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Fuel Oxygen Effects on Exhaust CO Emissions

Recommendations for MOBILE6

Report Number M6.FUL.002

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Objective

This document describes EPA's effort to estimate simple relationships between fuel oxygen content and exhaust carbon monoxide (CO) emissions as a function of vehicle technology, fuel blending scenario, vehicle emitter classification, ambient temperature, and oxygenate type for gasoline-powered vehicles. These relationships will be used in MOBILE6 to supplant the current estimates of the effects of oxygen on exhaust CO emissions. This report is divided into two major parts: the first part describes the methodology used to determine effects for Tier 0 and older vehicles and the second part outlines the methodology for Tier 1 and Low Emitting Vehicles (LEVs). An attached report provides more details of the analysis and the actual numbers to be used in MOBILE6 for Tier 0 and older vehicles.

Background

The Clean Air Act Amendments of 1990 mandated use of oxygenated gasolines in areas that did not meet the Federal ambient air standard for CO. Motor vehicle emissions are the primary source of ambient CO levels in most areas and CO is generally at its highest levels during the cold weather months. Oxygenated gasoline is designed to increase the combustion efficiency of gasoline, thereby reducing exhaust CO emissions.

As more and more areas of the country come into attainment with the current ambient CO standard, less emphasis has been placed on CO control in the on-highway fleet. However, accurate modeling of the impacts of oxygenated fuels is important for those areas that remain out of attainment for CO. The MOBILE5/MOBILE5B model is the standard tool currently available to make fleet-wide estimates of the effects of oxygenated fuels for area-wide inventories. MOBILE5/MOBILE5B estimates emission levels in grams of pollutant per vehicle mile (g/mi) under a wide variety of conditions.

MOBILE5/MOBILE5B estimates exhaust emission benefits of oxygenated fuels as a function of fuel oxygen content, baseline emission rate, and model year. Embedded in the model-year-specific corrections are assumptions regarding the interaction of specific vehicle technologies and specific oxygenates. However, MOBILE5/MOBILE5B predictions of oxygenated fuel CO benefits are not supported by current ambient CO monitoring data. For example, under the following conditions:

- An area without an Inspection/Maintenance (I/M) program that requires oxygenated fuel with 3.5 weight percent oxygen content,
- Calendar year 2000

MOBILE5B predicts a light-duty gasoline vehicle (LDGV) fleet-average CO reduction of approximately 33% due to: 1) relatively large benefits ascribed to oxygenated fuels in MOBILE5B for vehicles with high CO emissions, and 2) high deterioration rates predicted under a non-I/M case. Such large reductions are not supported by ambient CO monitoring data. For this reason, EPA is currently revisiting the oxygenated fuel adjustment factors for MOBILE6. This document presents EPA's final proposal for determining revised oxygenated fuel adjustment factors in MOBILE6.

EPA Preliminary Proposal for MOBLE6 on 10/1/97

At the October 1, 1997 MOBILE6 workshop held in Ann Arbor, MI, EPA presented its first-cut proposal for modeling the effects of fuel oxygenates on exhaust CO emissions. To keep the analysis as simple as possible while at the same time matching MOBILE6 predictions with ambient CO data, the following proposal was made:

- The recently developed CO exhaust emissions model would be used for 1988 and later model year Tier 0 vehicles[1].
- For 1981-1987 model year vehicles, a recent analysis performed for ARCO Chemical Company would be used. This analysis was performed by Air Improvement Resources using the California Air Resources Board predictive database[2].
- For all pre-1981 model year vehicles, EPA proposed using the current (MOBILE5a) estimates for older technology vehicles[3].

Table 1 summarizes the emission reductions associated with the approach outlined above.

Table 1
CO Emission Reductions Proposed for MOBILE6
Assumes Splash-Blended Fuels
Based on October 1, 1997 MOBILE6 Workshop

Model Year Group	2.7 wt% MTBE		3.5 wt% Ethanol	
	Normal	High	Normal	High
1988+	13.8 %	9.33 %	15.4 %	10.1 %
1981-1987	18.2 %		19.1 %	
Pre-1981 Open-Loop	26.9 %		34.9%	
Pre-1981 Non-Catalyst	18.9 %		24.5 %	

Some comments received since this proposal was made questioned whether use of the CO model and the methodology outlined above would provide the most accurate estimates of the effects of fuel oxygen on CO emissions. In response to these comments, EPA decided to use existing data to attempt an alternative, less-complicated "paired" data analysis (i.e., data pairs in which a vehicle was tested on both a baseline, non-oxygenated fuel and a corresponding oxygenated fuel with all other fuel parameters as matched as much as possible) to develop estimates of the impacts of fuel oxygen on CO emissions. Sierra Research conducted the bulk of the analysis and their final report is attached. The next section briefly describes the conclusions reached by Sierra Research. These conclusions have been reviewed by EPA. The last part of the report provides final estimates for scenarios that the Sierra report did not address, namely oxygen's effect on CO emissions from vehicles certified to Tier 1 and cleaner emission standards.

EPA's Proposed Final Methodology for MOBILE6

Pre-1981 Vehicles

Because new data on older technology vehicles (i.e., pre-1981 oxidation catalyst and non-catalyst vehicles) have not been collected in recent years and since the last version of MOBILE was developed, the CO emissions impacts for those vehicles will be based on EPA's 1988 Guidance Document on the emissions impacts of oxygenated fuels[3]. These impacts are already embedded in MOBILE5/MOBILE5B.

Tier 0 Vehicles (Model Years 1981-1994)

The attached report entitled "Effects of Fuel Oxygen Content on CO Emissions" (February 13, 1998) outlines the data sources, final methodology, and emission effects for Tier 0 and older vehicles that EPA proposes to insert into MOBILE6 for the effect of oxygen/oxygenates on exhaust CO emissions. A summary of the major conclusions reached in the report are as follows:

- For model years 1981-1994 (Tier 0 vehicles), the results described in the report apply for estimating effects of oxygen/oxygenates on exhaust CO emissions. Table 17 represents the effects that will be input into MOBILE6.

- The effect of oxygen content on exhaust CO emissions is linear for all model years.

- The percentage CO emissions impacts developed from FTP-composite data can be applied to both starting and running exhaust emission estimates.

- No clear, significant trends were found for the CO effects of oxygenates at different ambient temperatures. Thus, in MOBILE6, the effect of oxygen on exhaust CO emissions will be the same at all ambient temperatures.

- For fuels with the same oxygen content, the effect of the type of oxygenate (MTBE, ethanol, etc.) on exhaust CO emissions was found to be statistically insignificant. The exception to this finding is splash blended ethanol fuels qualifying for an RVP waiver. In this case, the emissions resulting from the RVP boost must be calculated and offset against oxygen-based exhaust CO benefits using the existent RVP flag in MOBILE.

- Sierra's analysis recommends that results in Table 18 of the attached report (which accounts for the RVP changes when splash blending) be used directly for ethanol splash blends at 75°F, a linear combination of the results shown in Tables 17 and 18 should be used for temperatures between 75°F and 45°F (where RVP will have a smaller effect on emissions than at 75°F), and the results in Table 17 should be used for temperatures less than 45°F since RVP will not have an effect on emissions at low ambient temperatures. EPA's proposal differs from what Sierra recommends. EPA's final proposal for ethanol splash blends is to use the results in Table 17 along with the RVP flag in MOBILE6 to offset any emission disbenefits accrued by elevated RVP levels in ethanol splash-blended fuels. This procedure will be explained in detail in the MOBILE6 User's Guide.

- The report does not address how to calculate effects for Tier1 and advanced technology vehicles due to the severe paucity of data for these types of vehicles. Estimating effects of oxygen on exhaust CO emissions for these class of vehicles is discussed below.

Tier 1 and Advanced Technology Vehicles

One other question that must be addressed relates to the oxygenated fuel CO emissions impact for vehicles certified to Tier 1 and lower emission standards. It is expected that the effects of oxygen on exhaust emissions will diminish with advanced technology vehicles since the oxygen effect is dependent on the inability of the engine to maintain the proper air-to-fuel ratio under all conditions. Due to improved engine technology, this inability has been decreasing over time and will continue to decrease. However, the question is to what degree. The only way to address this is to have oxygen-effect data on Tier 1 and advanced technology vehicles. There is only a minimal amount of data that allows for examination of these effects and those data will be used to bracket the possible oxygen-related CO emission impacts of these types of vehicles.

Available Data and Analysis

Six certified Tier 1 vehicles (five passenger cars and one Class 2 Light Duty Truck (LDT)) and six advanced technology vehicles (five prototype passenger car models and one prototype Class 1 LDT), not necessarily representing eventual production technology, were tested as part of the Auto-Oil program (technical bulletin 17) in which a baseline non-oxygenated fuel (Industry Average reference gasoline) was tested along with two reformulated fuels on a series of four vehicle fleets designed for progressively lower emission standards[4]. The two reformulated gasolines were a gasoline meeting 1996 California Phase 2 regulatory requirements (fuel C2) and a gasoline blended to the same specifications, but without an oxygenated component (fuel C1). The Industry Average gasoline represented a 1988 national average composition. It was found that CO emission differences between reformulated test gasoline C2 with oxygenate (MTBE at a 2 weight percent level) and a very similar gasoline C1 without oxygenate were generally not statistically significant.

The percent differences in exhaust CO emissions for the Tier 1 and advanced fleets is summarized in Table 2 below:

Table 2

Auto/Oil Technical Bulletin 19 Results for Effects of Fuel Oxygen (at a 2 weight percent level) on Exhaust CO Emissions for Tier 1 and Advanced Technology Fleet of Vehicles

Vehicle Fleet	Average CO Emissions for fuel C1* (grams/mile)	Average CO Emissions for fuel C2** (grams/mile)	Percent Difference in Emissions, C1–>C2
Certified Tier 1 Vehicles (n=6)	1.392	1.376	-1.20
Prototype Advanced Technology Vehicles (n=6)	0.893	0.902	+1.00

* Fuel C1 contains no oxygen
** Fuel C2 contains 11.2 volume percent (2 weight percent oxygen) MTBE oxygenate

It should also be noted that while oxygen was the primary fuel parameter varied between fuels C1 and C2, other parameters (sulfur, olefins, RVP) also varied slightly which could have confounded the effects of oxygen alone between these fuels on exhaust emissions. Thus, due to the small effects seen and the uncertainty in these effects, it will be assumed that the effect of oxygen on exhaust CO emissions from normal emitting Tier 1 vehicles (please see discussion below on high emitters for clearer definitions of emitter classes) is zero. These effects can be revisited and revised in the future, if necessary, as more data become available on the effects of oxygen on CO emissions from Tier 1 vehicles.

Recently, the Coordinating Research Council (CRC) performed a study[5] to examine the effects of fuel properties (mainly sulfur) on LEV certified vehicles. Specifically, the CRC study involved 6 Light Duty Vehicle (LDV) models which were certified for sale in California in 1997. Two vehicles from each model type were tested on seven fuels. One fuel was a California RFG with 40 ppmW sulfur, while another was the same fuel doped to 150 ppmW sulfur. The other five fuels were national average conventional gasolines, except that their sulfur levels were 40, 100, 150, 330, and 600 ppmW. The same base gasoline was used for all five of these fuels and the sulfur levels were varied by adding representative sulfur-containing hydrocarbons. The vehicles were leased from rental companies and averaged 10,200 miles of use. The vehicles were tested in an as-received condition and with their catalyst aged to 100,000 miles by the manufacturer of each vehicle. All testing was conducted at a single laboratory.

While sulfur was the main parameter varied and tested for its effect on emissions in the CRC program, emissions from the base fuel (containing no oxygenate–fuels C1 and C3 with sulfur levels of 30 and 150 ppmW, respectively) can be compared to the two CA RFG fuels with matching sulfur levels (fuels S1 and S2 containing 28 and 147 ppmW sulfur, respectively), to get a rough estimate of non-sulfur effects on emissions. The fuel properties for these fuels are listed in Table 3 below:

Table 3
Summary of Non- Sulfur Fuel Properties for
Fuels C1, C3, S1 and S2 from the CRC Testing Program

Fuel Property	Fuel C1 (sulfur = 30 ppmW)	Fuel S1 (sulfur = 28 ppmW)	Fuel C3 (sulfur = 150 ppmW)	Fuel S2 (sulfur = 147 ppmW)
RVP, psi	7.6-8.6	6.7-7.0	7.6-8.6	6.7-7.0
Aromatics, vol%	27-35	22-25	27-35	22-25
Olefins, vol%	6-14	4-6	6-14	4-6
MTBE, vol%	0.1 maximum (Taken as 0)	10.8-11.2 (Taken as 2 weight percent oxygen)	0.1 maximum (Taken as 0)	10.8-11.2 (Taken as 2 weight percent oxygen)
T50, F	210-220	200-210	210-220	200-210
T90, F	330-340	290-300	330-340	290-300

Since this is the only data available at this time on LEVs for the effects of oxygen addition on exhaust emissions, it will be used to gauge this effect. The discussion following the numbers in Table 5 outlines the difficulty in isolating an oxygen effect from these data. Emissions data are compared for fuels C1 and S1 and for fuels C3 and S2 in Table 4 for the 10K catalyst as well as the aged 100K catalyst. Table 5 shows the average effects of changing non-sulfur fuel parameters on exhaust CO emissions based on the average g/mile emissions shown in Table 4.

Table 4 Average CO Emissions in grams/mile for Fuels C1, C3, S1 and S3 from Vehicles with 10K and 100K Catalysts				
Vehicle Id	Fuel C1 10K/100K	Fuel S1 10K/100K	Fuel C3 10K/100K	Fuel S2 10K/100K
Escort	0.586/1.005	0.653/0.990	0.742/2.008	0.788/1.602
Taurus	0.349/0.439	0.457/0.588	0.395/0.723	0.599/0.885
Civic	1.055/1.983	1.007/1.912	1.374/2.355	1.433/2.283
Sentra	0.433/0.553	0.534/0.653	0.733/0.851	0.870/0.860
Camry	0.662/0.987	0.692/1.015	0.875/1.098	0.927/1.268
Metro	0.316/0.616	0.356/0.545	0.446/0.654	0.425/0.611

Table 5 Average Percent Change in CO Emissions for the Fuel Pairs C1/S1 (with Sulfur ~ 50 ppmW) and C3/S2 (with Sulfur ~150 ppmW) with 10K and 100K Catalysts				
Vehicle Type	Fuel C1—>S1		Fuel C3—>S2	
	10K Catalyst	100K Catalyst	10K Catalyst	100K Catalyst
Escort	11.4	-1.49	6.20	-20.2
Taurus	31.0	34.0	51.6	22.4
Civic	-4.54	-3.60	4.29	-3.06
Sentra	23.3	18.1	18.7	1.06
Camry	4.53	2.84	5.94	15.4
Metro	12.7	-11.5	-4.71	-6.57
Fleet Averages:	**13.1**	**6.4**	**13.6**	**1.5**

Table 5 indicates an overall increase in CO emissions when oxygen is added to base fuel regardless of the age of the catalyst. The Auto/Oil data in Table 2 also indicates a small insignificant increase in CO emissions when oxygen is added to base fuel. It is likely that the increase for LEVs in CO emissions in this test program is due to other-than-oxygen parameters changing in fuel combinations C1, S1 and C3, S2. Though LEV vehicles are expected to have a smaller response for the effects of oxygen on emissions, it is unlikely that oxygen will cause an increase in tailpipe CO emissions.

Thus, with this limited amount of data on these types of vehicles for the effects of oxygen on exhaust CO emissions, it will be assumed that the effects of oxygen addition on CO emissions from normal emitting LEV vehicles (see discussion below on high emitters for more details on emitter class definitions) is zero. This effect can be revisited and revised, if necessary, as more testing data becomes available on the effects of oxygen alone on advanced technology vehicles.

High Emitters

Tier 0 CO high emitters (defined as any vehicle emitting more than 7 grams/mile on base, non-oxygenated fuel) were seen in Table 17 of Sierra's report to have slightly different emission effects than Tier 0 normal emitters. However, there is no test data available on the effects of Tier 1 and LEV "higher" emitters. There are several ways to define higher emitters for these advanced technology vehicles. However, since we have data only on the effects of Tier 0 higher emitters (in the attached report the nomenclature for this is "1981 + TWC/CL systems"), it will be assumed that the higher emitter effects of oxygen on exhaust CO emissions can be applied only to those Tier 1 and LEV vehicles that are higher emitters as defined for Tier 0 (CO emissions on base fuel must be 7 grams/mile or higher). All other Tier 1 and LEV vehicles will be considered to be normal emitters for which the effects of oxygen on exhaust CO emissions will be zero.

Summary

Table 6 (next page) summarizes the effects from the addition of oxygen on exhaust emissions for all vehicle technologies, oxygenate type, oxygen content of fuel, and vehicle emitter classifications.

Table 6 Recommended CO Effects (CO Impact (in percent) Per Weight Percent Oxygen) From the Use of Oxygenated Fuels on Light-Duty Gasoline Powered Vehicles			
Emitter Classification	Vehicle Technology	Start Emissions	Running Emissions
Normal Emitting Vehicles (CO Emissions on base, non-oxygenated fuel of ≤ 7 grams/mile)	LEV and Advanced Technology (Year 1999+)	0.00	0.00
	Tier 1 (1994-1999)	0.00	0.00
	1988 + TWC/ADL	-3.10	-3.10
	1986-1987 TWC/ADL	-4.80	-4.80
	1986+TWC/No ADL	-5.70	-5.70
	1981-1985 TWC/CL	-4.0	-4.0
	OX/OL	-9.40	-9.40
	Non-Catalyst	-6.60	-6.60
Higher Emitting Vehicles (CO Emissions on base, non-oxygenated fuel of > 7 grams/mile)	LEV and Advanced Technology	-5.30	-5.30
	Tier 1	-5.30	-5.30
	1981 +	-5.30	-5.30
	OX/OL	-9.40	-9.40
	Non-Catalyst	-6.60	-6.60

Some notes on the entries in Table 6:

- LEV stands for “Low Emitting Vehicles”
- TWC stands for “three-way catalysts”
- ADL stands for “adaptive learning”
- OX stands for “oxygen sensors”
- OL stands for “open loop” operation
- The entries under the “OX/OL” and “Non-Catalyst” are already programmed into MOBILE5. The same numbers will be used in MOBILE6.
- The numbers from Table 6 must be used in conjunction with the RVP flag (which will be unchanged from MOBILE5) for fuels in which the RVP increases significantly upon addition

of oxygenate, specifically for splash-blended ethanol fuels. Details will be provided in the guidance document.

- The numbers in Table 6 will be used at all ambient temperatures (no temperature correction factors for the effect of oxygen/oxygenates on CO emissions)
- With the exception of splash-blended ethanol fuels, all oxygenates will be treated the same and only the oxygen content of a fuel will determine exhaust CO emission effects as identified by the emission factors in Table 6.
- The CO effects of oxygenates on Light-duty trucks (LDTs) and heavy-duty gasoline vehicles (HDGVs) will be assumed to be the same as the effects on LDVs

References

1. Rao, V., "Development of an Exhaust Carbon Monoxide Emissions Model," SAE Paper No. 961214, 1996.

2. Rykowski, R., Air Improvement Resources Draft Analysis: "Effect of Oxygenated Gasoline on CO Emissions Based on the ARB Predictive Model Database for Older Vehicles," for ARCO Chemical Company, September 1997.

3. "Derivation of Technology Specific Effects of the Use of Oxygenated Fuel Blends on Motor Vehicle Exhaust Emissions," U.S. Environmental Protection Agency, October 1988.

4. "Auto/Oil Air Quality Improvement Research Program, Technical Bulletin No. 17: Gasoline Reformulation and Vehicle Technology Effects on Exhaust Emissions," Coordinating Research Council, August 1995.

5. "CRC Sulfur/LEV Program" Presentation Materials from the Coordinating Research Council, December 1997.

February 13, 1998

Memo To: David H. Lax
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From: Philip Heirigs

Subject: Effects of Fuel Oxygen Content on CO Emissions

This memorandum transmits the findings of Sierra's analysis of the effects of fuel oxygen content on exhaust emissions. The review has been focused on FTP composite CO emissions under "winter" fuel scenarios (i.e., simple addition of oxygenate with minimal changes to fuel parameters other than those related to dilution or distillation characteristics). If you have any questions regarding this material, please call me or Bob Dulla at (916) 444-6666.

Background

The use of oxygenated gasoline is mandated in many urban areas as a wintertime CO control strategy. As such, EPA has included the emissions impacts of oxygenated fuel in its MOBILE series of on-road motor vehicle emission factors models since the MOBILE4.1 version of the model. As more and more areas of the country come into attainment with the ambient CO standard, less emphasis has been placed on CO control in the on-highway fleet. However, proper modeling of the impacts of oxygenated fuels is important for those areas that remain out of attainment so that air quality planners can make intelligent decisions about the mix of control measures that are available to them. (This is also an issue for attainment areas developing maintenance plans.) Thus, EPA has indicated that it will update the oxygenated fuel correction factors in the next release of the MOBILE model, MOBILE6.

Modeling the Effects of Fuel Oxygen Content With MOBILE5a - The exhaust emission benefits of oxygenated fuels modeled by MOBILE5a are a function of fuel oxygen content (wt%), baseline (non-oxygenate) emission rate, and model year. Embedded in the model-year-specific corrections are assumptions regarding the impact of vehicle technology on the effect of oxygenates on emissions. (The model-year-specific corrections are developed from a subroutine contained in the TECH5 model.) Although the model was structured to account for the differences in HC benefits between alcohol and ether blends, MOBILE5a assumes the same benefit (as a function of oxygen content) for both.

In the TECH5 model, the impact of fuel oxygen is modeled separately for the following technology groups:

- Multipoint fuel injection/closed-loop;
- Throttle-body injection/closed-loop;
- Carbureted/closed-loop; and
- Open-loop (carbureted and fuel-injected).

To generate the oxygenate effect for a specific model year, the reductions estimated for each of the above technology groups are weighted by the fraction of those vehicles in the fleet. To illustrate the magnitude of the projected impact of oxygenated fuels determined by MOBILE5a, Figure 1 shows the calculated CO benefits (as a percent reduction from the base emission rate) for 1990 model year light-duty gasoline vehicles (LDGVs). The benefits increase with increasing wt% oxygen content and with increasing base emission rate, resulting in a maximum benefit of approximately 37.5% at an oxygen content of 3.5%. For alcohol blends (e.g., ethanol), the maximum oxygenate content modeled is 3.5%, while the maximum content modeled for ether blends (e.g., MTBE) is 2.7%.

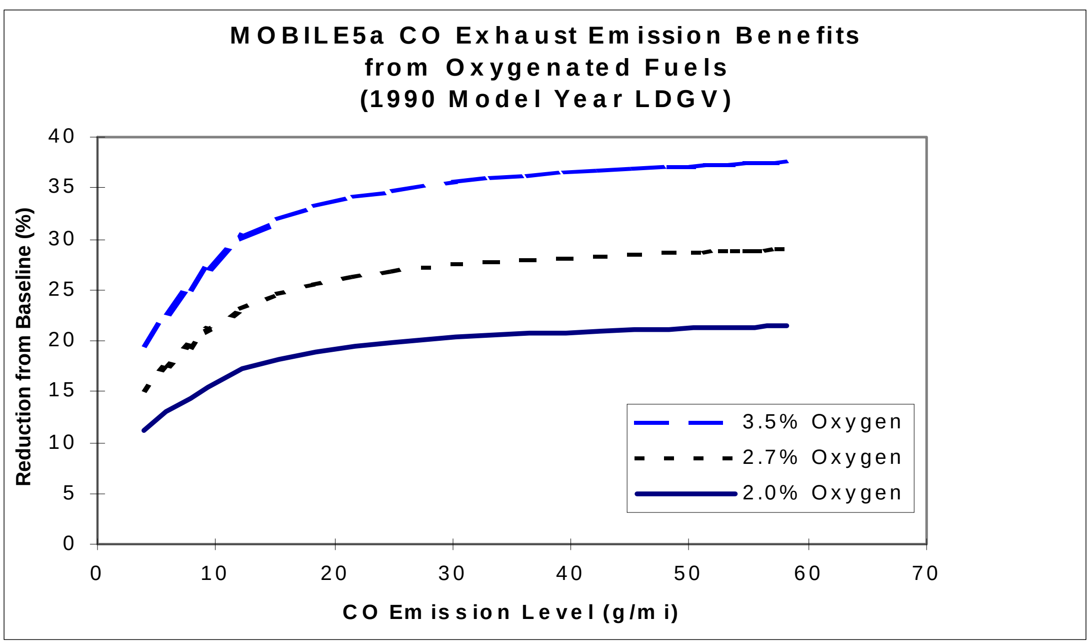

Figure 1

The relatively large benefits ascribed to oxygenated fuels in MOBILE5a for vehicles with high CO emissions, coupled with high deterioration rates under a non-I/M case, result in a LDGV fleet-average CO reduction of approximately 33% in calendar year 2000 for an area without an I/M program that requires oxygenated fuel with a 3.5% oxygen content. Because reductions of this magnitude are not supported by ambient CO monitoring, EPA intends to revisit the oxygenated fuel adjustment factors for MOBILE6.

<u>EPA Preliminary Proposal for MOBILE6</u> - At the October 1, 1997 MOBILE6 workshop held in Ann Arbor, EPA presented its preliminary proposal for modeling the effects on CO emissions resulting from the addition of fuel oxygen. Due to a desire to keep the analysis as simple as possible (primarily because EPA feels that the CO nonattainment problem is diminishing), EPA proposed the following for MOBILE6:

- The recently developed CO exhaust emissions model[1*] that was based on the data and methodologies used for the reformulated gasoline (RFG) Complex model would be used for 1988 and later model year vehicles.
- For 1981 to 1987 model year vehicles, a recent analysis performed for ARCO Chemical Co. would be used. In that study, a model to estimate the CO impact of fuel parameter changes was constructed for 1981 to 1987 model year vehicles based on the CARB Predictive model database. The methodologies used to develop that model were based on the Complex model methodologies.

- For pre-1981 model year vehicles, EPA proposes to use the current (MOBILE5a) estimates for older technology vehicles.

A summary of the emission reductions associated with the approach outlined above, as presented at the MOBILE6 workshop, is presented in Table 1.

<u>Concerns with the EPA MOBILE6 Proposal</u> - After reviewing the CO model developed by V. Rao, the Western States Petroleum Association (WSPA) expressed concern about its use.[2] The more important concerns with respect to modeling the impacts of oxygenated fuels include the following:

- Weighting factors used to combine normal and high emitters were based on the RFG Complex model VOC weighting factors – CO-specific factors were not developed.

- The CO model is based primarily on summer fuels, with the majority of testing performed with fuel RVP between 6.5 and 10 psi.

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[*] Superscripts denote references provided at the end of this memorandum.

Table 1
CO Emission Reductions Proposed for MOBILE6
Assumes Splash-Blended Fuels
(From the October 1, 1997 MOBILE6 Workshop Handouts)

Model Year Group	2.7 wt% MTBE		3.5 wt% Ethanol	
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1988+	13.8%	9.33%	15.4%	10.1%
1981-1987	18.2%		19.1%	
Pre-1981 Open-Loop	26.9%		34.9%	
Pre-1981 Non-Catalyst	18.9%		24.5%	

- The CO response to RVP reduction shows a minima at approximately 8 psi. It is unclear that such a trend would exist at the cold temperatures under which winter oxygenated fuels are normally used. (And it is clear that the RVP used under winter conditions is nowhere near 8 psi.)

- Normal emitters show a stronger response to oxygen than high emitters. Based on the physical mechanisms involved, the opposite would have been expected.

Given the above, it is unclear that use of the CO Complex model will provide the most accurate estimates of the effects of fuel oxygen on CO emissions. Thus, Sierra has analyzed available "paired" data (i.e., data pairs in which a vehicle was tested on both a baseline, non-oxygenated fuel and a corresponding oxygenated fuel) to develop alternative estimates of the impacts of fuel oxygen on emissions.

Data Sources

Since the development of the fuel oxygen correction factors for MOBILE5a, a number of test programs aimed at investigating the impacts of gasoline modifications on emissions have been conducted. Primary among those is the Auto/Oil Air Quality Improvement Research Program (AQIRP). In addition, smaller programs have been sponsored by industry and government agencies, and EPA has generated additional data that were not used in the development of the MOBILE5a factors. Much of this testing was generated with summertime reformulated gasoline in mind; however, some of the test results can be used to predict the emissions impact of adding oxygenates to wintertime fuels. A brief summary of the data sources investigated in this effort is presented below.

Auto/Oil - The Auto/Oil AQIRP represents perhaps the best-designed, most extensive test program ever conducted to study the effects of fuel parameters on emissions from light-duty vehicles. The primary drawback from the use of those data to predict CO changes from the addition of fuel oxygen is that the fuels investigated in that effort were generally reflective of summertime fuels. This is particularly true of the Phase 2 testing conducted in the program in which many of the fuels had RVP levels below 7 psi, and there were few paired tests conducted with and without oxygenate in the fuel. However, two data sets are available from Phase 1 that can be used to estimate the impact of fuel oxygen on CO emissions, and one data set from Phase 2 can be used to assess the impact of fuel oxygen on advanced technology vehicles. These data sets are described below.

- *AMOT data set* - The AMOT (Aromatics/MTBE/Olefins/T90) data set consists of tests conducted with 16 fuels with combinations of high and low levels of those four fuel parameters.[3] The RVP of the fuels in this series of tests was held around 8.7 psi for all of the fuel blends. Comparing the high (2.7 wt%) and low (0 wt%) MTBE-paired tests (keeping all other fuel parameters constant) gives an estimate of the impact of fuel oxygen on emissions.

- *RVP/Oxygenate data set* - Following the AMOT testing, a test program was conducted in which the impact of both RVP and fuel oxygen was investigated.[4] Three oxygenates were assessed in this program – MTBE (15 vol%, 2.7 wt% oxygen) , ethanol (10 vol%, 3.5 wt% oxygen), and ETBE (17 vol%, 2.5 wt% oxygen). The ethanol blends were "splash" blends (with and without an RVP adjustment to maintain constant RVP) and reflected dilution effects, while the MTBE and ETBE were "match" blends that did not reflect dilution of other fuel parameters. Fuel blends were prepared with both a 1990 commercial gasoline (RF-A) and a "reformulated" base gasoline that had low aromatics, low olefins, and low T90.

- *Technology effects data set* - As part of Phase 2 of the program, emissions tests were conducted with a reformulated gasoline meeting the 1996 California specifications and a gasoline blended to the California specifications but without an oxygenated component.[5] Tests on these two fuels (and RF-A) were conducted on the AQIRP "current" fleet, a fleet of vehicles meeting federal Tier I standards, and a fleet of advanced technology vehicles. Although the testing was not extensive, it provides some insight regarding the effects of fuel oxygen on emissions from advanced technology vehicles.

EPA Emission Factors Database - The historical EPA emission factors database has a considerable number of tests in which vehicles were tested with a baseline gasoline (typically Indolene) and an oxygenate blend (primarily ethanol and MTBE). However, in many cases the RVP was not controlled on the oxygenate blend, which causes difficulty when attempting to evaluate only the effect of fuel oxygen on CO emissions. In addition to testing at 75°F, the EPA emission factors database contains results from vehicles tested at 50°F and 20°F.

EPA RFG Study - This study was conducted to support the development of EPA's Complex model for RFG and consisted of three phases:

- *Phase I* was an initial evaluation of the impact of oxygenate, volatility, distillation parameters and sulfur on emissions;[6]

- *Phase II* was a continuance of Phase 1 investigating the effects of oxygenate content, oxygenate type, volatility, sulfur, olefins, and distillation parameters;[7] and

- *Phase III* investigated sulfur, olefins, volatility, aromatics, and the interactions between olefins and volatility or sulfur.[8]

Although this was an extensive test program, the focus of the testing was on summertime, reformulated fuels. For the most part, oxygen levels were kept near 2.0 wt% in most of the fuels, and the non-oxygenated fuels in the program were typically industry average (RF-A) or Indolene. There are few paired data points to make a direct comparison between a non-oxygenated gasoline and an oxygenated gasoline. Although there were two levels of oxygen (2.0 wt% versus 3.7 wt%) investigated in the Phase I program in which a fuel pair was blended with similar base gasoline, those fuels utilized different oxygenates (MTBE and ethanol) and the results reveal only the difference between one level of oxygen and another. (Unfortunately, the non-oxygenated base gasoline used to derive these fuels was not included in the test matrix for this program.)

API RVP/Oxygenates Test Program - In 1988, API initiated a two-year study of the effects of changes in RVP and oxygenates on emissions from gasoline-fueled vehicles at varying ambient temperature.[9] Eleven vehicles were tested in that effort, ranging in model year from 1981 to 1989. The RVP of the fuels in the program ranged from 7 to 13 psi, and three temperatures were investigated: 80°, 55°, and 35°F. Although the number of vehicles tested in this program was not extensive, the wide range of temperatures and fuels investigated allows for an evaluation of the impact of ambient temperature on the benefits attributed to oxygenated fuel. In this program, the magnitude of the response of CO to fuel oxygen content was greatest at 55°F and lowest at 35°F.

CARB Low Oxygenate Gasoline Blends Test Program - This study, sponsored by the California Air Resources Board (CARB), investigated the impacts of oxygenated gasoline on emissions of light-duty vehicles under both summer and winter conditions.[10] The winter fuel study included gasolines blended with ethanol, MTBE, and ETBE to a 2.7 wt% oxygen level. Thirteen vehicles were tested in this program, ranging in model year from 1973 to 1991. Vehicles were tested at 75°F and 50°F. As with the API test program, the small number of vehicles tested in the program (which covered a broad range of control technologies) makes it difficult to generate accurate estimates of the emissions impacts of fuel oxygen on CO emissions; however, the varying test temperatures may provide insight into how the oxygen effect changes with temperature.

CRC Study of Winter Gasoline/Oxygenate Blends[11] - In the late 1980s, the Coordinating Research Council (CRC) sponsored a test program investigating the effects of fuel oxygen content on exhaust emissions for three technology types (six vehicles equipped with three-way catalysts and adaptive learning, six vehicles equipped with three-way catalysts without adaptive learning, and four oxidation catalyst vehicles) at three temperatures (75°, 50°, and 35°F). Tests were conducted at sea level and at high altitude. The primary fuel set used in this testing included a 13 psi RVP non-oxygenate base fuel, a 11 vol% MTBE blend, and a 10 vol% ethanol splash blend. The sea level tests also included a 10 vol% ethanol matched volatility blend. Again, the small number of vehicles tested in the program makes it difficult to generate accurate estimates of the emissions impacts of fuel oxygen on CO emissions, but the varying test temperatures may provide insight into how the oxygen effect changes with temperature.

Analysis of Paired Data at 75°F

This section of the memorandum presents the mean emission levels of paired non-oxygenate/oxygenate tests run at 75°F from the programs summarized above. In general, the results are presented by emitter category using a 7.0 g/mi CO emission rate (on Indolene at 75°F) as the cut-off between normal- and high-emitters. In addition, the data were analyzed according to the following model year/technology groups, as it is expected that the CO response to fuel oxygen content will be a function of the emission control system employed on the vehicle:

- 1981 and later model year oxidation catalyst (OX) or open-loop three-way catalyst (TWC);
- 1981-85 model year closed-loop (CL) TWC;
- 1986 and later model year closed-loop TWC without adaptive learning (ADL);
- 1986-87 model year closed-loop TWC with ADL; and
- 1988 and later model year closed-loop TWC with ADL.

In some cases, sample sizes were not sufficient to analyze the data as outlined above and broader model year/technology groups were utilized. In addition, it was not always possible to determine if a vehicle was equipped with ADL; in those cases, all TWC/CL were combined. A vehicle was considered to have ADL if it was so specified in the database being analyzed or if it was included in the Complex model database. (EPA had carefully screened all of those vehicles to ensure that they were "1990 technology" vehicles with adaptive learning capability.)

In the tables that follow, test pairs were generally selected in which the oxygenated blend was as close as possible to the base gasoline, with only dilution causing the other fuel parameters to differ. Particular attention was paid to differences in RVP between the non-oxygenate and oxygenate blends. Much of the available oxygenated fuel data have been collected using simple splash blends of ethanol and gasoline. Although this reflects what occurs in practice, there is concern that the extra 1 psi RVP of the oxygenate blend will mask the impact of the oxygen, particularly with a 75°F test. (In fact, some of the test results from the EPA emission factors database show an increase in CO emissions from late-model cars when tested on a 10.2 psi RVP Indolene/EtOH versus a 9.0 psi RVP Indolene base fuel.) Since MOBILE has a separate exhaust correction for RVP, the analysis of fuel oxygen effects should eliminate the RVP effect as much as possible. Alternatively, the splash-blend ethanol data could be used to develop a combined RVP/oxygenate adjustment for cases in which an RVP waiver is granted. Such an approch would be valid for higher temperature regions, but for colder temperatures (i.e., below 35° to 45°F), the impact of the RVP difference is expected to diminish.

Auto/Oil AMOT Data set - Mean CO emissions from the Auto/Oil AMOT testing (aromatics - MTBE - olefins - T90) are shown in Table 2. In each case, the difference between the non-oxygenated fuel and the oxygenated fuel is the MTBE content (either 0 or 15 vol%). As in the A/O reports and SAE papers presenting the results of this testing, lower case refers to the lower levels of these fuel parameters; upper case refers to the higher levels of these fuel parameters. This fuel set was tested in both the current fleet (noted by the 1988+ model year group in the table) and the older fleet (noted by the 83-85 model year group in the table). One of the vehicles in the current fleet was eliminated from the Complex model database because it was not considered representative of 1990 technology (a carbureted 1989 Honda Accord). Hence, it is labeled as not having adaptive learning, and results are presented separately for that vehicle (actually, that pair of vehicles). As seen in the table, this vehicle had a substantial impact on the overall results. It is also interesting to note that the addition of MTBE had a larger impact on the older fleet than the current fleet, even for the normal emitters. Finally, the high emitters in the table had a strong response to MTBE, but it should be noted that four of the five were open-loop/oxidation catalyst vehicles.

Auto/Oil RVP/Oxygenate Data set - Table 3 summarizes the paired data from the Auto/Oil RVP/Oxygenate test program. Comparisons are made for the same RVP fuels as well as for the splash-blend ethanol fuels. One item of particular interest in this table is the small effect observed for the MTBE blends relative to the EtOH and ETBE blends. This was surprising because it is inconsistent with other available data. It is interesting to note, however, that the SAE paper presenting the results of this test program reports a benefit of 9.3 ± 6.7% in going from 0% to 15% MTBE (based on a regression analysis of the data rather than a comparison of paired tests). Also, the EtOH benefit of 14.9% shown in Table 3 for the ADL fleet on the F-T fuel pair (matched RVP) is very close to the results from the EPA database for 10% EtOH in Indolene (also matched RVP) presented below.

Table 2
Mean CO Emissions from Paired Tests In the Auto/Oil AMOT Database
("Current" and "Older" Fleets)

Emitter Class	Model Year	ADL	Non-Oxy Fuel	Oxy Fuel	Wt% Oxygen	n	Mean CO (g/mi) Non-Oxy	Mean CO (g/mi) Oxy	CO Impact	CO Impact Per Wt% O
Normal	1988+	All	D- amOT	M- aMOT	2.6	20	2.55	2.33	-8.6%	-3.3%
		Vehicles	F - amot	N - aMot	2.5	20	2.73	2.46	-9.5%	-3.8%
		with and	G - AmOt	O - AMOt	2.6	20	2.96	2.74	-7.4%	-2.9%
		without	I - AmoT	R- AMoT	2.7	20	3.14	3.16	+0.6%	+0.2%
		ADL	K - Amot	C - AMot	2.8	20	2.96	2.68	-9.5%	-3.4%
			L- AmOT	E- AMOT	2.7	20	3.11	2.92	-5.8%	-2.1%
			P - amOt	H - aMOt	2.6	20	2.69	2.45	-8.9%	-3.4%
			Q - amoT	J - aMoT	2.7	20	2.70	2.32	-13.7%	-5.1%
Normal	1988+	Yes	D- amOT	M- aMOT	2.6	18	2.59	2.44	-6.2%	-2.4%
			F - amot	N - aMot	2.5	18	2.74	2.56	-6.6%	-2.6%
			G - AmOt	O - AMOt	2.6	18	2.99	2.84	-5.0%	-1.9%
			I - AmoT	R- AMoT	2.7	18	3.31	3.37	+1.8%	+0.7%
			K - Amot	C - AMot	2.8	18	2.95	2.78	-6.1%	-2.2%
			L- AmOT	E- AMOT	2.7	18	3.23	3.12	-3.4%	-1.3%
			P - amOt	H - aMOt	2.6	18	2.69	2.53	-5.9%	-2.3%
			Q - amoT	J - aMoT	2.7	18	2.77	2.44	-11.9%	-4.4%
All	83-85	No	D- amOT	M- aMOT	2.6	14	5.33	4.89	-8.3%	-3.2%
			F - amot	N - aMot	2.5	14	6.08	5.41	-10.9%	-4.3%
			G - AmOt	O - AMOt	2.6	14	6.54	5.74	-12.2%	-4.7%
			I - AmoT	R- AMoT	2.7	14	6.49	5.36	-17.6%	-6.5%
			K - Amot	C - AMot	2.8	14	6.19	5.29	-14.5%	-5.2%
			L- AmOT	E- AMOT	2.7	14	6.52	4.79	-26.5%	-9.8%
			P - amOt	H - aMOt	2.6	14	7.41	5.58	-24.7%	-9.5%
			Q - amoT	J - aMoT	2.7	14	6.26	4.69	-25.1%	-9.3%
Normal	83-85	No	D- amOT	M- aMOT	2.6	9	3.85	3.38	-12.2%	-4.7%
			F - amot	N - aMot	2.5	9	4.48	4.33	-3.3%	-1.3%
			G - AmOt	O - AMOt	2.6	9	4.55	4.20	-7.7%	-3.0%
			I - AmoT	R- AMoT	2.7	9	4.13	4.14	+0.2%	+0.1%
			K - Amot	C - AMot	2.8	9	4.27	3.97	-7.0%	-2.5%
			L- AmOT	E- AMOT	2.7	9	4.37	3.75	-14.4%	-5.3%
			P - amOt	H - aMOt	2.6	9	5.05	4.19	-16.8%	-6.5%
			Q - amoT	J - aMoT	2.7	9	4.14	3.43	-17.1%	-6.4%
High	83-85	No	D- amOT	M- aMOT	2.6	5	7.99	7.60	-4.9%	-1.9%
			F - amot	N - aMot	2.7	5	8.95	7.36	-17.8%	-7.1%
			G - AmOt	O - AMOt	2.6	5	10.12	8.50	-16.0%	-6.2%
			I - AmoT	R- AMoT	2.7	5	10.75	7.55	-29.8%	-11.0%
			K - Amot	C - AMot	2.8	5	9.65	7.66	-20.6%	-7.4%
			L- AmOT	E- AMOT	2.7	5	10.38	6.68	-35.6%	-13.2%
			P - amOt	H - aMOt	2.6	5	11.67	8.09	-30.8%	-11.8%
			Q - amoT	J - aMoT		5	10.07	6.96	-30.9%	-11.4%

Table 3

Mean CO Emissions from Paired Tests In the Auto/Oil RVP/Oxygenate Database

Constant RVP Between Fuel Pairs										
Emtter Class	Model Year	ADL	Non-Oxy Fuel	Oxy Fuel	Wt% Oxygen	n	Mean CO (g/mi)		CO Impact	CO Impact Per Wt% O
							Non-Oxy	Oxy		
Normal	1988+	All Vehicles with and without ADL	A - Ind Ave/9 psi	W - 10% EtOH	3.5	20	2.85	2.32	-18.6%	-5.3%
			F - Reform/9 psi	T - 10% EtOH	3.5	20	2.74	2.27	-17.2%	-4.9%
			F - Reform/9 psi	N2 - 15% MTBE	2.6	20	2.74	2.53	-7.7%	-2.9%
			S - Reform/8 psi	MM - 15% MTBE	2.7	20	2.50	2.43	-2.8%	-1.0%
			F - Reform/9 psi	NN - 17% ETBE	2.5	20	2.74	2.40	-12.4%	-5.0%
Normal	1988+	Yes	A - Ind Ave/9 psi	W - 10% EtOH	3.5	18	2.99	2.45	-18.1%	-5.2%
			F - Reform/9 psi	T - 10% EtOH	3.5	18	2.76	2.35	-14.9%	-4.2%
			F - Reform/9 psi	N2 - 15% MTBE	2.6	18	2.76	2.64	-4.3%	-1.7%
			S - Reform/8 psi	MM - 15% MTBE	2.7	18	2.55	2.51	-1.6%	-0.6%
			F - Reform/9 psi	NN - 17% ETBE	2.5	18	2.76	2.46	-10.9%	-4.3%
Splash-Blended Ethanol Pairs with an Increase of 1 psi RVP for the Ethanol Blend										
Emitter Class	Model Year	ADL	Non-Oxy Fuel	Oxy Fuel	Wt% Oxygen	n	Mean CO (g/mi)		CO Impact	CO Impact Per Wt% O
							Non-Oxy	Oxy		
Normal	1988+	All Vehicles with and w/o ADL	A - Ind Ave/9 psi	X - 10% EtOH	3.5	20	2.85	2.42	-15.1%	-4.3%
			V - Ind Ave/8 psi	W - 10% EtOH	3.5	20	2.61	2.32	-11.1%	-3.2%
			F - Reform/9 psi	U - 10% EtOH	2.6	20	2.74	2.59	-5.5%	-2.1%
			S - Reform/8 psi	T - 10% EtOH	2.7	20	2.50	2.27	-9.2%	-3.4%
Normal	1988+	Yes	A - Ind Ave/9 psi	X - 10% EtOH	3.5	18	2.99	2.54	-15.1%	-4.3%
			V - Ind Ave/8 psi	W - 10% EtOH	3.5	18	2.76	2.45	-11.2%	-3.2%
			F - Reform/9 psi	U - 10% EtOH	2.6	18	2.76	2.72	-1.4%	-0.6%
			S - Reform/8 psi	T - 10% EtOH	2.5	18	2.55	2.35	-7.8%	-3.1%

<u>EPA Emission Factors Database - Matched RVP Data Pairs</u> - Table 4 shows the mean CO emission rates for paired data from the EPA Emission Factors database for the fuel pairs in which the RVP between the non-oxygenate and oxygenated blend matched. Results of three different fuels are included in this table:

- The baseline, non-oxygenated tests were conducted on Indolene (nominally 9.0 psi RVP) and are recorded as "RECV" in the EPA database;

- The MTBE blend is a 15 vol% volatility matched blend of MTBE and gasoline with an RVP of 9.1 psi (these tests are logged as “TST93” in the EPA database); and

- The ethanol blend is a 10 vol% volatility matched blend of ethanol and gasoline with an RVP of 9.0 psi (these tests are logged as “TST92” in the EPA database).

Because the results from this series of tests were included in the development of the Complex model, it was a simple matter of merging the EPA vehicles that were included in the Complex model database with the EPA emission factors database to determine which vehicles in the EPA emission factors database were equipped with adaptive learning (i.e., vehicles in the EPA database that were also included in the Complex model database were assumed to have ADL, those not in the Complex model database were assumed not to have ADL).

Table 4
Mean CO Emissions From Paired Tests in the EPA Emission Factors Database
(Based on Matched RVP Non-Oxy/Oxy Pairs)

Emitter Group	Tech Group	Oxy Fuel	Wt% Oxygen	n	Mean CO (g/mi) Non-Oxy	Mean CO (g/mi) Oxy	CO Impact[a]			CO Impact Per Wt% O
Normal	81+ OX/OL	10% EtOH	3.5	1	5.99	5.09	-15.0%	±	na	-4.3%
	81-85 3W/CL	10% EtOH	3.5	8	4.65	3.89	-16.3%	±	10.8%	-4.7%
	86+ 3W/NoADL	10% EtOH	3.5	141	3.22	2.55	-20.8%	±	3.4%	-5.9%
	86-87 3W/ADL	10% EtOH	3.5	89	3.19	2.59	-18.8%	±	4.3%	-5.4%
		10% EtOH	3.5	110	2.99	2.54	-15.1%	±	3.9%	-4.3%
	81+ OX/OL	15% MTBE	2.7	6	3.70	2.35	-36.8%	±	27.8%	-13.5%
	81-85 3W/CL	15% MTBE	2.7	12	4.42	3.77	-14.7%	±	9.7%	-5.4%
	86+ 3W/NoADL	15% MTBE	2.7	62	3.06	2.56	-16.3%	±	6.4%	-6.1%
	86-87 3W/ADL	15% MTBE	2.7	65	3.38	2.89	-14.5%	±	4.5%	-5.4%
	1988+ 3W/ADL	15% MTBE	2.7	58	2.77	2.49	-10.1%	±	5.5%	-3.7%
High	81+ OX/OL	10% EtOH	3.5	0	na	na	na	±	na	na
	81-85 3W/CL	10% EtOH	3.5	7	13.67	10.11	-26.0%	±	37.1%	-7.4%
	86+ 3W/NoADL	10% EtOH	3.5	25	17.16	12.29	-28.4%	±	11.0%	-8.1%
	86-87 3W/ADL	10% EtOH	3.5	22	19.03	16.36	-14.1%	±	8.3%	-4.0%
	1988+ 3W/ADL	10% EtOH	3.5	4	8.33	4.84	-41.9%	±	29.2%	-12.0%
	81+ OX/OL	15% MTBE	2.7	8	32.16	20.11	-37.5%	±	10.7%	-13.9%
	81-85 3W/CL	15% MTBE	2.7	18	22.84	18.33	-19.7%	±	8.1%	-7.3%
	86+ 3W/NoADL	15% MTBE	2.7	20	18.61	14.71	-21.0%	±	12.3%	-7.8%
	86-87 3W/ADL	15% MTBE	2.7	23	18.37	17.93	-2.3%	±	20.3%	-0.9%
	1988+ 3W/ADL	15% MTBE	2.7	2	7.62	4.85	-36.5%	±	53.3%	-13.5%

[a] Confidence interval reflects a 90% confidence level.

The results presented in Table 4 show that for normal-emitting vehicles, newer technology vehicles are less impacted by the presence of oxygen in the fuel than older technology vehicles. This is true for both the ethanol and the MTBE blends. (Because of the small sample size of the 1981+ OX/OL and 1981-85 TWC/CL vehicles, it is difficult to draw conclusions about those technologies from this test program.) For high-emitting vehicles, the effect of fuel oxygen on CO emissions is more variable, likely because of the inherent variability of high-emitting vehicles.

Another series of tests included in the EPA emission factors database consisted of testing with a 17.5 vol% MTBE blend with an RVP of 9 psi. (This test is logged as “TST15” in the database.) The results of that testing are given in Table 5, which compares non-oxygenated fuel results (based on Indolene) to the 17.5 vol% MTBE blend. For normal-emitting vehicles, those results are similar to the 15 vol% MTBE results given in Table 4. As with the previous results, the impact of fuel oxygen content on high-emitter CO levels is more variable.

Table 5
Mean CO Emissions From Paired Tests in the EPA Emission Factors Database
(Based on Matched RVP Non-Oxy/Oxy Pairs with 17.5% MTBE Fuel)

Emitter Group	Tech Group	Oxy Fuel	Wt% Oxygen	n	Mean CO (g/mi)		CO Impact[a]	CO Impact Per Wt% O
					Non-Oxy	Oxy		
Normal	81+ OX/OL	17.5% MTBE	3.1	6	3.70	2.32	-37.3% ± 17.1%	-12.0%
	81-85 3W/CL	17.5% MTBE	3.1	4	3.95	4.45	+12.7% ± 89.7%	+4.1%
	86+ 3W/NoADL	17.5% MTBE	3.1	24	3.30	2.42	-26.7% ± 8.3%	-8.6%
	86-87 3W/ADL	17.5% MTBE	3.1	24	3.06	2.68	-12.4% ± 8.9%	-4.0%
	1988+ 3W/ADL	17.5% MTBE	3.1	38	2.68	2.44	-9.0% ± 6.1%	-2.9%
High	81+ OX/OL	17.5% MTBE	3.1	8	32.16	21.20	-34.1% ± 11.5%	-11.0%
	81-85 3W/CL	17.5% MTBE	3.1	11	28.68	21.23	-26.0% ± 13.5%	-8.4%
	86+ 3W/NoADL	17.5% MTBE	3.1	9	27.03	24.20	-10.5% ± 24.1%	-3.4%
	86-87 3W/ADL	17.5% MTBE	3.1	7	28.13	37.94	+34.9% ± 57.3%	+11.2%
	1988+ 3W/ADL	17.5% MTBE	3.1	2	7.62	5.16	-32.3% ± 111.3%	-10.4%

[a] Confidence interval reflects a 90% confidence level.

A final comparison of paired tests performed with matching RVP fuel sets in the EPA database is given in Table 6. That table compares a non-oxygenated commercial fuel (termed “CMFUEL” in the database) to an 11 vol% MTBE blend (“TST68” in the database) and a 10 vol% ethanol blend (“TST65” in the database). All fuels in this series of tests had a nominal RVP of 11.7 psi. Because the results of these tests were not included in the Complex model database, it was not possible to determine if vehicles were equipped with ADL. Thus, the following broader technology groups were used for the analysis:

- 1981 and later OX catalyst or open-loop TWC;
- 1981 to 1985 TWC/CL; and
- 1986 and later TWC/CL.

The results from normal emitters in this testing are reasonably consistent with previous results for the ethanol blend; however, the MTBE blend results indicate an increase in CO emissions for the 1986+ TWC/CL group when using the oxygenated fuel. It should be noted, however, that this increase is not significant at the 90% confidence level. (In fact, the confidence interval for that technology group is very broad.) As observed in the previous results, the impact of fuel oxygen on high-emitter CO levels is quite variable.

Table 6

Mean CO Emissions From Paired Tests in the EPA Emission Factors Database

Based on Nominal 11.7 psi Matched RVP Non-Oxy/Oxy Pairs

Emitter Group	Tech Group	Oxy Fuel	Wt% O	n	Mean CO (g/mi)		CO Impact[a]	CO Impact Per Wt% O
					Non-Oxy	Oxy		
Normal	81+ OX/OL	11% MTBE	2.0	2	7.09	5.28	-25.5% ± 188.9%	-12.8%
	81-85 3W/CL	11% MTBE	2.0	42	4.81	4.41	-8.3% ± 6.8%	-4.2%
	86+ 3W/CL	11% MTBE	2.0	47	3.23	3.41	+5.6% ± 14.3%	+2.8%
	81+ OX/OL	10% EtOH	3.6	2	7.09	3.37	-52.5% ± 297.2%	-14.6%
	81-85 3W/CL	10% EtOH	3.6	54	5.10	4.26	-16.5% ± 5.1%	-4.6%
	86+ 3W/CL	10% EtOH	3.6	83	3.44	2.76	-19.8% ± 5.6%	-5.5%
High	81+ OX/OL	11% MTBE	2.0	1	53.10	41.50	-21.8% ± na	-10.9%
	81-85 3W/CL	11% MTBE	2.0	31	23.02	21.81	-5.3% ± 9.4%	-2.6%
	86+ 3W/CL	11% MTBE	2.0	3	91.14	86.54	-5.0% ± 19.4%	-2.5%
	81+ OX/OL	10% EtOH	3.6	5	34.72	17.20	-50.5% ± 23.8%	-14.0%
	81-85 3W/CL	10% EtOH	3.6	36	23.46	20.71	-11.7% ± 32.0%	-3.3%
	86+ 3W/CL	10% EtOH	3.6	7	58.61	48.47	-17.3% ± 12.5%	-4.8%

[a] Confidence interval reflects a 90% confidence level.

<u>EPA Emission Factors Database - Non-Matching RVP Data Pairs</u> - In addition to the matched RVP oxygenated fuel test results in the EPA emission factors database, a series of tests was performed with non-matching RVP fuel sets. In this testing, the following fuels were used:

- The baseline, non-oxygenated tests were conducted on Indolene (nominally 9.0 psi RVP) and are recorded as "RECV" in the EPA database;
- The MTBE blend is a 15 vol% "splash" blend of MTBE and Indolene with an RVP of 9.6 psi (these tests are logged as "TST69" in the EPA database); and
- The ethanol blend is a 10 vol% "splash" blend of ethanol and Indolene with an RVP of 10.2 psi (these tests are logged as "TST34" in the EPA database).

Mean CO emission results from this testing are summarized in Table 7, which shows a generally smaller reduction as a result of adding oxygen to the fuel for normal-emitting vehicles than that observed for the matched RVP fuel set (i.e., Table 4). In fact, the 1988+ TWC/ADL group shows an increase in CO emissions for both the MTBE and ethanol blend relative to non-oxygenated gasoline (although those increases are not significant at the 90% confidence level). It appears that these vehicles are more sensitive to the increased RVP level than they are to the presence of oxygen in the fuel. The results for the high-emitting vehicles are more consistent with previous findings, indicating less sensitivity to changes in fuel volatility.

Table 7

Mean CO Emissions From Paired Tests in the EPA Emission Factors Database

Based on Splash-Blended, Non-Matching RVP Non-Oxy/Oxy Pairs

Emitter Group	Tech Group	Oxy Fuel	Wt% O	n	Mean CO (g/mi) Non-Oxy	Mean CO (g/mi) Oxy	CO Impact[a]			CO Impact Per Wt% O
Normal	81+ OX/OL	10% EtOH	3.5	1	5.92	3.16	-46.6%	±	na	-13.3%
	81-85 3W/CL	10% EtOH	3.5	30	3.81	3.13	-17.8%	±	7.9%	-5.1%
	86+ 3W/NoADL	10% EtOH	3.5	24	3.33	3.20	-3.9%	±	10.3%	-1.1%
	86-87 3W/ADL	10% EtOH	3.5	24	2.50	2.17	-13.2%	±	7.1%	-3.8%
	1988+ 3W/ADL	10% EtOH	3.5	9	2.13	2.39	+12.2%	±	23.9%	+3.5%
	81+ OX/OL	15% MTBE	2.6	2	5.96	3.57	-40.1%	±	41.2%	-15.4%
	81-85 3W/CL	15% MTBE	2.6	30	3.81	3.32	-12.9%	±	7.0%	-4.9%
	86+ 3W/NoADL	15% MTBE	2.6	26	3.31	2.94	-11.2%	±	9.8%	-4.3%
	86-87 3W/ADL	15% MTBE	2.6	36	2.38	2.06	-13.4%	±	7.2%	-5.2%
	1988+ 3W/ADL	15% MTBE	2.6	11	2.02	2.11	+4.5%	±	12.7%	+1.7%
High	81+ OX/OL	10% EtOH	3.5	2	7.45	4.90	-34.2%	±	106.1%	-9.8%
	81-85 3W/CL	10% EtOH	3.5	12	37.42	26.13	-30.2%	±	23.2%	-8.6%
	86+ 3W/NoADL	10% EtOH	3.5	4	26.55	17.39	-34.5%	±	82.2%	-9.9%
	86-87 3W/ADL	10% EtOH	3.5	3	13.76	10.11	-26.5%	±	42.3%	-7.6%
	1988+ 3W/ADL	10% EtOH	3.5	0	0.00	0.00	na	±	na	na
	81+ OX/OL	15% MTBE	2.6	2	7.45	5.13	-31.1%	±	10.2%	-12.0%
	81-85 3W/CL	15% MTBE	2.6	12	37.42	28.52	-23.8%	±	17.2%	-9.1%
	86+ 3W/NoADL	15% MTBE	2.6	5	23.78	13.48	-43.3%	±	96.3%	-16.7%
	86-87 3W/ADL	15% MTBE	2.6	3	13.76	11.65	-15.3%	±	20.2%	-5.9%
	1988+ 3W/ADL	15% MTBE	2.6	0	0.00	0.00	na	±	na	na

[a] Confidence interval reflects a 90% confidence level.

Linearity of Response to Oxygen Content

In previous versions of MOBILE, the emissions response to oxygenated fuel has been assumed to be proportional to the wt% oxygen in the fuel. For a 15 vol% MTBE blend, this typically corresponds to 2.7 wt% oxygen, whereas a 10 vol% ethanol blend generally contains from 3.5 to 3.7 wt% oxygen. Thus, based on an assumption of linearity, a 10 vol% ethanol blend would show a 33% increase in "CO effect" relative to a 15 vol% MTBE fuel. For high-emitting vehicles that are running rich a significant portion of the time, the linearity assumption is probably valid. However, for normal-emitting vehicles, it has been suggested that a point may be reached where additional oxygen does little to further reduce CO emissions. (This issue is discussed in detail in a 1989 SAE paper.[12])

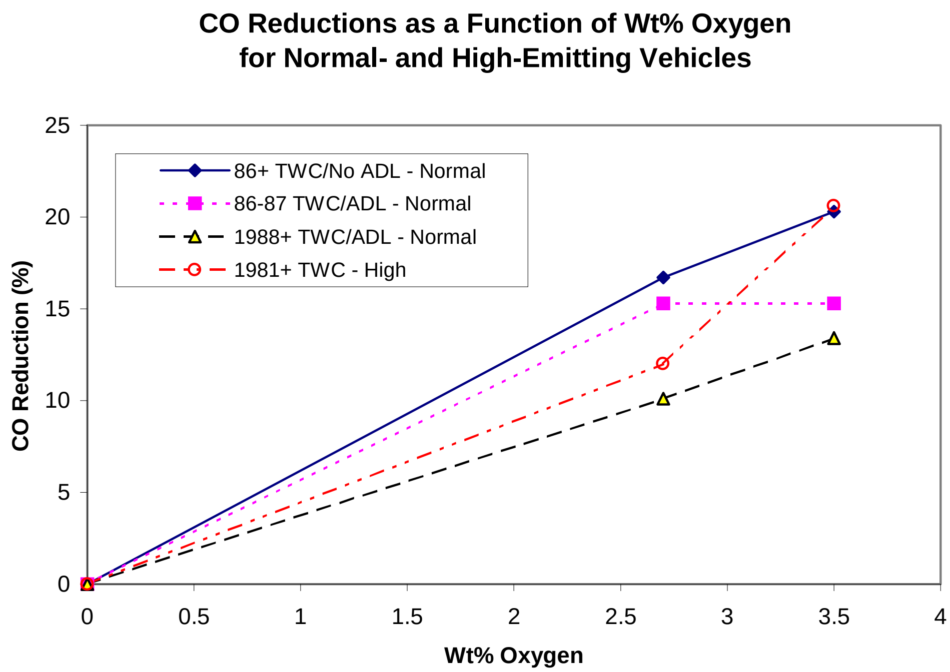
To investigate this issue, results from vehicles in the EPA emission factors database that were tested on both a 10 vol% ethanol blend and a 15 vol% MTBE blend were analyzed. (The fuel set used in this analysis is the same as that used to construct Table 4.) The mean CO emission levels, by emitter category, technology group, and fuel blend, are summarized in Table 8. The oxygen content in the ethanol blend was 3.5 wt% and the

Table 8
Mean CO Emissions From Paired Tests in the EPA Emission Factors Database
(Vehicles Tested on Both EtOH and MTBE Matched RVP Oxygenated Blends)

Emitter Group	Tech Group	Oxy Fuel	Wt% O	n	Mean CO (g/mi)		CO Impact[a]	CO Impact Per Wt% O
					Non-Oxy	Oxy		
Normal	81-85 3W/CL	10% EtOH	3.5	8	4.65	3.89	-16.3% ± 10.8%	-4.7%
	86+ 3W/NoADL	10% EtOH	3.5	57	3.00	2.39	-20.3% ± 6.3%	-5.8%
	86-87 3W/ADL	10% EtOH	3.5	58	3.34	2.83	-15.3% ± 5.7%	-4.4%
	1988+ 3W/ADL	10% EtOH	3.5	58	2.77	2.40	-13.4% ± 4.8%	-3.8%
	81-85 3W/CL	15% MTBE	2.7	8	4.65	3.87	-16.8% ± 13.3%	-6.2%
	86+ 3W/NoADL	15% MTBE	2.7	57	3.00	2.50	-16.7% ± 6.9%	-6.2%
	86-87 3W/ADL	15% MTBE	2.7	58	3.34	2.83	-15.3% ± 4.9%	-5.7%
	1988+ 3W/ADL	15% MTBE	2.7	58	2.77	2.49	-10.1% ± 5.5%	-3.7%
High	81-85 3W/CL	10% EtOH	3.5	7	13.67	10.11	-26.0% ± 37.1%	-7.4%
	86+ 3W/NoADL	10% EtOH	3.5	11	11.72	7.18	-38.7% ± 12.0%	-11.1%
	86-87 3W/ADL	10% EtOH	3.5	19	19.47	17.03	-12.5% ± 9.2%	-3.6%
	1988+ 3W/ADL	10% EtOH	3.5	2	7.62	5.38	-29.5% ± 76.8%	-8.4%
	81-85 3W/CL	15% MTBE	2.7	7	13.67	10.99	-19.6% ± 25.2%	-7.3%
	86+ 3W/NoADL	15% MTBE	2.7	11	11.72	7.49	-36.2% ± 11.1%	-13.4%
	86-87 3W/ADL	15% MTBE	2.7	19	19.47	19.34	-0.7% ± 23.4%	-0.2%
	1988+ 3W/ADL	15% MTBE	2.7	2	7.62	4.85	-36.5% ± 53.3%	-13.5%

[a] Confidence interval reflects a 90% confidence level.

Figure 2



oxygen content in the MTBE blend was 2.7 wt%. The results for normal- and high-emitting vehicles (all data were combined for the high emitters) are illustrated in Figure 2, which indicates a linear response to fuel oxygen content for the 1986+ TWC/No ADL and 1988+ TWC/ADL technology groups (normal emitters). Although the mean CO emission reductions from the normal-emitting 1986-87 TWC/ADL group and the high-emitters show a non-linear trend, the confidence interval for those estimates is such that the trend is linear within the error associated with the estimates. Given this, a linear response should be assumed unless a more rigorous test program evaluating this effect is conducted.

Temperature Effects

One issue that has received considerable attention in the past is whether the benefits predicted for oxygenated blends at moderate temperatures also hold at lower temperatures. A vast majority of the vehicle testing used to generate oxygenated fuel adjustment factors has been conducted at the standard FTP temperature of 75°F. However, these fuels are typically used at much lower temperatures. Because ambient CO studies generally support a lower benefit than that predicted by emission models, it has been postulated that the benefits of oxygenated fuels are diminished at low temperature.

In 1995, Hood and Farina[13] published a review of studies on the effects of oxygenated fuels on emissions at low ambient temperature. Although the available data are quite scattered, the authors concluded that the directionality of the impact of oxygenates at low temperature is consistent with testing at 75°F, i.e., addition of 2% to 3% (by weight) of oxygen generally decreases fleet emissions of HC and CO at lower temperatures. However, they also concluded that the CO reductions are lower (on a percentage basis) compared to what has been observed at 75°F.

Because many of the test programs cited in the above paper tested only a limited number of vehicles, and because the fuel/temperature combinations varied among programs, it is difficult to quantitatively establish an adjustment to account for the impact of cold temperature on the effects of oxygenated fuels. Nonetheless, data from several of the papers cited by Hood and Farina were obtained and analyzed. In addition, the EPA emission factors database contains a number of vehicles that were tested with and without an oxygenated fuel at 75°, 50°, and 20°F. Those data were also evaluated in this effort.

CRC Study - A summary of paired tests from the CRC study is given in Tables 9 and 10. To maintain consistency with other data analyzed in this effort, only the low-altitude data were used in this analysis. The results are stratified by the technologies evaluated in that study – three-way catalysts with adaptive learning and three-way catalysts without adaptive learning are shown in Table 9. All of the vehicles included in Table 9 are normal emitters (i.e., CO emissions less than 7 g/mi when tested at 75°F on Indolene). Results from the four oxidation catalyst vehicles in the program are shown in Table 10. Two of those vehicles were high emitters, and the results are shown separately for normal and high emitters.

Table 9
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from TWC Vehicles in the CRC Study

Model Year/ Technology	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1986-1988 TWC/ADL	5[a]	12.8	MTBE 2.0 wt% O 12.5 psi RVP	75	2.44	2.23	-8.6%
				50	5.43	5.03	-7.4%
				35	8.20	7.70	-6.1%
			EtOH-Splash 3.7 wt% O 13.2 psi RVP	75	2.44	2.12	-13.1%
				50	5.43	4.74	-12.7%
				35	8.20	7.98	-2.7%
			EtOH-Matched 3.7 wt% O 12.7 psi RVP	75	2.44	2.43	-0.4%
				50	5.43	5.13	-5.5%
				35	8.20	7.04	-14.1%
1983-1986 TWC/No ADL	6	12.8	MTBE 2.0 wt% O 12.5 psi RVP	75	3.42	3.14	-8.2%
				50	10.39	10.12	-2.6%
				35	16.79	16.43	-2.1%
			EtOH-Splash 3.7 wt% O 13.2 psi RVP	75	3.42	2.87	-16.1%
				50	10.39	9.16	-11.8%
				35	16.79	14.24	-15.2%
			EtOH-Matched 3.7 wt% O 12.7 psi RVP	75	3.42	3.18	-7.0%
				50	10.39	9.06	-12.8%
				35	16.79	14.49	-13.7%

[a] Note that one of the six TWC/ADL vehicles in the original program had been removed from the database that Sierra received from CRC because of its erratic behavior.

The results presented in Table 9 show a decrease in the magnitude of the oxygenated fuel benefit as temperature is decreased for the MTBE fuel and for the ethanol splash blended fuel. For the ethanol match blended fuel, the opposite occurs for both the TWC/ADL and TWC/No ADL technologies. It is not clear why this occurs, since the RVP and distillation characteristics of this fuel are nearly identical to the MTBE blend (as well as the base gasoline). For the OX CAT vehicles, the results are more variable. This is likely due to the small sample size for these vehicles.

Table 10
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from OX CAT Vehicles in the CRC Study

Model Year/ Technology/ Emitter Cat.	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1979-1980 OX CAT Normal Emitters	2	12.8	MTBE 2.0 wt% O 12.5 psi RVP	75	7.50	7.11	-5.2%
				50	14.73	12.65	-13.9%
				35	24.44	17.03	-30.3%
			EtOH-Splash 3.7 wt% O 13.2 psi RVP	75	7.50	4.83	-35.6%
				50	14.73	11.09	-24.7%
				35	24.44	18.97	-22.4%
1979-1980 OX CAT High Emitters	2	12.8	MTBE 2.0 wt% O 12.5 psi RVP	75	49.89	33.75	-32.4%
				50	32.54	28.86	-11.3%
				35	42.90	35.82	-16.5%
			EtOH-Splash 3.7 wt% O 13.2 psi RVP	75	49.89	35.96	-27.9%
				50	32.54	22.52	-30.8%
				35	42.90	30.44	-29.0%

API Study - A summary of paired data at different temperatures from the API study is given in Tables 11 and 12 for two different oxygenated blends – a 15 vol% MTBE blend and a 10 vol% ethanol splash blend. Table 11 summarizes the results for the nominal 13 psi RVP fuel set, while Table 12 contains the results for the nominal 9 psi RVP fuel set. Three different technology types are shown in these tables: TWC/ADL, TWC/No ADL, and open-loop. Although the results are somewhat scattered, the trends observed in this test program are consistent with the CRC program. In general, the relative reductions in exhaust CO observed with the use of oxygenated blends decrease with decreasing temperature.

One item of note is that in some cases, particularly for the ethanol blends, the maximum reduction is observed at the 55°F test temperature (see Table 12). Because the ethanol blend used in this program was a splash blend, its RVP was about 1 psi higher than the other fuels in the fuel set. (Two fuel sets were tested in this work – one with a nominal RVP of 13 psi and one with a nominal RVP of 9 psi.) It is likely that under the 80°F testing the higher RVP of the ethanol blends is partially offsetting the benefit from the addition of oxygenate (due to higher canister loading and subsequent purge). As found in this test program, the effect of fuel volatility on CO emissions is much more pronounced at 80°F than it is at 55° or 35°F.

Table 11
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from Vehicles in the API Study
13 psi RVP Fuel Set

Model Year/ Technology/	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1986-1988 TWC/ADL Normal Emitters	4[a]	13.1	MTBE 2.6 wt% O 12.7 psi RVP	80	6.35	4.66	-26.6%
				55	4.90	4.20	-14.3%
				35	10.02	10.60	+5.8%
			EtOH-Splash 3.9 wt% O 13.9 psi RVP	80	6.35	5.01	-21.1%
				55	4.90	3.60	-26.5%
				35	10.02	9.72	-3.0%
1981+ TWC/No ADL	3	13.1	MTBE 2.6 wt% O 12.7 psi RVP	80	12.46	7.80	-37.4%
				55	11.97	10.02	-16.3%
				35	22.00	16.78	-23.7%
			EtOH-Splash 3.9 wt% O 13.9 psi RVP	80	12.46	9.86	-20.9%
				55	11.97	10.56	-11.8%
				35	22.00	20.67	-6.0%
1981+ Open-Loop	3	13.1	MTBE 2.6 wt% O 12.7 psi RVP	80	9.55	5.02	-47.4%
				55	11.30	7.05	-37.6%
				35	21.12	20.40	-3.4%
			EtOH-Splash 3.9 wt% O 13.9 psi RVP	80	9.55	7.31	-23.5%
				55	11.30	5.27	-53.4%
				35	21.12	17.61	-16.6%

[a]One of the five TWC/ADL vehicles in the API study was a high emitter and demonstrated erratic behavior.

Table 12
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from Vehicles in the API Study
9 psi RVP Fuel Set

Model Year/ Technology/	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1986-1988 TWC/ADL	4[a]	8.9	MTBE 2.7 wt% O 9.1 psi RVP	80	2.47	2.59	+4.9%
				55	4.84	3.55	-26.7%
				35	10.58	9.26	-12.5%
			EtOH-Splash 3.7 wt% O 9.9 psi RVP	80	2.47	2.36	-4.5%
				55	4.84	3.26	-32.6%
				35	10.58	8.92	-15.7%
1981+ TWC/No ADL	3	8.9	MTBE 2.7 wt% O 9.1 psi RVP	80	9.84	7.60	-22.8%
				55	13.52	12.13	-10.3%
				35	20.95	19.56	-6.6%
			EtOH-Splash 3.7 wt% O 9.9 psi RVP	80	9.84	7.57	-23.1%
				55	13.52	12.01	-11.2%
				35	20.95	22.13	+5.6%
1981+ Open-Loop	3	8.9	MTBE 2.7 wt% O 9.1 psi RVP	80	6.08	4.50	-26.0%
				55	8.73	6.99	-19.9%
				35	20.90	20.90	0.0%
			EtOH-Splash 3.7 wt% O 9.9 psi RVP	80	6.08	4.43	-27.1%
				55	8.73	5.21	-40.3%
				35	20.9	18.53	-11.3%

[a] One of the five TWC/ADL vehicles in the API study was a high emitter and demonstrated erratic behavior. It was excluded from the calculations presented in this table.

<u>CARB Study</u> - As with the test programs described above, the CARB Low Oxygenates test program was limited in terms of the number of vehicles tested (13). In addition, the winter fuel set used in this program was tested only at 75° and 50°F. Nonetheless, those data were obtained and analyzed for this study. A summary of the results, by technology type, is given in Table 13, which shows mixed results with respect to the impact of oxygenate at the lower temperature. For TWC/ADL vehicles operating on an MTBE blend, the oxygen effect diminishes at 50°F relative to 75°F. However, the results for that

Table 13
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from Vehicles in the CARB Study
Winter Fuel Set

Model Year/ Technology/	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1987-1990 TWC/ADL (All Normals)	5	9.6	MTBE 2.7 wt% O 9.6 psi RVP	75	3.65	3.25	-10.9%
				50	5.08	5.15	+1.3%
			EtOH-Match 2.7 wt% O 9.6 psi RVP	75	3.65	3.89	+6.7%
				50	5.08	4.79	-5.8%
1983-1985 TWC/No ADL (All Highs)	3	9.6	MTBE 2.7 wt% O 9.6 psi RVP	75	13.36	11.37	-14.9%
				50	15.19	11.90	-21.6%
			EtOH-Match 2.7 wt% O 9.6 psi RVP	75	13.36	12.01	-10.1%
				50	15.19	11.72	-22.8%
1976-1978 Open-Loop Ox Cat (All Highs)	2	9.6	MTBE 2.7 wt% O 9.6 psi RVP	75	27.70	20.13	-27.3%
				50	24.31	36.46	+31.6%
			EtOH-Match 2.7 wt% O 9.6 psi RVP	75	27.70	19.21	-30.7%
				50	24.31	38.35	+38.5%

technology group tested on an ethanol matched RVP blend show an increase in the oxygenate benefit at 50°F. (In fact, that fuel caused an increase in CO emissions for these vehicles at 75°F, and a slight decrease at 50°F relative to the non-oxygenated base fuel.) Again, the small number of vehicles in this test program makes it difficult to definitively predict the effect of temperature on the impact of oxygenated fuels.

EPA Emission Factors Database - The final database evaluated to assess the impact of ambient temperature on the CO emissions effects of fuel oxygenates was the EPA emission factors database. That database contains emissions data from vehicles tested on a variety of fuels at a number of ambient temperatures (tests at 75°, 50°, and 20°F were analyzed in this effort). For the most part, the oxygenated fuel low-temperature testing has been conducted with 10 vol% ethanol blends, although there is a limited number of low-temperature tests that were conducted with 15 vol% MTBE blends.

The most comprehensive (in terms of temperatures) and consistent (in terms of fuels) series of tests in this database includes 29 vehicles that were tested with a base gasoline with an RVP of 11.7 psi and a 10 vol% ethanol blend with an RVP of approximately 11.8 psi. The test sequence designations from the EPA database were as follows:

Temperature	Non-Oxygenate Fuel	Oxygenated Fuel
75°F	CMFUEL	TST65
50°F	TST23	TST66
20°F	TST25	TST67

Although the EPA database does not have detailed fuel specification information, it has been assumed here that the oxygenated blend used for this series of tests was generally consistent with the 11.7 psi RVP commercial fuel used in the non-oxygenated tests.

The mean emissions and oxygen effect from the paired tests outlined above are summarized in Table 14 by technology and emitter class. Only two of the 29 vehicles in this series of tests were equipped with open-loop systems, so they were removed from the analysis. The 21 normal-emitting three-way/closed-loop vehicles were segregated by model year (1981 to 1985 and 1986+), while the high emitters were combined into a single group. As observed in Table 14, the impact of oxygenated fuel is diminished at 50° and 20°F (relative to 75°F) for the normal emitters. The results for the high-emitting vehicles show considerable scatter.

Table 14
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from TWC Vehicles in the EPA Database
Fuels Having a Nominal RVP of 11.7 psi - Tests Conducted at 75°, 50°, and 20°F

Model Year/ Technology	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1986+ TWC/CL Normal Emitters	13	11.7	EtOH 10 vol% 11.8 psi RVP	75	3.14	2.48	-21.0%
				50	7.04	5.87	-16.6%
				20	13.78	11.32	-17.9%
1981-1985 TWC/CL Normal Emitters	8	11.7	EtOH 10 vol% 11.8 psi RVP	75	5.21	3.88	-23.4%
				50	6.89	5.80	-16.2%
				20	11.11	9.64	-16.3%
1981+ TWC/CL High Emitters	6	11.7	EtOH 10 vol% 11.8 psi RVP	75	55.53	35.31	-36.4%
				50	34.65	28.53	-17.7%
				20	39.76	22.38	-43.7%

A similar analysis is shown in Table 15. However, in this case, only tests at 75° and 20°F were considered, and all paired tests in which the oxygenated fuel was a 10 vol% ethanol blend were included, regardless of whether the RVP between the non-oxygenated fuel and the oxygenated fuel matched. (For the majority of those tests, the RVP for the 75°F tests did match. For the 20°F testing, the impact of differences in fuel volatility is less of a concern.) As observed in the table, this approach increased the sample size considerably. The results from this analysis show that the effect of fuel oxygen content on CO emissions diminishes at lower temperatures. For this group of vehicles, both normal and high emitters had lower CO reductions at the 20°F test temperature relative to 75°F.

Table 15
Effect of Oxygenated Gasoline and Temperature on Mean CO Emissions of Paired Tests from TWC Vehicles in the EPA Database
All Paired Ethanol Blend Tests Conducted at 75° and 20°F

Model Year/ Technology	Sample Size	Base Fuel RVP (psi)	Oxygen Blend	Temp (°F)	Base CO (g/mi)	Oxy CO (g/mi)	Oxygen Effect
1986+ TWC/CL Normal Emitters	45	9.0 or 11.7	EtOH 10 vol% Misc. RVP	75	3.40	2.84	-16.5%
				20	15.31	13.54	-11.6%
1981-1985 TWC/CL Normal Emitters	15	9.0 or 11.7	EtOH 10 vol% Misc. RVP	75	4.50	3.75	-16.7%
				20	14.98	12.68	-15.4%
1981+ TWC/CL High Emitters	16	9.0 or 11.7	EtOH 10 vol% Misc. RVP	75	52.53	34.99	-33.4%
				20	53.93	41.50	-23.0%

In summary, many of the variable-temperature test programs support the contention that as ambient temperature is decreased, the impact of fuel oxygen content on exhaust CO emissions is diminished. However, the available data are highly variable, making a precise quantitative correction for temperature difficult. At this time, there is no basis for offering a specific recommendation to account for temperature effects on the CO benefits attributable to oxygenated fuels, although EPA should revisit this issue if/when additional cold-temperature oxygenated fuel data are collected.

Oxygen Impacts on FTP, Starting, and Running CO Emissions

One of the questions that came up during the course of this study was whether the fuel oxygen effects on CO emissions calculated from FTP composite data could be applied equally to all operating modes (i.e., cold start, hot start, and stabilized). Because EPA has indicated that running and starting emissions will be modeled separately in MOBILE6, this issue will take on greater importance with the release of that model.

As a check on the validity of using FTP-composite fuel oxygen impacts for all operating modes, Sierra compared mean emissions from the EPA matched RVP data pairs for the FTP-composite results (presented above in Table 4), hot-running emissions, and cold-start emissions. Two approaches were used to estimate hot-running and cold-start emissions from the individual bag results. First, Sierra has previously estimated cold-start emissions (in terms of grams per engine start) from FTP bag data by subtracting bag 3 from bag 1 and multiplying the result by the length of bags 1 and 3 (3.59 miles). Although bag 3 occurs after a 10-minute soak, it has been reported that the degree of fuel enrichment is diminished and catalyst light-off is rapid in bag 3 for properly functioning late-model vehicles. Thus, bag 3 is a reasonable estimate of stabilized emissions over the same cycle as bag 1 and can be used to develop a cold-start emissions estimate. For overall hot-running emissions, Sierra's methodology combines bag 2 with bag 3 of the FTP using weighting factors of 0.521 for bag 2 and 0.473 for bag 3. These weighting factors are consistent with the length (in miles) of bags 2 and 3. Shown elow are the equations used by Sierra to calculate cold-start and hot-running emissions, where the bag data are reported in g/mi.

$$CS_{Sierra}\text{ (grams/start)} = (\text{Bag 1} - \text{Bag 3}) * 3.59\text{ miles}$$

$$HR_{Sierra}\text{ (grams/mile)} = (\text{Bag 2} * 0.521) + (\text{Bag 3} * 0.473)$$

EPA is taking a similar approach to developing cold-start and hot running emission estimates for MOBILE6. However, its approach is a little more sophisticated in that "Hot Running 505" (HR505) emissions, defined as bag 3 without an engine start and in a completely warmed-up state, are substituted for the bag 3 results in the above equations. HR505 emissions can be estimated from individual bag data with regression equations recently developed by EPA.[14] For CO, that equation is:

$$HR505 = \exp(-0.3452*\ln(\text{Bag 1}) + 0.4304*\ln(\text{Bag 2}) + 0.5375*\ln(\text{Bag 3}) - 0.0674)$$

where exp denotes the exponential function and ln is the natural logarithm. Using the HR505 results obtained from the equation above, cold-start and running exhaust emission rates are generated from individual bag data according to the following equations:

$$CS_{EPA}\text{ (grams/start)} = (\text{Bag 1} - HR505) * 3.59\text{ miles}$$

$$HR_{EPA}\text{ (grams/mile)} = (\text{Bag 2} * 0.521) + (HR505 * 0.473)$$

The above methodology was applied to the EPA matched RVP data set (i.e., Table 4) to obtain cold-start and hot-running emission estimates for each vehicle for the baseline fuel and for the oxygenated blends. The CO emissions impacts of the oxygenated fuel blends were then estimated for the composite FTP and for the hot-running and cold-start emissions estimates using both the Sierra methodology and the EPA methodology outlined above. The results of that analysis are summarized in Table 16. In general, for the groups with larger sample sizes, the results show consistent impacts across the FTP composite, hot-running, and cold-start modes. For cases in which the impacts show a noticeable difference, e.g., normal-emitting 1988+ 3W/ADL vehicles operated on 10 vol % ethanol, the FTP, hot-running, and cold-start impacts are within the uncertainty intervals computed for these operating modes. Based on these results, the use of FTP-composite CO emissions impacts for hot-running and cold-start emissions is valid.

Recommended Methodology for MOBILE6

As evidenced by the information presented above, there is a considerable body of data with which to predict the emissions impacts of oxygenated fuels. One area of concern, however, is whether the comparisons being made with the various data sets reflect only the impact of the oxygenate, or whether other fuel parameter changes are contributing to the differences observed (e.g., RVP differences). With this in mind, the following recommendations are being made.

CO Impacts as a Function of Oxygen Content for Tier 0 Vehicles - To generate an overall adjustment to account for the impact of oxygen content on CO emissions, paired test results from the databases described above were combined into a single data set.* In all cases, only testing conducted at a nominal temperature of 75°F was included in the final database used to develop the oxygen content fuel adjustments.

For each vehicle in the final database, the percentage CO impact from the use of oxygenated gasoline was determined for each fuel pair (i.e., oxygenated versus non-oxygenated gasoline) over which the vehicle was tested. These results were then put on a consistent basis by dividing the impact by the oxygen content in the oxygenated test fuel (i.e., the wt% oxygen), giving a CO impact per 1 wt% oxygen for each fuel pair. (This approach is supported by the linearity demonstration presented above.) So that individual vehicles receiving multiple tests (e.g., those in the Auto/Oil program) would not have an undue influence on the final results, the average CO impact (per 1 wt% oxygen) was determined for each vehicle by taking the mean of the impacts determined for each fuel pair (i.e., an average CO impact per wt% oxygen was calculated for each vehicle).

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* Note that data from 1986 and later model year vehicles in the EPA 11.7 psi matched RVP testing (i.e., Table 6) were not used because it was not possible to determine which of these vehicles had ADL systems. In addition, data from the Auto/Oil AMOT study (Table 2) were not used because it was felt that the results from the RVP/Oxygenate testing (Table 3) for those vehicles were more applicable for determining a winter CO impact of fuel oxygen content.

Table 16

Oxygen Impacts on Mean CO Emissions Based on FTP, Running, and Starting Emissions (EPA Matched RVP Non-Oxy/Oxy Pairs)

Oxygenated Fuel	Technology Group	Emitter Class	n	FTP Impact[a]	Sierra Hot-Running Impact[a]	Sierra Cold-Start Impact[a]	EPA Hot-Running Impact[b]	EPA Cold-Start Impact[b]
10 vol% EtOH	81+ OX/OL	Normal	1	-15.0% ± na	4.7% ± na	-36.2% ± na	4.3% ± na	-33.4% ± na
10 vol% EtOH	81-85 3W/CL	Normal	8	-16.4% ± 10.8%	-14.2% ± 8.5%	-23.0% ± 42.1%	-15.5% ± 9.7%	-20.8% ± 38.0%
10 vol% EtOH	86+ 3W/NoADL	Normal	141	-20.8% ± 3.4%	-21.4% ± 4.9%	-19.3% ± 4.8%	-20.9% ± 5.3%	-19.9% ± 4.5%
10 vol% EtOH	86-87 3W/ADL	Normal	89	-18.7% ± 4.3%	-19.5% ± 5.8%	-17.1% ± 7.2%	-18.4% ± 7.1%	-18.4% ± 5.9%
10 vol% EtOH	88+ 3W/ADL	Normal	110	-15.2% ± 3.9%	-17.0% ± 5.3%	-11.0% ± 5.1%	-18.3% ± 5.6%	-10.7% ± 4.6%
15 vol% MTBE	81+ OX/OL	Normal	6	-36.6% ± 27.7%	-30.4% ± 42.0%	-44.9% ± 19.0%	-32.3% ± 38.8%	-43.1% ± 20.9%
15 vol% MTBE	81-85 3W/CL	Normal	12	-14.7% ± 9.7%	-18.0% ± 6.9%	-1.8% ± 29.4%	-13.6% ± 8.4%	-9.4% ± 23.9%
15 vol% MTBE	86+ 3W/NoADL	Normal	62	-16.2% ± 6.4%	-16.5% ± 8.6%	-15.8% ± 6.6%	-15.3% ± 9.0%	-16.5% ± 6.8%
15 vol% MTBE	86-87 3W/ADL	Normal	65	-14.5% ± 4.6%	-17.6% ± 6.5%	-6.3% ± 7.6%	-18.4% ± 7.5%	-8.0% ± 6.4%
15 vol% MTBE	88+ 3W/ADL	Normal	58	-10.2% ± 5.6%	-10.9% ± 7.1%	-8.3% ± 10.5%	-11.1% ± 9.0%	-8.5% ± 9.1%
10 vol% EtOH	81+ OX/OL	High	0	na	na	na	na	na
10 vol% EtOH	81-85 3W/CL	High	7	-26.0% ± 37.1%	-33.1% ± 41.9%	-7.5% ± 25.3%	-34.4% ± 42.9%	-5.2% ± 23.9%
10 vol% EtOH	86+ 3W/NoADL	High	25	-28.4% ± 11.0%	-28.8% ± 12.6%	-25.1% ± 14.8%	-28.7% ± 14.6%	-26.3% ± 15.1%
10 vol% EtOH	86-87 3W/ADL	High	22	-14.1% ± 8.2%	-14.6% ± 7.7%	-16.0% ± 43.9%	-11.0% ± 7.5%	-18.3% ± 42.2%
10 vol% EtOH	88+ 3W/ADL	High	4	-41.9% ± 29.3%	-41.1% ± 28.6%	-45.9% ± 43.4%	-41.6% ± 27.3%	-44.3% ± 41.1%
15 vol% MTBE	81+ OX/OL	High	8	-37.5% ± 10.7%	-38.2% ± 12.8%	-34.6% ± 15.3%	-37.7% ± 18.1%	-34.4% ± 15.5%
15 vol% MTBE	81-85 3W/CL	High	18	-19.8% ± 8.1%	-23.9% ± 11.0%	-5.5% ± 16.9%	-24.6% ± 12.9%	-5.8% ± 17.5%
15 vol% MTBE	86+ 3W/NoADL	High	20	-21.0% ± 12.3%	-22.9% ± 17.8%	-13.4% ± 14.6%	-20.5% ± 17.6%	-17.7% ± 12.0%
15 vol% MTBE	86-87 3W/ADL	High	23	-2.4% ± 20.3%	-4.1% ± 19.3%	-4.1% ± 47.2%	1.3% ± 25.7%	-5.9% ± 44.7%
15 vol% MTBE	88+ 3W/ADL	High	2	-36.4% ± 53.4%	-30.5% ± 59.3%	-77.6% ± 59.4%	-34.3% ± 66.2%	-67.7% ± 10.2%

[a] Confidence interval reflects a 90% confidence level.

[b] Does not include the uncertainty associated with EPA's HR505 regression equation.

Once the individual vehicle impacts were determined, the overall fleet impacts were calculated by taking the mean of the per-vehicle impacts* according to the technology groups described previously. This was done as a function of emitter category and whether the fuel pairs had matched or mis-matched RVPs. For the matched RVP fuel pairs, all oxygenate types were combined (i.e., ethanol, MTBE, and ETBE). For the mis-matched RVP fuel pairs, only ethanol splash blends were considered since, in practice, that is the fuel most likely to have a higher RVP than the non-oxygenated base fuel. The results of this analysis are given in Table 17 for the matched RVP blends. Note that because of the large variability observed in the high-emitting vehicles, all 1981 and later three-way catalyst/closed-loop vehicles were combined. Also, because of the small number of non-catalyst and oxidation catalyst/open-loop vehicles in the databases evaluated in this effort, it is recommended that the CO impacts developed by EPA in the 1988 technical guidance on oxygenated fuels[15] continue to be used for those technologies.

Table 17
Recommended CO Effects From the Use of Oxygenated Fuels for Matched RVP Blends at 75°F

Emitter Category	Technology	CO Impact Per Wt% Oxygen	Typical MTBE Blend (2.7 wt% O)	Typical Ethanol Blend (3.5 wt% O)
Normal	1988+ TWC/ADL	-3.1% (n=133)[a]	-8.4%	-10.9%
	1986-87 TWC/ADL	-4.8% (n=104)	-13.0%	-16.8%
	1986+ TWC/No ADL	-5.7% (n=151)	-15.4%	-20.0%
	1981-85 TWC/CL	-4.0% (n=73)	-10.8%	-14.0%
	OX/OL[b]	-9.4%	-25.4%	-32.9%
	Non-Catalyst[b]	-6.6%	-17.8%	-23.1%
High	1981+ TWC/CL	-5.3% (n=134)[a]	-14.3%	-18.6%
	OX/OL[b]	-9.4%	-25.4%	-32.9%
	Non-Catalyst[b]	-6.6%	-17.8%	-23.1%

[a] Sample size shown in parentheses.
[b] CO impacts for these technologies are based on reference 15.

* One might argue that calculating the percent reduction in fleet-average CO is more reflective of the fleet-wide impact of oxygenated fuels. However, because of the widely variable base fuels used in the test programs evaluated in this study, and because the data were segregated by emitter category, it was felt that the approach taken was less prone to being heavily influenced by a few vehicles that may or may not be reflective of the in-use population.

Table 18 summarizes the results of the paired-data analysis for the ethanol splash blends that have a nominal 1 psi RVP increase over the base fuel. Outlined below are several items worth noting with respect to that table.

Table 18
Recommended CO Effects From the Use of Oxygenated Fuels for Ethanol Splash Blends with Mis-Matched RVP at 75°F

Emitter Category	Technology	CO Impact Per Wt% Oxygen	Typical Ethanol Blend (3.5 wt% O)
Normal	1988+ TWC/ADL	+0.3% (n=34)[a]	+1.1%
	1986-87 TWC/ADL	-3.1% (n=44)	-10.9%
	1986+ TWC/No ADL	-3.6% (n=31)	-12.6%
	1981-85 TWC/CL	-5.0% (n=35)	-17.5%
High	1981+ TWC/CL	-4.5% (n=27)[a]	-15.8%

[a] Sample size shown in parentheses.

- In general, the CO emissions impacts listed in Table 18 are lower than those listed in Table 17. This is the result of the higher RVP of the oxygenated fuel relative to the base fuel (i.e., the increase in RVP leading to higher CO emissions partially offsets the benefits of the fuel oxygen). This is particularly evident for the 1988+ TWC/ADL technology, which appears to show a stronger response to the RVP increase than to the presence of fuel oxygen, resulting in a slight increase in CO emissions with ethanol splash blends.

- Recommendations for OX/OL and non-catalyst vehicles are not included in Table 18 because EPA adjusted those data for RVP differences prior to developing the CO impacts. MOBILE contains a separate RVP adjustment, and that adjustment should be applied to the impacts listed in Table 17 to reflect fuels receiving an RVP waiver for these technology types.

- The results presented in Table 18 are valid at 75°F and are valid only for ethanol splash blends receiving an RVP waiver. As the test temperature decreases, it was shown previously that the RVP effect will be less pronounced. For “warm-weather” areas, the results in Table 18 should be used directly to determine the CO impacts of ethanol splash blends receiving an RVP waiver. However, at temperatures below 75°F, some combination of Tables 17 and 18 should be used because the effect of RVP on CO emissions decreases with decreasing temperature. One means to account for this is to linearly interpolate between the two tables from 75°F (Table 18) down to 45°F (Table 17), which is the temperature at which the RVP adjustment in MOBILE5 is turned off. Below 45°F, the results presented in Table 17 should be used for both matched RVP and mis-matched RVP blends. This approach is supported by data from the API RVP/Oxygenates program[9] which show that the effect of RVP on CO emissions is greatly reduced at 55°F and negligible at 35°F. In addition, data from recent testing representative of the Las Vegas vehicle fleet showed that RVP has a statistically significant effect on CO emissions collected at “afternoon” winter temperatures (65°F), while no statistically significant effect was observed for the “morning” temperatures (40°F).[16]

Tier 1 and Advanced Technology Vehicles - A significant question that remains relates to the oxygenated fuel CO emissions impact assumed for vehicles certified to Tier 1 and lower emission standards. Based on testing performed in the Auto/Oil program,[5] the response to fuel oxygen (at a 2.0 wt% level) in a Tier 1 fleet and in an advanced technology fleet was very small (i.e., +1.2% and -1.0%, respectively). In addition, recent testing conducted by CRC[17] to support an investigation of fuel sulfur impacts on low-emission vehicles indicates that the presence of oxygen has little or no effect on CO emissions from advanced technology vehicles. Given the importance of these technologies on future emission estimates prepared with MOBILE6, it is recommended that testing be performed to better define the emissions impact of oxygenated fuels on late-model vehicles.

Conclusions and Final Recommendations for MOBILE6

Based on the analyses presented above, the following recommendations are being made with respect to modeling the CO emissions impacts of oxygenated fuel blends in MOBILE6:

- For Tier 0 vehicles, the CO emissions impacts listed in Table 17 should be used for matched RVP blends at all temperatures. Those impacts should also be used for mis-matched RVP blends (i.e., ethanol splash blends receiving an RVP waiver) at temperatures below 45°F. The CO emissions impacts listed in Table 18 should be used for ethanol splash blends receiving an RVP waiver at temperatures of 75°F. Between 45° and 75°F, the CO impacts of ethanol splash blends receiving an RVP waiver should be modeled by interpolating between Table 17 (= 45°F) and Table 18 (= 75°F).

- Because new data on older technology vehicles (i.e., pre-1981 oxidation catalyst and non-catalyst vehicles) have not been collected in recent years, the CO emissions impacts for those vehicles should be based on EPA’s 1988 Guidance

Document on the emissions impacts of oxygenated fuels.[15] These effects are currently used in MOBILE5a.

- With the exception of ethanol splash blends receiving an RVP waiver, the CO emissions impacts are not a function of oxygenate type. Further, the CO emissions impacts are a linear function of the wt% oxygen in the fuel.

- The percentage CO emissions impacts developed from FTP-composite data can be applied to both starting and running exhaust emission estimates.

- Although available data appear to indicate that the CO impacts of oxygenated fuels are diminished at low ambient temperatures, the data are highly variable, making a precise quantitative estimate of this effect difficult. Thus, no specific recommendation is being made at this time to adjust the oxygenated fuel CO impacts for low ambient temperature. (Recall that the temperature adjustment of the splash-blended ethanol CO impacts is an RVP adjustment, not an oxygenate adjustment.)

- Very few data are available with which to estimate the impact of oxygenated fuel on CO emissions from Tier 1 and advanced technology vehicles. The data that are available indicate only a small effect is observed for these technologies. Given the importance of these vehicles on future CO emissions estimates prepared with MOBILE6, testing needs to be conducted to better define the emissions impacts of using oxygenated fuels with these vehicles. Until a more robust dataset is available, estimates prepared with the existing data should be used in MOBILE6.

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