 12-hour soak, is defined as:

Start Increment (grams) = [(Bag1 g/mi) – (HR505 g/mi)] × (3.59 mi)

MOBILE next adjusts start increment for soak times on the order of one minute to 12 hours based on a two-point curve fit that derives its shape from California emissions versus soak time data.

In summary, MOBILE6 separates emissions into two categories: (1) the start increment, as described above; and (2) running emissions, which are emissions from Bag 2 and Bag 3 of the FTP.

AKMOBILE6 - AKMOBILE6 was developed[26] in 2004 for ADEC to account for shortcomings in MOBILE6 when estimating on-road vehicle CO emissions under Alaskan wintertime conditions. MOBILE6 does not adequately address two very common wintertime vehicle operating practices in Alaska that significantly affect CO emissions:

1. Extended initial idling of vehicles to warm them up prior to travel; and

2. Use of "plug-in" heaters to keep the engine warm while parked for long periods to aid cold start drivability.

As summarized earlier in this section, vehicle emission factors in MOBILE6 are based on the driving trace in the FTP, which contains only about 20 seconds of initial idling. During winter in Alaska, vehicles are often idled for periods of up to 20 minutes, especially when cold-started after being parked for several hours or more. Under these conditions, initial idling emissions are significant. And depending on the length of the idling period (and thus the degree the engine and catalyst warm-up), this can also affect the amount of emissions during the ensuing "traveling" portion of a vehicle trip.

Unlike MOBILE6, AKMOBILE directly accounts for the effects of the use of "plug-in" heaters, which are common in Alaska during wintertime. As the name implies, plug-in heaters are small devices that are retrofitted on many vehicles in Alaska and, by being plugged into a nearby electrical outlet, partially warm the engine (and contained fluids) and maintain it at a minimum temperature well above the ambient temperature, which can drop to below -50°F. Plug-in heaters are used primarily to maintain vehicle startability when parked for extended periods (more than a few hours) under extreme cold temperatures.

AKMOBILE6 uses warm-up idle CO emission measurements collected in testing programs under winter conditions in Alaska[27] to represent initial idling emissions as a function of two variables: (1) the preceding soak time (i.e., the period over which the vehicle was shut off prior to the trip); and (2) the initial idle time. AKMOBILE6 then accounts for the amount of engine and catalyst warm-up that occurs during the initial idling period using a "thermal state" tracking methodology. This methodology employs engine and catalyst warm-up and cool-down relationships derived from the Alaska testing programs to calculate a vehicle's thermal state* at two points in time: (1) prior to initial idling (reflecting soak effects); and (2) after initial idling and just prior to the traveling portion of the vehicle trip (reflecting initial idle warm-up effects). Based on the thermal state after initial idling, AKMOBILE6 recalculates the MOBILE6 soak time adjustment factor to account for the amount of warm-up that occurred during initial idling. (This recalculation is necessary since MOBILE6 assumes no initial idling.) The recalculated soak time factor is then used exactly as in MOBILE6 and accounts for incremental "start" emissions reflecting the level of warm-up of the vehicle over the remaining traveling portion of a trip.

Emission impacts from use of a plug-in heater are modeled in AKMOBILE6 on the basis of data from paired warm-up idling and transient driving emission tests of the same vehicles both with and without being plugged in that were collected in the aforementioned Alaska testing programs. (Since plug-ins keep the engine warmer than ambient temperature, they provide a significant emission benefit compared to a vehicle that was started and driven after a long soak under ambient conditions.) Relative benefits (in percent) calculated from the paired with and without plug-in measurements were applied in AMOBILE6. Plug-in CO benefits during initial idling were defined as a function of model year range and average just over 50%. During the traveling portion of a trip, AKMOBILE6 applies roughly a 20% CO benefit for plug-ins, independent of model year.

AKMOBILE6 was designed as a "shell" program that operates around MOBILE6, and actually runs MOBILE6 during its execution. (AKMOBILE6 input files are compatible with MOBILE6. AKMOBILE6 files can be processed by MOBILE6 since MOBILE6 ignores the "extra" inputs used by AKMOBILE6 to model initial idling and plug-in effects.) AKMOBILE6 is intended only to represent wintertime Alaskan vehicle operation (e.g., initial idling and plug-in use) and thus generates emission factors only for CO. In addition, AKMOBILE6 supports only one kind of MOBILE6 output, called "spreadsheet" output. In this format, two separate types of CO emission factors are output by AKMOBILE6:

1. Initial idling factors (in grams per trip); and
2. Traveling emission factors (in grams per mile).

Note that the traveling or "on-road" emission factors are composite factors that include both the "base" running (i.e., fully warmed-up) emission factor and start increment as calculated in MOBILE6 (using adjusted soak factors supplied by AKMOBILE6). For

* The thermal state is quantified using a set of continuous functions that return a value between zero (reflecting a fully-warmed vehicle) and one (reflecting a completely cold vehicle, e.g., when soaked overnight).

reasons described later in Section 6.2, supplemental MOBILE6 runs were used to produce separate outputs of running and start increment emission factors using the "DATABASE EMISSIONS" command to produce separate exhaust "running" (i.e. stabilized) and "start increment" emission factors.

The AKMOBILE6 and MOBILE6 models were executed and combined with the results from the low-sulfur gasoline testing program in order to translate the impacts of low-sulfur gasoline into fleet-wide on-road vehicle emission impacts using the same vehicle activity and operating assumptions as contained in the Fairbanks CO Maintenance Plan inventory. This integration of study results with the emission factor models to calculate low-sulfur gasoline impacts that are consistent with the planning inventory is described in the following sub-section.

6.2 Integration of Study Results with Emission Factor Models

As described earlier in Section 4, vehicle emissions were measured in the testing phase of the study with and without low-sulfur gasoline over the following test segments:

- Cold Idle – engine start up followed by 5 minutes of idle at the beginning of the cold start test;
- Cold Drive – the simulated 4.7-mile ADC driven during the cold start test after the initial 5-minute idle is concluded; and
- Hot-Start – the complete hot start test, including emissions generated during engine start and the simulated 4.7-mile ADC.

Table 6-1 shows average measured emission levels and percentage benefits by model year group with and without low-sulfur (1.9 ppm) gasoline for each of the above test segments. Table 6-1 is an expanded version of Table 5-1 shown earlier in Section 5.2 that also includes emission levels as well as the relative benefits (i.e., percentage impacts) of low-sulfur gasoline.

As explained earlier in Sections 3.5 and 5.1, the test segments listed in Table 6-1 were selected to measure emissions during different operating "events" that typically occur under Alaskan wintertime in-use driving. Although these test segments are typical or common, they do not represent the entire spectrum of in-use vehicle operation that must be accounted for when calculating an on-road emissions inventory. For example, although the average idling period for cold-started vehicle trips that include extended initial idling is about five minutes, a number of vehicle trips exhibit both shorter and longer initial idling times. (Vehicles that are parked for shorter periods or are parked in a partially heated environment such as a garage do not need to be initially idled as long. Conversely, vehicles parked for longer periods [e.g., overnight] or in extremely cold temperatures [below 0°F] are often idled for periods up to 20 minutes.)

Table 6-1 Average Measured CO Emissions With and Without Low-Sulfur Gasoline by Test Segment and Model Year Range				
Test Segment	Model Year Group	"High"[a] Sulfur CO (grams)	Low[b] Sulfur CO (grams)	% Change (from High Sulfur)
Cold Idle	Pre-1996	170.9	170.2	-0.4%
	1996-2000	67.6	87.6	29.7%
	2001and Later	43.4	56.3	29.7%
Cold Drive	Pre-1996	29.2	25.2	-13.6%
	1996-2000	5.5	3.1	-44.6%
	2001and Later	5.7	2.1	-64.0%
Hot Start	Pre-1996	17.8	14.2	-20.3%
	1996-2000	4.3	1.4	-66.7%
	2001and Later	2.0	0.6	-66.7%

[a] Baseline or "as-received" fuel.
[b] Tested 1.9 ppm low-sulfur fuel.

In the emission inventory generated for the Fairbanks CO Maintenance Plan,[28] vehicle activity was categorized into 14 distinct trip types representing different trip purposes (e.g., home-based work trips), parking locations (garaged or outside), plug-in heater usage, park (i.e., soak) period, ambient temperature, and initial idling time. Table 6-2 lists these trip types.

Table 6-2 Fairbanks On-Road Vehicle Inventory Trip Types and Characteristics						
Trip Type	Direction	Location	Plug-In?	Soak Time (hrs)	Soak Temp (°F)	Initial Idle (min)
HBW1	Home to Work	Garage	No	10	50	0.5
HBW2	Home to Work	Outside	Yes	10	20	5.0
HBW3	Home to Work	Outside	No	10	20	5.0
HBW4	Work to Home	Outside	Yes	8	20	5.0
HBW5	Work to Home	Outside	No	8	20	5.0
HBW6	Work to Home	Outside	Yes	4	20	5.0
HBW7	Work to Home	Outside	No	4	20	5.0
HBO1	Home to Other	Garage	No	10	50	0.5
HBO2	Home to Other	Outside	Yes	10	20	5.0
HBO3	Home to Other	Outside	No	10	20	5.0
HBO4	Other to Home	Outside	No	2	20	5.0
NHB1	Other to Other	Outside	No	0.5	20	0.5
NHB2	Other to Other	Outside	No	1	20	0.5
NHB3	Other to Other	Outside	No	2	20	1.0

As explained earlier in Section 6.1, AKMOBILE6 (in conjunction with MOBILE6) was designed to calculate CO emission factors for an entire vehicle fleet under any given operating conditions such as soak (i.e., parked) time, initial idling time, and ambient temperature. These emission factors are computed for three separate operating/emission modes: (1) initial idling; (2) traveling-start increment; and (3) traveling-stabilized. In calculating an emissions inventory, vehicle activity data (e.g., trips or vehicle miles traveled) for each trip type shown in Table 6-2 are combined with the appropriate AKMOBILE6 emission factors that represent the park/soak, ambient temperature, and initial idling characteristics of each trip type. The emissions for each trip type are then totaled across all trip types to estimate total on-road emissions.

Thus, the results from the testing program had to be translated into operating modes employed in the AKMOBILE6 and MOBILE6 models.

Issues and Their Effects in Translating Test Results – A number of key issues and their effects were considered in translating the test results into a framework that could be properly used within the AKMOBILE6 and MOBILE6 models for calculating the overall inventory-based CO impacts of low-sulfur gasoline. These issues are listed and summarized below.

Soak and Initial Idling Distributions – As introduced by the example above, the entire vehicle fleet exhibits a distribution of initial idling times that ranges from several seconds to 20 minutes. These idling times are generally related to the soak time (i.e., the length of time the vehicle was parked prior to its trip) and the ambient temperature during which the soak occurred. (Longer initial idling follows longer, colder soak periods and vice versa.) In order to optimize the number of different vehicles sampled, the testing program measured emissions over a single initial idling period of five minutes that was preceded by a "full" overnight soak. Thus, one question consists of the applicability of low-sulfur gasoline impacts measured during the five-minute "Cold Idle" test segment to other initial idling periods (and prior soak periods).

Warm-up Effects on "After-Idle" Traveling Emissions – Under the low-sulfur gasoline testing program, traveling emissions (i.e., those after initial idling) were measured over the transient Alaska Driving Cycle (ADC) under the Cold Drive and Hot Start test segments. As described in Section 4, the Cold Drive segment immediately follows the five-minute Cold Idle segment. The Cold Drive segment does not include engine cranking (which occurs during the Cold Idle phase), but it still reflects the fact that the vehicle is not fully warmed up since the Cold Idle was preceded by a long overnight soak. Conversely, the Hot Start segment includes cranking emissions (since it starts when the engine is restarted), but reflects a fully warmed-up vehicle.

As described earlier in Section 6.1, AKMOBILE6 (in conjunction with MOBILE6) quantifies the degree to which a vehicle is warmed-up after idling at the start of the "traveling" portion of a trip. This after-idle "thermal state" is used to calculate the starting emissions increment as defined in MOBILE6. Thus, the traveling emission factor calculated in AMOBILE6/MOBILE6 represents two separate components: (1) emissions of a fully warmed-up vehicle; and (2) "start" emissions that reflect the incremental emissions occurring when a vehicle's engine and catalyst are not fully warmed-up. Therefore, the low-sulfur gasoline test results for the Cold Drive segment had to be translated to a basis that reflects these warmed-up and start increment components.

Impacts of Low-Sulfur Gasoline on Plug-In Benefits – Again to optimize the tested sample, all vehicles were plugged in to an engine pre-heater prior to measuring emissions with and without low-sulfur gasoline. As such, there was no way to explicitly quantify separate low-sulfur gasoline impacts of vehicles not plugging in while parked prior to trip making. As described in greater detail later in this sub-section, about half of the wintertime vehicle trips in Fairbanks are preceded by outdoor plug-in or garaged soaks,[*] while the remaining trips are not plugged in. Thus, the measured results had to be translated in a manner that minimized the bias of plug-in only testing.

Fleet Effects – As described earlier in the report, the low-sulfur gasoline vehicle procurement and testing was done on the basis of representing three separate model year groups:

1. Pre-1996 models;
2. 1996-2000 models; and
3. 2001 and later models.

Since the low-sulfur gasoline testing was conducted during winter 2005-2006, these model year ranges represent vehicle age ranges of 11 years or more, 6-10 years, and 5 years or less, respectively.

Conversely, AKMOBILE6 was developed based upon warm-up idle testing conducted largely during winter 1998-1999 and stratified warm-up idling and plug-in benefits on the basis of three different model year groups:

1. Pre-1988 models;
2. 1988-1993 models; and
3. 1993 and later models.

These AKMOBILE6 groups at the time of the warm-up idle testing corresponded to similar vehicle age ranges of 12 years or more, 7-11 years, and 6 years or less, respectively.

Measured emissions from both the Low-Sulfur Gasoline and Warm-Up Idle testing programs represent "snapshots" of emissions that existed in the vehicle fleet at the time of testing. The data from each testing program were separated into model year groups to explicitly account for technology differences and in-use deterioration[†] effects.

[*] Garaged soaks are similar to outdoor plug-in soaks in keeping the vehicle warmer than the outdoor ambient temperature.
[†] Vehicle emission controls (e.g., the catalyst) deteriorate in their control efficiency with vehicle age and use (mileage).

In AKMOBILE6, initial idling emissions developed from the Warm-Up Idle testing were scaled in future calendars beyond the 1999 timeframe to reflect the combined impacts of technology improvements, deterioration with age, and fleet turnover effects. (These scaling factors were based on outputs from MOBILE6.) Thus, one must consider how impacts from the low-sulfur gasoline testing might be expected to change over time.

In addition, since the low-sulfur gasoline test measurements were conducted on a limited sample of vehicles, the measured results had to be translated using an approach that minimized small sample bias when comparing emissions to model-based estimates that more robustly represent the entire vehicle fleet and in-use deterioration.

Translation of Low-Sulfur Gasoline Test Results to AKMOBILE6 Framework – The first step in integrating the measured test results shown earlier in Table 6-1 into emission inventory impacts consisted of translating these results into operating modes employed in the AKMOBILE6 and MOBILE6 inventory models.

As explained earlier, AKMOBILE6 computes initial idling emissions (in grams/trip) as a function of soak time and idling time. After calculating how warmed-up a vehicle is after idling, it uses MOBILE6 to calculate the traveling (i.e., the portion of the trip after initial idling) emission factor (in grams per mile). Within MOBILE6, the traveling emission factor is made up of two components: (1) the fully warmed-up or "stabilized" emission rate; and (2) the start increment reflecting higher emissions when a vehicle is not fully warmed-up. Thus, measured Cold Idle, Cold Drive, and Hot Start test results were used in the following manner to best "mesh" with AKMOBILE6.

First, the relative (i.e., percentage) impacts of low-sulfur gasoline by model year group from the Cold Idle segment were applied to the initial idle emission estimates produced by AKMOBILE6 assuming baseline "high" sulfur fuel. (AKMOBILE6 was executed separately for the three model year groups defined under the low-sulfur gasoline test program in order to apply the relative low-sulfur gasoline impacts of each group measured in the testing.) For example, assume AKMOBILE6 calculated initial CO idling emissions of 50 grams (per trip) with baseline fuel for a 1996-2000 model year vehicle that was parked for eight hours and then began its trip with a five-minute initial idle. The relative Cold Idle low-sulfur impact for the 1996-2000 model year group shown earlier in Table 6-1 was 29.7%, indicating an emissions increase (or disbenefit) with low-sulfur test fuel for that model year group. As explained in Section 5.2, a factor of 0.83 was then applied to adjust the relative impacts from the 1.9 ppm test fuel to 30 ppm compliance fuel; thus, for this example, the relative CO idling impact using compliance fuel was estimated to be 24.6% (29.7% × 0.83). This compliance fuel-adjusted relative impact was then applied to the AKMOBILE6 baseline fuel emission factor of 50 grams per trip to estimate initial CO idling emissions using low-sulfur compliance fuel of 62.3 grams per trip (50 × [1 + 0.246]).

As explained in Section 5.2, the test results exhibited a CO disbenefit (i.e., increase) from the use of low-sulfur gasoline during the Cold Idle test segment for the newest model year groups. An examination of second-by-second emission test results showed that this disbenefit largely occurred well within the first minute of idling. Therefore, it was assumed that the relative impacts from the five-minute Cold Idle test segment could be reasonably applied over a broader range of idling periods modeled in the emissions inventory (e.g., from just under a minute to five minutes or more). This assumption and use of the Cold Idle test results on a relative (rather than absolute) basis enabled the low-sulfur gasoline impacts measured during initial idling to be consistently applied to idle emission factors from AKMOBILE6 for a variety of trip types (with differing soak and initial idling periods) in the emissions inventory.

Second, measured CO emissions by model year group from the Hot Start test segment were subtracted from Cold Drive segment to determine start increment impacts for use with AKMOBILE6. These calculations are shown below in Table 6-3.

Table 6-3
Calculation of Low-Sulfur Gasoline Start Increment Impacts by Model Year Range

Test Segment	Model Year Group	High Sulfur CO (grams)	Low Sulfur CO (grams)	% Change (from High Sulfur)
Cold Drive	Pre-1996	29.2	25.2	-13.6%
	1996-2000	5.5	3.1	-44.6%
	2001and Later	5.7	2.1	-64.0%
Hot Start	Pre-1996	17.8	14.2	-20.3%
	1996-2000	4.3	1.4	-66.7%
	2001and Later	2.0	0.6	-66.7%
Start Increment	**Pre-1996**	**11.4**	**11.1**	**-3.1%**
	1996-2000	**1.3**	**1.6**	**29.5%**
	2001and Later	**3.8**	**1.4**	**-62.5%**

The Cold Drive and Hot Start test results in Table 6-3 are carried over from Table 6-1 to show how the start increment impacts were determined. As shown in Table 6-3, measured CO emissions (in grams) from the Cold Drive segment were subtracted from the Hot Start segment by model year group. This was done separately for emissions measured with high- (as-received) and low- (1.9 ppm) sulfur test fuels. For example, the high-sulfur start increment was calculated as 11.4 grams (29.2-17.8) for the pre-1996 model year group. In the inventory calculations, the start increment low-sulfur gasoline impacts were then expressed on a relative basis (shown in the rightmost column in Table 6-3) by model year group and applied to the start increment emission factors generated by MOBILE6.*

* As explained earlier, AKMOBILE6 generates a combined "traveling" emission factor that represents emissions (in grams/mile) for the remainder of a vehicle trip that follows initial idling. Supplemental MOBILE6 runs were used to separate this traveling emission factor into its two component parts: (1) start increment; and (2) stabilized.

Finally, the measured results for the Hot Start test segment were used to apply low-sulfur gasoline benefits to stabilized (fully warmed-up) running emission rates contained in MOBILE6. As with the other operating modes, the results were applied on a relative basis by model year group. For example, the relative low-sulfur fuel impact of -66.7% for 2001 and later model year vehicles shown for the Hot Start test in Table 6-3 was applied to MOBILE6 stabilized emission factors to model the impact of low-sulfur gasoline on the stabilized portion of the trip for that model year range.

As with idling emissions, the relative impacts for the start increment and stabilized emissions were also adjusted by a factor of 0.83 to account for differences in sulfur content between compliance and tested low-sulfur fuel (30 ppm vs. 1.9 ppm, respectively).

By translating the low-sulfur gasoline test results from actual emissions to <u>relative impacts</u> for each <u>operating mode</u> defined in AKMOBILE6/MOBILE6, the <u>measured</u> impacts of low-sulfur fuel could be compared on a consistent basis with the <u>model</u>-based CO emissions inventory. By running AKMOBILE6 separately for each model year group defined in the low-sulfur gasoline testing, separate benefits (or disbenefits) by model year group were weighted together in proportion to the amount of travel represented in each group based on local fleet registration and mileage accumulation rate inputs to MOBILE6.

Having explained the basis for translating the low-sulfur gasoline test results into an AKMOBILE6 (and MOBILE6)-consistent framework, the actual calculation of Fairbanks vehicle fleet-wide CO emissions with baseline ("high" sulfur) gasoline and "compliance" (30 ppm S) low-sulfur gasoline is described below.

<u>Calculation of Fleet-Wide CO Emission Impacts of Low-Sulfur Gasoline</u> – Daily on-road vehicle emissions during wintertime in Fairbanks were calculated for baseline and low-sulfur compliant fuel scenarios in calendar years 2005 and 2010. Calendar year 2005 was selected for comparison to measured emissions under the 2005-06 Low-Sulfur Gasoline testing study. Fleet emissions were also calculated for calendar year 2010 to provide a longer-term estimate of the effects of low-sulfur fuel after full implementation.

Vehicle trip type and travel activity data consistent with the Fairbanks CO Maintenance Plan inventory for years 2005 and 2010 were used and are presented in Table 6-4.

Since low-sulfur gasoline impacts were quantified from the measurement study for three separate model year groups (pre-1996, 1996-2000, 2001 and later), separate AKMOBILE6 runs were executed for each of these model year groups. Travel fractions for each model year group (which differ by calendar year) were extracted from supplemental MOBILE6 runs by individual model year. These model year group travel fractions for each calendar year are presented in Table 6-5.

The Fairbanks vehicle fleet mix (i.e., the fraction of cars, light-duty trucks, heavy-duty trucks, etc.) used in the Maintenance Plan inventory was also applied under this analysis.

Table 6-4
Fairbanks On-Road Inventory Trip Types and Activity Data

Trip Type	Trip & VMT[a] Fraction	Year 2005 Daily Travel		Year 2010 Daily Travel	
		Trips	VMT[a]	Trips	VMT[a]
HBW1	0.120	27,613	94,773	29,348	100,727
HBW2	0.020	4,694	16,111	4,989	17,124
HBW3	0.010	2,209	7,582	2,348	8,058
HBW4	0.041	9,494	32,585	10,090	34,632
HBW5	0.022	5,003	17,171	5,317	18,249
HBW6	0.057	13,111	44,998	13,934	47,826
HBW7	0.030	6,909	23,712	7,343	25,201
HBO1	0.200	46,021	157,954	48,913	167,879
HBO2	0.034	7,824	26,852	8,315	28,539
HBO3	0.016	3,682	12,636	3,913	13,430
HBO4	0.250	57,527	197,443	61,141	209,848
NHB1	0.100	23,011	78,977	24,456	83,939
NHB2	0.060	13,806	47,386	14,674	50,364
NHB3	0.040	9,204	31,591	9,783	33,576
All	1.000	230,106	789,771	244,564	839,393

[a] VMT = Vehicle Miles Traveled.

Table 6-5
Travel Fractions by Model Year Group for Calendar Years 2005 and 2010

Model Year Group	Year 2005	Year 2010
Pre-1996	0.215	0.077
1996-2000	0.314	0.139
2001and Later	0.471	0.784
Total	1.000	1.000

On-road light-duty gasoline vehicle* daily emissions were calculated for Fairbanks during winter in calendar years 2005 and 2010. Slightly different approaches were employed for the 2005 and 2010 emission calculations, each of which is discussed separately below.

* Only light-duty gasoline vehicle (passenger cars and light-duty trucks) emissions were calculated since the testing study included only light-duty vehicles and since AKMOBILE6 was designed to represent initial idling only from light-duty gasoline vehicles. (AKMOBILE does represent traveling emissions from all vehicle types, including heavy-duty vehicles.) Thus, model-based emission totals shown in this section of the report will not perfectly match those in the Maintenance Plan inventory, which also includes heavy-duty vehicle emissions. However, the fraction of heavy-duty CO emissions is small (less than 10%). Therefore, exclusion of these vehicles will not demonstrably affect comparisons of the fleet impacts of low-sulfur gasoline.

Calendar Year 2005 Emissions – For the 2005 analysis, three emission scenarios were evaluated:

1. *Modeled-High (MDH)* – model-based emissions using baseline fuel;

2. *Modeled-Low (MDL)* – model-based emissions using low-sulfur fuel; and

3. *Measured-Low (MSL)* – emissions calculated by scaling the Model-High estimates using the <u>relative</u> low-sulfur impacts for each model year group and operating mode (initial idling, start increment, running) developed from the low-sulfur gasoline testing measurements (and adjusted to 30 ppm S).

These analysis scenarios were selected in order to compare "current" fleet impacts of replacing existing gasoline with Tier 2-compliant low-sulfur gasoline simulated by AKMOBILE6/MOBILE6 with those based on the actual low-sulfur gasoline test measurements. Relative (i.e., percentage) impacts based on <u>modeling</u> were developed from a comparison of fleet emissions under Scenarios 1 and 2. Relative impacts based on <u>measurements</u> were derived from a comparison of Scenarios 1 and 3. (Since measured impacts were applied to the "baseline" emissions as scaling factors under Scenario 3, an equivalent comparison of modeled and measured low-sulfur gasoline fleet impacts could be made.)

The model-based light-duty fleet emission estimates under Scenarios 1 and 2 were developed from AKMOBILE6 runs by model year group for each of the 14 Fairbanks trip types (representing unique soak, initial idling, and ambient temperature characteristics).

Under Scenario 1, baseline or "high" sulfur fuel was modeled assuming a 164 ppm sulfur level to match average values reported by Flint Hills Resources and the mix of regular and premium fuel use reported by recent Fairbanks telephone survey participants. The maximum fuel sulfur level for high-sulfur fuel was assumed to be 200 ppm. Scenario 2 is assumed to represent fully implemented low-sulfur compliance after EPA requirements take effect in 2006. Thus under Scenario 2, the average sulfur level was modeled at 30 ppm and the maximum sulfur level at 80 ppm to reflect complete Tier 2 compliance.

As stated earlier, AKMOBILE6 outputs two separate emission factors: (1) initial idling factors (in grams per trip); and (2) traveling factors (in grams per mile) that represent travel after initial idling. The Scenario 1 and 2 runs were also supplemented by MOBILE6 runs (using similar inputs) to separate the traveling emission factor into the start increment and stabilized (running) components. (This last step was done to "mesh" the model outputs with the relative low-sulfur gasoline impacts measured from the test program for use under Scenario 3.)

The emission factors described above were multiplied by the number of daily trips (for initial idling) and vehicle miles traveled or VMT (for start increment and running) shown for each trip type presented earlier in Table 6-4 to compute wintertime daily light-duty vehicle fleet CO emissions (in tons/day) under Scenarios 1 and 2. Fleet CO emissions were calculated under Scenario 3 by scaling the Scenario 1 results (by model year group) with the measurement-based relative low-sulfur gasoline impacts shown earlier in Tables 6-1 (for idle and running) and 6-3 (for the start increment).

The model-based baseline (Scenario 1) and low-sulfur fuel (Scenario 2) fleet emissions in calendar year 2005 are presented in Table 6-6. As shown in the table, emissions were calculated and tabulated by model year group and operating mode. Total emissions (across all model years) by operating mode and across all operating modes are shown in boldface at the bottom of Table 6-6.

Table 6-6
Fairbanks Light-Duty Gasoline Fleet CO Emissions (tons/day) in Calendar Year 2005

Model Year Group	Operating Mode	Model-Based Emissions (tpd)		Measured Low-Sulfur Gasoline Impacts (% Change[a])	Measured-Low (MSL) Emissions (tpd)
		Modeled-High (MDH)	Modeled-Low (MDL)		
Pre-1996	Initial Idle	1.64	1.64	-0.3%	1.63
	Running	4.02	3.32	-16.8%	3.35
	Start Incr.	4.09	4.27	-2.5%	3.98
1996-2000	Initial Idle	2.04	2.04	+24.6%	2.55
	Running	2.61	2.17	-55.1%	1.17
	Start Incr.	2.28	2.36	+24.4%	2.84
2001 and later	Initial Idle	2.46	2.46	+24.6%	3.07
	Running	1.53	1.03	-55.1%	0.69
	Start Incr.	3.56	2.19	-51.7%	1.72
All	**Initial Idle**	**6.15**	**6.15**	**-**	**7.25**
	Running	**8.16**	**6.53**	**-**	**5.20**
	Start Incr.	**9.93**	**8.82**	**-**	**8.54**
All	**All**	**24.23**	**21.49**	**-**	**20.99**
Fleet Low-Sulfur Gasoline Impact (% Change from Scenario1 Baseline)			**-11.3%**	**-**	**-13.4%**

[a] Percentage change from measured baseline "high" sulfur fuel and adjusted from 1.9 ppm S low-sulfur test fuel to 30 ppm S low-sulfur "compliance" fuel using 0.83 multiplier.

The right-most two columns in Table 6-6 show how measurement-scaled emissions were calculated under Scenario 3. The relative measured impacts (in the second column from the right) were multiplied by baseline Scenario 1 modeling emissions to calculate measurement-based fleet emissions shown in the rightmost column. This scaling was performed separately by operating model and model year range to reflect differing low-sulfur gasoline effects measured within these strata (e.g., disbenefits during idle and benefits during traveling). For example, running emissions for pre-1996 model year vehicles under Scenario 3 of 3.35 tpd were calculated by scaling the baseline Scenario 1 emissions (4.02 tpd) by the relative measured impact (1-16.8%, or 1-0.168).

Note that the baseline emissions do not exactly match those reported for all on-road vehicles in the Fairbanks Maintenance Plan inventory for 2005. This discrepancy is primarily due to the fact that this analysis examined only light-duty gasoline vehicle fleet emissions (instead of all on-road vehicles), but also reflects slight changes to other modeling inputs such as the baseline fuel sulfur content (Plan – 193 ppm, Low-Sulfur Gasoline Analysis –164 ppm) and I/M grace period (Plan –2 years, Low-Sulfur Gasoline Analysis – 4 years).

Low-sulfur gasoline fleet emission impacts relative to the Scenario 1 baseline are presented at the bottom of Table 6-6. As shown, the model- (Scenario 2) and measurement-based (Scenario 3) fleet impacts were calculated as 11.3% and 13.4% emission benefits, respectively, and are in reasonable agreement with each other. (This comparison is discussed in further detail in Section 6.3)

Calendar Year 2010 Emissions – Under the year 2010 analysis, only two scenarios were examined—Model-Low (MDL), and Measured-Low (MSL)—because a "high" sulfur baseline case in 2010 cannot be accurately modeled by AKMOBILE6/MOBILE6. (The models reflect the Tier 2 low-sulfur fuel phase in, which is complete by year 2008 and cannot properly represent baseline fuel sulfur emissions beyond 2006.)

As a result, the same scaling approach used for the year 2005 analysis to compute measurement-based low-sulfur gasoline emissions from the high-sulfur baseline emissions could not be applied for 2010. Instead, measurement-based low-sulfur emissions in 2010 were estimated by assuming the same ratios between measured and modeled low-sulfur fleet emissions in 2005 by model year group and operating mode are applicable in 2010.

The modeled low-sulfur emissions in 2010 were computed similarly to those in 2005 using AKMOBILE6 and MOBILE6, using the projected activity levels and model year group weightings for 2010 shown earlier in Tables 6-4 and 6-5, respectively.

These modeled low-sulfur emissions, the emission ratios described above, and resulting measured low-sulfur emission estimates for 2010 are presented in Table 6-7. As explained, measured low-sulfur emissions were estimated by applying the Measured/Model low-sulfur emissions from 2005 to the 2010 modeled emissions. For example, the start increment emissions for 1996-2000 model vehicles were calculated as 1.13 tpd by multiplying modeled emissions by the 2005-based ratio (0.94 tpd × 1.203).

Because of the ratio-based assumption used to generate measured low-sulfur emission estimates in 2010,[*] the estimates are in close agreement to modeled 2010 emissions seen in 2005.

A more thorough evaluation and comparison of the impacts of low-sulfur fuel on fleet CO emissions is presented in the following sub-section.

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[*] The 2010 Measured scenario is based on the ratio of 2005-Measured to 2005-Modeled. Thus, the only difference in 2005 and 2010 Modeled vs. Measured comparisons is due to fleet turnover.

Table 6-7 Fairbanks Light-Duty Gasoline Fleet CO Emissions (tons/day) in Calendar Year 2010				
Model Year Group	Operating Mode	Modeled-Low (MDL) Emissions (tpd)	2005 Measured-Low/ Modeled-Low Ratio	Measured-Low (MSL) Emissions (tpd)
Pre-1996	Initial Idle	0.43	0.997	0.42
	Running	1.00	1.009	1.01
	Start Incr.	1.14	0.934	1.07
1996-2000	Initial Idle	0.64	1.246	0.80
	Running	0.71	0.538	0.38
	Start Incr.	0.94	1.203	1.13
2001 and later	Initial Idle	2.90	1.246	3.61
	Running	1.56	0.664	1.04
	Start Incr.	3.27	0.784	2.57
All	**Initial Idle**	**3.96**	**-**	**4.83**
	Running	**3.27**	**-**	**2.43**
	Start Incr.	**5.36**	**-**	**4.77**
All	**All**	**12.60**	**-**	**12.03**

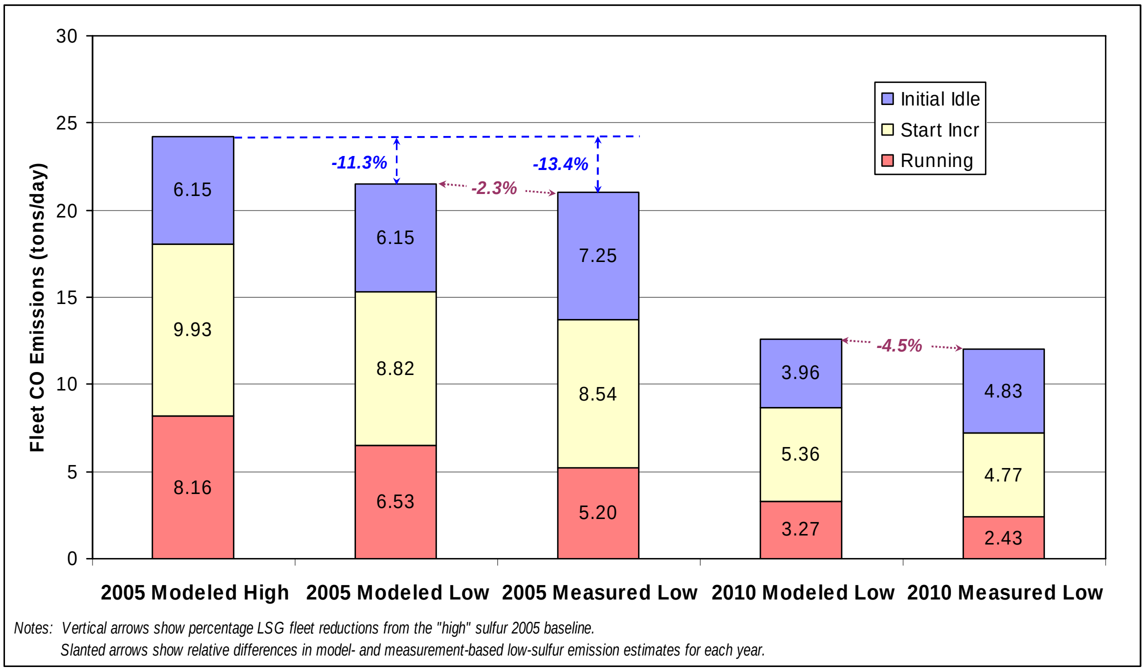
6.3 Interpretation of Fleet Inventory Impacts

As described in the Section 6.2, measurements from the low-sulfur gasoline test program were translated into a framework for comparison to AKMOBILE6/MOBILE6 modeling-based estimates of the impacts of low-sulfur gasoline on fleet emissions. A broader interpretation of these results is discussed here.

Figure 6-1 graphically summarizes and compares the key low-sulfur fuel impacts on Fairbanks light-duty vehicle fleet CO emissions quantified earlier. Winter daily emissions (using travel activity consistent with the Maintenance Plan inventory) are shown in segmented bar chart form for the three calendar year 2005 and two calendar year 2010 analysis scenarios considered: 2005 Modeled-High, 2005 Modeled-Low, 2005 Measured-Low, 2010 Modeled-Low, and 2010 Measured Low. ("High" and "Low" here refer to baseline gasoline and Tier 2-compliant low-sulfur gasoline, respectively.)

The segmented bars shown for each analysis scenario in Figure 6-1 represent the contributions by individual operating mode (initial idling, start increment, and running/stabilized) to the total fleet emissions. The percentages beside vertical arrows show the relative impacts of low-sulfur fuel (compared to baseline "high" sulfur fuel) on fleet CO emissions using AKMOBILE6/MOBILE6 model-based estimates and measurement-based estimates derived from the low-sulfur gasoline testing study. (These model- and measurement-based low-sulfur impacts are compared only for 2005 since the comparison is only relevant for calendar years before Tier 2 low-sulfur compliance occurs.) The percentages shown between slanted horizontal arrows denote the relative difference in measurement-based low-sulfur emissions to model estimates for each calendar year.

Figure 6-1
Comparison of Low-Sulfur Fuel Impacts on
Fairbanks Light-Duty Fleet CO Emissions (tons/day)



The results shown in Figure 6-1 and their underlying uncertainties are discussed below.

Consistency with EPA Model Impacts – The low-sulfur CO inventory impacts (from a high-sulfur baseline) contained in EPA's MOBILE6 model are quite consistent with those developed from emission measurements under the low-sulfur gasoline study. As shown in the calendar year 2005 scenarios contained in Figure 6-1, the relative model-based fleet emission benefits (reduction) were estimated at 11.3%, compared to 13.4% as derived from the test measurements. Given the range of uncertainties in the analysis (which are discussed later), these model- and measurement-based benefits are in reasonably good agreement.

Model-based low-sulfur impacts are contained only in MOBILE6, not AKMOBILE6. At the time AKMOBILE6 was developed, no direct measurements of low-sulfur impacts on initial idling were available. Although AKMOBILE6 was designed to account for plug-in benefits, oxygenated fuel benefits (where applicable*), and fleet turnover effects on initial idling, it did not include low-sulfur impacts because of the lack of data available at the time. Results from this effort should be integrated into an AKMOBILE6 revision that accounts for low-sulfur impacts during initial idling. This will effectively transfer the low-sulfur disbenefit now contained in the start increment for certain model years

* Oxygenated fuel is not used in Fairbanks.

(supplied by MOBILE6) to the initial idling portion of a vehicle trip in a revised version of AKMOBILE6.

Comparison with Actual Measurements – As discussed earlier in the report, the emission measurements recorded for Cold Idle, Cold Drive, and Hot Start test segments cannot be directly used to represent fleet-wide emissions from a variety of vehicle trips with different soak times, initial idling times, and plug-in usage. Given that a combination of low-sulfur emission benefits (reductions) and disbenefits (increases) was observed in the actual measurements, it is important to understand how and why the measurements were translated to a framework for use in assessing fleet inventory impacts.

From a simple tabulation of the average high- and low-sulfur emissions measured by model year group and test segment and reported earlier in Table 6-1, one might erroneously conclude that low-sulfur fuel produces a disbenefit because of the relative magnitude of measured Cold Idle CO emissions compared to the other test segments and the fact that these emissions were roughly 30% higher (for the newest two model year groups) when tested with low-sulfur fuel. There are several reasons for this apparent disconnect between "net" impacts seen from the direct measurements and those translated for use in the fleet inventory comparisons.

First, the test segments over which emissions were measured, though common, are not broadly representative of all trips (and soak, idling, plug-in effects) modeled in the fleet inventory. For example, as shown earlier in Table 6-2, vehicles exhibit a distribution of soak times and initial idling times. By contrast, the Cold Idle test segment was always run after a full overnight (12-hour or more) soak over a full five-minute idling period. This is not entirely representative of the broader spectrum of trip types in Table 6-2 that included a range of soak and idling times that were less than those in the Cold Idle test segment. In addition, the testing was conducted with all vehicles plugged-in during soaks. In a fleet inventory calculation, a mixture of plug-in and no plug-in soaks is represented.

Second, the Cold Drive test segment does not directly represent after-idle traveling emissions of all vehicle trips, but only those with a plugged-in overnight soak and five-minute idling period. Nor does the Hot Start segment represent all trips because it reflects a vehicle in a fully warmed-up state. The spectrum of trip types in Table 6-2 that are modeled in a fleet inventory calculation represents a range of vehicle warm-up states when the traveling portion of the trip occurs.

Finally, the roughly 50-60 vehicle sample size of the low-sulfur gasoline testing study may not be broadly representative of an entire vehicle fleet. Although the testing study was designed and executed to achieve specific sampling targets by model year group, there was no practical way to assess whether the resulting samples reflect the technology mix and in-use deterioration represented in the entire fleet.

Thus, because the range of soak and idling times was not varied in the low-sulfur gasoline testing program (and could not be due to resource limitations) and because the sampling bias is unknown, "direct" analysis of the low-sulfur gasoline emissions measurements (and resulting net low-sulfur impacts) may not necessarily correlate with inventory-based net impacts. These uncertainties are briefly explained below.

Test Result Translation Uncertainties – Because the testing program was designed and executed using a protocol of fixed soak periods and test segments, a number of uncertainties remained for which their impact on low-sulfur benefits could not be quantified. These are summarized below.

- *Plug-In Impacts* – All testing was performed with vehicles plugged-in during soaks. Thus, the analysis could not distinguish between low-sulfur impacts with and without plug-in during soaks.

- *Idle Period Variation Impacts* – As mentioned earlier in the report, examination of modal results found that low-sulfur disbenefits seen during the Cold Idle test segment were often confined to the first minute of the five-minute idling period. However, development of statistically significant and distinct low-sulfur impacts within the idling period was beyond the scope of this effort.

- *After-Idle Thermal State Impacts* – Similarly, low-sulfur impacts as a function of variations in the thermal state (i.e., level of warm-up) after-idling could not be reliably interpreted from the limited test measurements and fixed testing protocol. As stated in Section 6.2, it was simply assumed that the low-sulfur benefits derived from the relative impacts of the Cold Drive and Hot Start segments applied under all levels of after-idle warm-up.

Thus, since the fleet inventory analysis demonstrated reasonable agreement between modeled and measured low-sulfur benefits (11.3% vs. 13.4%, respectively) in light of these unquantifiable uncertainties, these differences are not yet statistically discernable. Until additional data can be gathered to isolate and quantify these uncertainties, we believe the AKMOBILE6/MOBILE6 model benefits of low-sulfur gasoline are reasonable and valid for Alaska.

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