

REVERSIBILITY OF GASOLINE SULFUR EFFECTS ON LOW EMISSION VEHICLES

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EXECUTIVE SUMMARY

This paper reviews two recent studies sponsored by the Coordinating Research Council (CRC) and the American Petroleum Institute (API) that examined the effects of gasoline sulfur on emissions of criteria pollutants. Specifically, these studies have examined vehicle operation over the following steps: (1) initial operation on low-sulfur gasoline, (2) operation on high-sulfur gasoline, and (3) return to operation on low-sulfur gasoline. These studies are designed to determine the reversibility of the sulfur effect, *i.e.*, the extent to which catalysts can recover their effectiveness when returned to the use of low-sulfur fuel after operating on high-sulfur fuel. The main conclusions that were found in these studies are summarized below:

- The effects of sulfur are reversible to a large degree. The extent of the reversibility varies from vehicle to vehicle and, for a given vehicle, is different for different pollutants.
- The amount of reversibility increased when the US06 cycle was used for preconditioning instead of the LA-4 cycle.
- There is some flexibility available to the automotive emission engineer for development of vehicles that demonstrate reduced sulfur sensitivity and improved reversibility.
- The final fleet-average emissions in the API study, computed as arithmetic averages of the five vehicles certified to LEV or ULEV standards, were less than the baseline emissions for NO_x. The final fleet average NMHC and CO emissions were, respectively, 8.6% and 7.8% higher than the baseline. The vehicles used in this average had catalysts with approximately 4,000 miles.

- The final fleet-average emissions in the CRC study, computed as arithmetic averages, were less than the baseline emissions for NMHC and CO. The final fleet average NO_x emissions were 10% higher than the baseline. All vehicles in this study were certified to LEV standards with catalysts aged to 100,000 miles.

INTRODUCTION

This paper reviews the recent work sponsored by the Coordinating Research Council (CRC) and the American Petroleum Institute (API) on the effects of sulfur on automotive catalysts. These studies evaluated reversibility of the gasoline sulfur effect, *i.e.*, the extent to which catalysts can recover their effectiveness when returned to the use of low-sulfur fuel after operating on high-sulfur fuel.

These studies were undertaken to provide information for the U. S. Environmental Protection Agency (EPA). The EPA is currently developing regulatory proposals for more stringent emission standards, known as the Tier 2 standards, for passenger cars and light-duty trucks. EPA has already released a report discussing the need and feasibility of such standards (EPA, 1998a). One of the issues identified in that report is the effect of gasoline sulfur on emissions. Because of this effect, EPA is considering regulations for gasoline sulfur and has prepared an additional report (EPA, 1998b) discussing the issues associated with fuel sulfur control. Reversibility of sulfur effects is one of the main issues that EPA is concerned about in considering different approaches to regulation of fuel sulfur. EPA's report on sulfur issues presents the following statement:

If sulfur's effect on catalyst performance is not substantially reversible, sulfur controls must be uniform nationwide and year-round, as the benefits of a regional sulfur control program would be permanently compromised whenever vehicles traveled between low and high-sulfur areas.

EPA acknowledged a lack of data on sulfur reversibility and is looking to the results of this test program and a sulfur reversibility program done by the CRC to "facilitate a more accurate projection of the degree of reversibility achievable with potential Tier 2 vehicles."

This paper reviews the API and CRC studies and the implications that they have for determining the sulfur reversibility of potential Tier 2 vehicles in the context of the Tier 2 regulations. The next section reviews the methods used in the API sulfur sensitivity and reversibility fleet program and compares these methods with those used in the CRC sulfur reversibility program. The subsequent section analyses the sulfur sensitivity results from the API program and compares and contrasts them with results obtained in the CRC programs. The next two sections analyze the sulfur reversibility results and the factors that contribute to the sulfur sensitivity and reversibility for individual vehicles. The final two sections present the conclusions and the regulatory implications.

METHODOLOGY

The results of the API study are contained in three reports. One report (Higinbotham, 1998) describes the experimental methods and reports the data; another report (Sierra Research, 1998) analyzes the data in terms of the emission control systems of the various vehicles. The final report (Gunst, 1999) presents a statistical analysis of the data. This methodology is compared with that employed in the CRC sulfur sensitivity and reversibility studies (Schleyer, et al., 1998; CRC, 1998) to identify factors that may lead to differences in results and conclusions.

All vehicles studied in the API reversibility study were production vehicles. The specific test vehicles are listed in Table 1.

Vehicle	Engine	Certification Level	50,000 and 100,000-mile Emission Standards (gm/mi)		
			NMOG ¹	CO	NO _x
1998 Lincoln Town Car	4.6 liter V-8	Tier 1	0.25	3.4	0.4
1997 Chevrolet S10	4.3 liter V-6		0.31	4.2	0.6
1998 Ford Taurus	3.0 liter V-6	LEV	0.075	3.4	0.2
1998 Mercury Grand Marquis	4.6 liter V-6		0.090	4.2	0.3
1998 Nissan Altima	2.4 liter I-4				
1998 Toyota Avalon	3.0 liter V-6				
1998 Honda Accord	2.3 liter I 4	ULEV	0.040	1.7	0.2
			0.055	2.1	0.3

¹The Tier 1 standards are expressed in terms of NMHC instead of NMOG.

With the exception of the Chevrolet S10, all vehicles were 1998 model year and had accumulated 6,000 to 10,000 miles of customer service driving prior to the start of the test program. The S10 was a 1997 vehicle that had accumulated approximately 50,000 miles of customer driving. The S10 and Town Car were certified to Tier 1 standards. The Honda was certified to the ultra-low-emission vehicle (ULEV) standard. The other vehicles were certified to the low-emission vehicle (LEV) standard. An initial screening and inspection was performed to assure each vehicle was operating according to the manufacturer specifications. In addition, each test vehicle was screened for emissions using the US06 driving schedule. This testing was done to evaluate the potential for the test vehicles to meet the US06 portion of the supplemental FTP emission test requirements. None of the vehicles in the study met those requirements for all pollutants, based on California Air Resources Board (CARB) 4,000-mile standards. At the end of the screening procedures, each vehicle was equipped with new original equipment catalysts and oxygen sensors. Each vehicle was then driven 4,000 miles prior to starting the sulfur reversibility test sequence.

Use of 4,000-mile road-aged catalysts in the API reversibility program is a significant difference from the procedure used in the CRC reversibility program. The CRC program used catalysts aged to the equivalent of 100,000 miles. Each vehicle manufacturer provided these aged catalysts. The differences in aging levels of the catalysts used in the two programs have a significant impact on the results. *As such, the two reversibility programs are not strictly comparable, but can be viewed as complementary where the API program highlights results using low-mileage catalysts and the CRC program highlights results using high-mileage catalysts.* Some comparisons of sulfur sensitivity can be made since the CRC low emission vehicle sulfur sensitivity program (Schleyer, et al., 1998) tested low-mileage (approximately 10,000 miles) catalysts in addition to 100,000-mile aged catalysts. In the API program, new original equipment catalysts for the Taurus and Altima were aged using the General Motors RAT-A driving schedule to 100,000 miles equivalent. For these vehicles, a comparison between low-mileage and high mileage-catalysts was obtained.

In the API study vehicles were equipped with thermocouples for measurement of catalyst temperatures and fitted with sample ports for engine-out and catalyst mid-bed sampling for catalyst efficiency analysis. In addition, the voltages of the upstream oxygen sensors were monitored and each vehicle was equipped with an upstream wide-range oxygen sensor for air-

fuel measurement. This provided additional engineering data for analysis and correlation with emission results.

California Phase II reformulated gasoline (RFG) was used in the API study and was doped with a sulfur mixture containing dimethylsulfide, thiophene, and benzothiophene. The CRC sulfur reversibility program utilized a conventional federal non-reformulated (non-oxygenated) fuel doped with a mixture containing the same three organosulfur compounds. In the earlier CRC low emission vehicle sulfur sensitivity program, studies were done with both federal and California Phase II reformulated base fuels. Although some differences were noted in emission levels with the two fuels, the effects of sulfur level were noted to be similar for the two fuels. Thus, it is not expected that the use of these different base fuels in the two programs should significantly affect the sulfur sensitivity or reversibility results.

Fuel change procedures used in the API program involved two or three cycles of draining the fuel, filling the fuel tank with three gallons of the new fuel and five miles of driving.. This sequence was followed by an additional fuel drain, filling the tank to 40% of its capacity and five minutes of operation at 60 mph to establish closed-loop operation and then preconditioning with either the LA-4, US06, or EPEFE driving cycle. Following a fifteen-hour soak, an emissions test using the federal test procedure (FTP) was conducted. To avoid residual canister effects with fuel changes, the Altima, Town Car, Taurus, and Grand Marquis had their canisters disconnected. For the Accord, Avalon, and S10, interchangeable canisters were loaded with the appropriate test fuel vapors during fuel changes. Fuel tank samples were analyzed to check the fuel change procedures. These identified problems with the Altima and Grand Marquis that resulted in the invalidation of some early tests that were subsequently repeated.

The CRC fuel change procedure involved a drain and 3-gallon fill followed by a LA-4 driving schedule and three idle/engine-off sequences. Another fuel drain was then conducted and a 40% fill followed by preconditioning either with the LA-4 or US06 driving schedule. After a cold soak, an FTP test was conducted. One additional element was placed in the CRC fuel change procedure prior to the initial/baseline testing with low-sulfur fuel and during the change to high-sulfur fuel. Prior to the initial LA-4 preconditioning, an EPEFE preconditioning cycle was performed. It appears that this was done to eliminate any fuel carry-over effects for the CRC fleet since these vehicles had previously been used in the low-emission vehicle program and had

been exposed to a variety of fuel sulfur levels. This was not necessary in the API program since immediately prior to the initial/baseline low-sulfur testing, these vehicles had been operated for 4000 road miles with low-sulfur fuel. Use of this EPEFE preconditioning during the high-sulfur fuel changeover could possibly cause differences in the sulfur sensitivity results obtained in the CRC and API programs. The EPEFE cycle is designed to assure high temperature/rich vehicle operation. Although this will result in decomposition of cerium sulfate, it is not clear what impact this will have on sulfur adsorption on the platinum group metals. This is discussed further in the next section on sulfur sensitivity

It could be argued that elaborate fuel change procedures should be avoided in evaluating the effects of sulfur reversibility in real-world situations. A simple drain and fill followed by a sequence of emission testing until stable results are obtained may give a better assessment of what happens in the real world.

LA-4 and US06 preconditioning were evaluated on most vehicles tested in the API reversibility program.* In the API program only one preconditioning cycle was run prior to each FTP test with this being repeated two, or if necessary due to test variability, three times. LA-4 and US06 preconditioning was used exclusively in the CRC reversibility program. With the LA-4 preconditioning, a total of eight FTP tests were performed. Prior to the first four, a single LA-4 preconditioning was utilized. For the next two, two LA-4 cycles were conducted prior to the FTP test and for the last two, four LA-4 cycles were conducted prior to the FTP test. With the US06 preconditioning, a series of six FTP tests were performed. For the first two, a single US06 preconditioning preceded the FTP. Two US06 preconditionings preceded the next two tests and four US06 preconditionings preceded the last two tests. As such, the CRC procedures produced many more repeat tests for statistical analysis and also provided an assessment of the impact of increased time or mileage of preconditioning on reversibility.

A feature of the API program, not present with the CRC program, was the evaluation of long-term (1000-mile) high-sulfur exposure on sulfur sensitivity for the Taurus, Accord, Avalon, and

* Some tests in the API study used the EPEFE cycle as a preconditioning cycle. In addition, tests on one vehicle, the Ford Taurus, used high dynamometer loads to increase the exhaust temperatures over the catalyst. Since these preconditionings were not representative of real world driving, they are not analyzed further in this review.

Grand Marquis. For the Altima, short- and long-term (2000-mile) high-sulfur exposure was evaluated with the 100,000-mile aged catalysts.

Finally, the overall API program examined the factors that may contribute to sulfur sensitivity and reversibility. These included catalyst formulation, catalyst volume, catalyst temperatures, and air/fuel ratios. This information is of importance in assessing parameters responsible for sulfur sensitivity and reversibility and the potential for improvements.

Summarizing, the methodologies used in the API program appear valid and the results generated are complementary to those generated by the CRC reversibility program. The complementary nature of the two programs mainly results from the emphasis on 4,000-mile aged catalysts in the API program and 100,000-mile aged catalysts in the CRC program. The two catalyst ages provide an assessment of impact of catalyst aging on reversibility. The API program also provides additional information on the effects of long- vs. short-term high-sulfur exposure on sensitivity and reversibility.

SULFUR SENSITIVITY

Tables 2 and 3 present results on sulfur sensitivity for the 4,000-mile and 100,000-mile aged catalysts, respectively, tested in the API program.

For each vehicle, the average emission rates obtained during initial testing with low-sulfur (40 ppm S) fuel and the average emission rates obtained for all tests with the high-sulfur (540 ppm S) fuel are presented. These tables also show the absolute increase in emission rates in going from 40 to 540 ppm S fuel and ratio of this increase to the high sulfur emissions. The latter number has been reported in the CRC studies as the percent reduction in going from high-sulfur to low-sulfur fuel. The relationship between the emission rates measured in this study and the applicable emission standards is discussed below in the section on reversibility.

Table 2. Sulfur Sensitivity for 4,000-mile Aged Catalysts					
Vehicle	Species	Baseline Emissions (gm/mi)	High Sulfur Emissions (gm/mi)	Emissions Increase (gm/mi)	Sulfur Sensitivity ²
Taurus Short-term	NMHC	0.033	0.051	0.018	35.3%
	CO	0.522	0.832	0.310	37.3%
	NOx	0.075	0.101	0.026	25.7%
Taurus Long-term	NMHC	0.033	0.073	0.040	54.8%
	CO	0.522	1.310	0.788	60.2%
	NOx	0.075	0.117	0.042	35.9%
Accord Short-term	NMHC	0.029	0.032	0.003	9.4%
	CO	0.285	0.299	0.014	4.7%
	NOx	0.100	0.192	0.092	47.9%
Accord Long-term	NMHC	0.029	0.041	0.012	29.3%
	CO	0.285	0.465	0.180	38.7%
	NOx	0.100	0.245	0.145	59.2%
Avalon Short-term	NMHC	0.040	0.061	0.021	34.4%
	CO	0.406	0.541	0.135	25.0%
	NOx	0.068	0.116	0.048	41.4%
Avalon Long-term	NMHC	0.040	0.060	0.020	33.3%
	CO	0.406	0.734	0.328	43.9%
	NOx	0.068	0.142	0.074	52.1%
S10 Short-term	NMHC	0.108	0.132	0.024	18.2%
	CO	1.628	2.071	0.443	21.4%
	NOx	0.214	0.352	0.138	39.2%
Grand Marquis ¹ Short-term	NMHC	0.044	0.075	0.031	41.3%
	CO	0.649	1.306	0.657	50.3%
	NOx	0.040	0.143	0.103	72.0%
Grand Marquis Long-term	NMHC	0.047	0.055	0.008	14.5%
	CO	0.684	0.943	0.259	27.5%
	NOx	0.079	0.152	0.073	48.0%
First Altima Short-term	NMHC	0.040	0.041	0.001	2.4%
	CO	0.821	0.747	-0.074	-9.9%
	NOx	0.053	0.081	0.028	34.6%
Town Car Short-term	NMHC	0.072	0.167	0.095	56.9%
	CO	1.762	2.870	1.108	38.6%
	NOx	0.031	0.212	0.181	85.4%
Average Short-term	NMHC				28.3%
	CO				23.9%
	NOx				49.5%

¹ The 4,000-mile (4,000-mile) short-term test was conducted after completion of the 4,000-mile long-term test. Thus, the initial low-sulfur (40 ppm S) emission rates are different for the short- and long-term tests.

²This is defined as the increase in emissions in going from the baseline to the high-sulfur fuel divided by the emissions with the high-sulfur fuel.

Table 3. Sulfur Sensitivity for 100K Aged Catalysts					
Vehicle	Species	Baseline Emissions (gm/mi)	High Sulfur Emissions (gm/mi)	Emissions Increase (gm/mi)	Sulfur Sensitivity ²
Taurus Short-term	NMHC	0.050	0.057	0.007	12.3%
	CO	0.812	1.801	0.989	54.9%
	NOx	0.077	0.227	0.150	66.1%
Second Altima Short-term	NMHC	0.041	0.059	0.018	30.5%
	CO	0.788	1.058	0.270	25.5%
	NOx	0.061	0.112	0.051	45.5%
Second Altima Long-term	NMHC	0.041	0.057	0.016	28.1%
	CO	0.788	0.987	0.199	20.2%
	NOx	0.061	0.132	0.071	53.8%

²This is defined as the increase in emissions in going from the baseline to the high-sulfur fuel divided by the emissions with the high-sulfur fuel.

The sulfur sensitivity is expressed as the increase in going from the baseline to the high-sulfur fuel divided by the emissions with the high-sulfur fuel. This is consistent with the approach used in the CRC study. With the possible exception of the Lincoln Town Car, the sulfur sensitivities found in the API study are considerably less than those reported in the CRC study. The 10,000-mile aged catalysts in the CRC low-emission-vehicle program showed a fleet average sulfur sensitivity in going from low-sulfur(30 ppm S) to high-sulfur (630 ppm S) fuel of 46% for NMHC, 57% for CO, and 63% for NOx. In this study the simple fleet average sulfur sensitivities in going from 40 to 540 PPM S were 28% for NMHC, 24% for CO and 50% for NOx. If the major contribution due to the high NOx sensitivity of the Lincoln Town Car (85%) is removed from the fleet average for the API program, the fleet average NOx sulfur sensitivity becomes 44%.

Sierra Research (1998) has proposed two possible explanations for the differences in sulfur sensitivity observed in this study compared with that found in the CRC low-emission-vehicle program. The first is potential reduced sensitivity of 1998 model year vehicles tested in the API program compared to 1997 vehicles tested in the CRC program. At present there is limited data to assess this possibility. The 1997 and the 1998 Ford Taurus were the only vehicle models tested in both programs. In the API study, the sulfur sensitivities for the 1998 Taurus in going from 40 to 540 ppm S fuel were 35% for NMHC, 37% for CO, and 27% for NOx. For the 1997

Taurus tested in the CRC program, the sulfur sensitivities in going from 30 to 630 ppm S were 62% for NMHC, 71% for CO, and 71% for NO_x. The Sierra Research analysis did indicate significantly higher engine-out HC and CO emission rates for the 1997 Taurus used in the CRC program compared to the 1998 Taurus used in the API program. This may indicate a change in vehicle calibration.

The other explanation proposed involves the use of the EPEFE driving schedule during fuel change preconditioning in the CRC program but not in the API program. The EPEFE cycle is specifically designed to assure that the catalyst is exposed to high temperature (>700 °C) rich conditions. It is well known that under high temperature reducing (fuel rich) conditions, cerium sulfate ($\text{Ce}_2(\text{SO}_4)_3$) decomposes. This reverses one of the mechanisms responsible for automotive catalyst sulfur poisoning. It has also been shown in vehicle and laboratory studies that high temperature reducing conditions are reasonably effective in reversing the effect of sulfur poisoning when switching from high- to low-sulfur fuel. What has not been studied are the effects of high temperature reducing conditions when switching from low- to high-sulfur fuel. DiMaggio, et al. (1994) and Beck, et al., (1991) have studied the effects of SO₂ exposure under reducing conditions on surface site blockage of Pd and Pt foils. Their results indicated only a very modest reduction in site blockage for Pt when the temperature was increased from 200 to 700 °C and no reduction in site blockage when a Pd surface was exposed to SO₂ under reducing conditions up to 900 °C. Their results also imply that exposure of a Pd surface to sulfur under high temperature reducing conditions may increase the formation of bulk sulfides in the Pd. These results imply that while the EPEFE cycle preconditioning can reverse the effects of sulfur in switching from high- to low-sulfur fuel, it may also increase the sulfur sensitivity, particularly for Pd catalysts, in switching from low- to high-sulfur fuel.

In addition to the short-term exposure experiments, the Taurus, Accord, Avalon, and Grand Marquis also underwent long-term exposure tests involving 1000-mile accumulation with high-sulfur fuel. The Taurus, Accord, and Avalon each showed increased sulfur sensitivity after the long-term exposure. This is consistent with laboratory studies that show an initial rapid poisoning followed by a longer-term gradual increase in poisoning. The longer-term poisoning effects have been associated with the presence of Ce and Pd in the catalyst formulations (Beck, et al., 1994, 1995).

The Grand Marquis results imply a reduction in sulfur sensitivity with long-term aging. These results should be viewed with caution since the long-term exposure results were obtained before the short-term exposure results. This reversal of the normal exposure pattern was necessary because there was an inadequate fuel change procedure during the initial short-term tests. This problem was not discovered before the long-term tests were started. Thus, the short-term tests were repeated after completion of the long-term test. As indicated in Table 2, the low-sulfur baseline NO_x results for the short- (0.04 gm/mi) and long-term (0.079 gm/mi) tests were substantially different, implying a potential shift in vehicle calibration. If a change in calibration did occur during testing of this vehicle, it is not clear where in the test sequence this occurred and its impact on the results.

With the exception of NMHC and NO_x emission rates after long-term exposure on the Accord, all other emission rates after short- and long-term operation with high-sulfur fuel with the 4,000-mile aged catalysts meet or are less than the specified emission standards.

Table 3 presents results for 100,000-mile aged catalysts for the Taurus and Altima. The initial emission rates with low-sulfur fuel are all well below the 100,000-mile emission standards. In addition, the NMHC and CO for the Taurus and NO_x emission rates for the Altima are only modestly higher than the corresponding 4,000-mile results. The NO_x emission rates for the Taurus and NMHC and CO emission rates for the Altima are very similar with the 4,000-mile and 100,000-mile aged catalysts.

Compared to the 4,000-mile catalysts, the sulfur sensitivity of the 100,000-mile catalysts has increased substantially for CO and NO_x with the Taurus and for all three pollutants with the Altima. In comparison with sulfur sensitivities obtained with 100,000-mile catalysts in the CRC low emission vehicle program, the Taurus CO and NO_x and the Altima NMHC sensitivities obtained in this program are comparable with those found in the CRC program. The Taurus NMHC and Altima CO and NO_x sensitivities are generally lower than those observed in the CRC program. As discussed above, this may result from model year or preconditioning differences but it may also relate to specifics of catalyst formulation and vehicle calibration for these two vehicles.

Long-term, high-sulfur exposure (2000 miles) for the Altima resulted in slightly increased sulfur sensitivity for NO_x, but did not affect the NMHC and CO sensitivity.

The above discussion and analysis has not concentrated on the substantial differences in sulfur sensitivities between individual vehicles. These differences arise due to differences in catalyst formulation, size, loading, operating temperature and vehicle calibration effects. These effects are discussed further in the analysis section following the discussion of reversibility data in the next section.

REVERSIBILITY

Two reversibility measures are used in this analysis:

- The Reversibility Ratio or Index (RI) used in the CRC program as defined below:

$$RI = \frac{E_H - E_R}{E_H - E_I}$$

where E_H is the emissions rate on the high-sulfur fuel,

E_I is the initial baseline emission rate on low-sulfur fuel, and

E_R is the emission rate after the return from high- to low-sulfur fuel

- The change in emission rate for the final 40 ppm S results compared to the initial (baseline) 40 ppm S result:

$$\text{Change} = \frac{E_R - E_I}{E_I}$$

Complete reversibility would be indicated by a reversibility index of 100% (or greater) or by a change of 0% (or less). Tables 4 and 5 show the emission results after return to operation on low-sulfur fuel, the difference in emissions between this value and the baseline emissions, and the reversibility parameters, RI and Change, defined above. The data used to calculate RI and Change are shown in Tables 2 and 3 which have the same structure as Tables 4, and 5, respectively.

Vehicle	Species	Results for LA4 Preconditioning				Results for US06 Preconditioning			
		Emissions (gm/mi)	Emissions Difference (gm/mi) ¹	Reversibility Index	Change from baseline	Emissions (gm/mi)	Emissions Difference (gm/mi) ¹	Reversibility Index	Change from baseline
Taurus Short-term	NMHC	0.033	0.000	100.0%	0.0%				
	CO	0.576	0.054	82.6%	10.3%				
	NO _x	0.076	0.001	96.2%	1.3%				
Taurus Long-term	NMHC	0.046	0.013	67.5%	39.4%	0.032	-0.001	102.5%	-3.0%
	CO	0.691	0.169	78.6%	32.4%	0.576	0.054	93.1%	10.3%
	NO _x	0.049	-0.026	161.9%	-34.7%	0.046	-0.029	169.0%	-38.7%
Accord Short-term	NMHC	0.034	0.005	-66.7%	17.2%	0.029	0.000	100.0%	0.0%
	CO	0.264	-0.021	250.0%	-7.4%	0.296	0.011	21.4%	3.9%
	NO _x	0.120	0.020	78.3%	20.0%	0.102	0.002	97.8%	2.0%
Accord Long-term	NMHC					0.029	0.000	100.0%	0.0%
	CO					0.260	-0.025	113.9%	-8.8%
	NO _x					0.108	0.008	94.5%	8.0%
Avalon Short-term	NMHC	0.046	0.006	71.4%	15.0%	0.052	0.012	42.9%	30.0%
	CO	0.429	0.023	83.0%	5.7%	0.469	0.063	53.3%	15.5%
	NO _x	0.091	0.023	52.1%	33.8%	0.065	-0.003	106.3%	-4.4%
Avalon Long-term	NMHC					0.045	0.005	75.0%	12.5%
	CO					0.446	0.040	87.8%	9.9%
	NO _x					0.067	-0.001	101.4%	-1.5%
S10 Short-term	NMHC	0.116	0.008	66.7%	7.4%	0.095	-0.013	154.2%	-12.0%
	CO	1.872	0.244	44.9%	15.0%	1.599	-0.029	106.5%	-1.8%
	NO _x	0.255	0.041	70.3%	19.2%	0.190	-0.024	117.4%	-11.2%
Grand Marquis Short-term	NMHC	0.043	-0.001	103.2%	-2.3%	0.050	0.006	80.6%	13.6%
	CO	0.617	-0.032	104.9%	-4.9%	0.648	-0.001	100.2%	-0.2%
	NO _x	0.056	0.016	84.5%	40.0%	0.069	0.029	71.8%	72.5%
Grand Marquis Long-term	NMHC					0.050	0.003	62.5%	6.4%
	CO					0.747	0.063	75.7%	9.2%
	NO _x					0.042	-0.037	150.7%	-46.8%
First Altima Short-term	NMHC	0.033	-0.007	800.0%	-17.5%				
	CO	0.786	-0.035	52.7%	-4.3%				
	NO _x	0.046	-0.007	125.0%	-13.2%				
Town Car Short-term	NMHC	0.123	0.051	46.3%	70.8%	0.110	0.038	60.0%	52.8%
	CO	2.291	0.529	52.3%	30.0%	2.073	0.311	71.9%	17.7%
	NO _x	0.040	0.009	95.0%	29.0%	0.022	-0.009	105.0%	-29.0%
All vehicle average Short-term	NMHC	0.061	0.009	67.9%	16.9%	0.067	0.015	45.9%	28.5%
	CO	0.976	0.109	70.6%	12.5%	1.017	0.149	59.7%	17.2%
	NO _x	0.098	0.015	83.3%	17.7%	0.090	0.007	92.5%	8.0%

¹The difference between the emissions shown in this table and the baseline emissions shown in Table 2.

Table 5 Reversibility Data for 100,000-mile catalysts									
	Species	Results for LA4 Preconditioning				Results for US06 Preconditioning			
		Emissions (gm/mi)	Emissions Difference (gm/mi) ¹	Reversibility Index	Change from baseline	Emissions (gm/mi)	Emissions Difference (gm/mi) ¹	Reversibility Index	Change from baseline
Taurus Short-term	NMHC	0.042	-0.008	214.3%	-16.0%	0.049	-0.001	114.3%	-2.0%
	CO	0.759	-0.053	105.4%	-6.5%	0.764	-0.048	104.9%	-5.9%
	NOx	0.094	0.017	88.7%	22.1%	0.099	0.022	85.3%	28.6%
Second Altima Short-term	NMHC	0.044	0.003	83.3%	7.3%	0.041	0.000	100.0%	0.0%
	CO	0.854	0.066	75.6%	8.4%	0.738	-0.050	118.5%	-6.3%
	NOx	0.072	0.011	78.4%	18.0%	0.067	0.006	88.2%	9.8%
Second Altima Long-term	NMHC					0.039	-0.002	112.5%	-4.9%
	CO					0.572	-0.216	208.5%	-27.4%
	NOx					0.065	0.004	94.4%	6.6%

¹The difference between the emissions shown in this table and the baseline emissions shown in Table 3.

The reversibility index used in the CRC program provides an apparently simple number to evaluate sulfur reversibility. It can, however, be misleading since it contains a dependence on sulfur sensitivity. For example, if the baseline emissions were 0.1 g/mi and the emissions upon return to the low-sulfur fuel were 0.11 g/mi, the Change defined above would be 10%. However, the reversibility index would depend on the increase in emissions when operated with high sulfur fuel. In the same example of an increase from 0.10 to 0.11 g/mi between the baseline fuel and the return to low-sulfur fuel, the reversibility would be 50% if the high-sulfur emissions were 0.12 g/mi and 90% if the high-sulfur emissions were 0.20 g/mi. In general, for the same Change between the baseline emissions and the emissions after return to low-sulfur fuel, the reversibility index increases as the sulfur sensitivity increases. This leads to small numbers when the sulfur sensitivity is low and also increases the variability. This is generally the case for the API results where sulfur sensitivities are lower than in the CRC studies. In the API study there were several instances where the high-sulfur emission rates were lower than the low-sulfur emission rates. This leads to a meaningless negative reversibility index and is indicated in Tables 4 and 5 as (NA). The percent change in emissions for the final low-sulfur test compared to the initial low-sulfur test does not suffer from this problem and provides a direct measure of the impact of reversibility on emission rates.

The results after LA-4 preconditioning are analyzed first. The Altima is the only vehicle that shows complete reversibility, with the Taurus showing almost complete reversibility for 4,000-mile catalysts and short-term high-sulfur exposure. The Taurus has incomplete reversibility after long-term high-sulfur exposure with only NO_x being completely reversible. With 100,000-mile catalysts, the Taurus showed full reversibility for NMHC and CO, but did not for NO_x. With 100,000-mile catalysts, the Altima demonstrated almost complete reversibility for NMHC and CO, but fell short on NO_x. With 4,000-mile catalysts and short-term exposure, NMHC and CO were reversible for the Grand Marquis, but not for NO_x. As mentioned previously, there was an apparent shift in calibration of the Grand Marquis that may be influencing the NO_x emissions and the evaluation of reversibility; thus, these results should be viewed with caution. The Accord and Avalon CO emissions and S10 NMHC were either reversible or close to reversible. The Town Car was highly irreversible for all three pollutants.

As was found in the CRC program, US06 preconditioning generally results in improved reversibility. The Taurus (4,000-mile catalysts, long-term), Accord (4,000-mile catalysts, short and long-term), S10 (4,000-mile catalysts, short-term), and Altima (100,000-mile catalysts, short and long-term) either showed complete or close to complete reversibility for all pollutants. The Taurus (100,000-mile catalysts) demonstrated NMHC and CO reversibility, but not NO_x. The Avalon demonstrated NO_x reversibility after short and long-term exposure, but did not for NMHC and CO. The Grand Marquis only demonstrated CO reversibility after short-term exposure. NMHC and NO_x were not completely reversible, although again it must be cautioned that the NO_x result may be influenced by calibration changes. After long-term exposure, the Grand Marquis did not show reversible behavior for any of the pollutants, although the degree of irreversibility was modest in each case. The Town Car showed NO_x reversibility, but highly irreversible NMHC and modestly irreversible CO emissions after the US06 preconditioning.

The emission results in Tables 2 to 5 are compared to the applicable emission standards in Tables 6 and 7. In these tables the baseline and high-sulfur data from Tables 2 and 3 and the data from Tables 4 and 5 on emissions after the return to the low-sulfur fuel are expressed as a percent of the applicable emission standards. These ratios are simply the ratio of the measured emissions (or emissions difference) using the fuels from the API study to the applicable emission standards. No attempt is made to correct for the effect of any differences in fuel properties between these test fuels and the indoline fuel used in the certification tests.

Table 6 Emissions values and differences (emissions after return to low-sulfur fuel minus baseline emissions) as a percent of emission standards for 4,000-mile catalysts						
Vehicle	Species	With baseline emissions	With high-sulfur emissions	After return to low-sulfur fuel		
				With LA4 preconditioning	With US06 preconditioning	Emission difference
Taurus Short-term	NMHC	44.0%	68.0%	44.0%		0.0%
	CO	15.4%	24.5%	16.9%		1.6%
	NOx	37.5%	51.5%	38.0%		0.5%
Taurus Long-term	NMHC	44.0%	97.3%	61.3%	42.7%	-1.3%
	CO	15.4%	38.5%	20.3%	16.9%	1.6%
	NOx	37.5%	58.5%	24.5%	23.0%	-14.5%
Accord Short-term	NMHC	72.5%	80.0%	85.0%	72.5%	0.0%
	CO	16.8%	17.6%	15.5%	17.4%	0.6%
	NOx	50.0%	96.0%	60.0%	51.0%	1.0%
Accord Long-term	NMHC	72.5%	102.5%		72.5%	0.0%
	CO	16.8%	27.4%		15.3%	-1.5%
	NOx	50.0%	122.5%		54.0%	4.0%
Avalon Short-term	NMHC	53.3%	81.3%	61.3%	69.3%	16.0%
	CO	11.9%	15.9%	12.6%	13.8%	1.9%
	NOx	34.0%	59.5%	45.5%	32.5%	-1.5%
Avalon Long-term	NMHC	53.3%	80.0%		60.0%	6.7%
	CO	11.9%	21.6%		13.1%	1.2%
	NOx	34.0%	71.0%		33.5%	-0.5%
S10 Short-term	NMHC	43.2%	52.8%	46.4%	38.0%	-5.2%
	CO	47.9%	60.9%	55.1%	47.0%	-0.9%
	NOx	53.5%	88.0%	63.8%	47.5%	-6.0%
Grand Marquis Short-term	NMHC	58.7%	100.0%	57.3%	66.7%	8.0%
	CO	19.1%	38.4%	18.1%	19.1%	0.0%
	NOx	20.0%	71.5%	28.0%	34.5%	14.5%
Grand Marquis Long-term	NMHC	62.7%	73.3%	0.0%	66.7%	4.0%
	CO	20.1%	27.7%	0.0%	22.0%	1.9%
	NOx	39.5%	76.0%	0.0%	21.0%	-18.5%
Altima 1 Short-term	NMHC	53.3%	54.7%	44.0%	0.0%	-9.3%
	CO	24.1%	22.0%	23.1%	0.0%	-1.0%
	NOx	26.5%	40.5%	23.0%	0.0%	-3.5%
Town Car Short-term	NMHC	28.8%	66.8%	49.2%	44.0%	15.2%
	CO	51.8%	84.4%	67.4%	61.0%	9.1%
	NOx	7.8%	53.0%	10.0%	5.5%	-2.3%
All vehicle average Short-term		50.5%	71.9%	55.3%	48.4%	3.5%
		26.7%	37.7%	29.8%	26.4%	1.6%
		32.8%	65.7%	38.3%	28.5%	0.4%

Table 7 Emissions values and differences (emissions after return to low-sulfur fuel minus baseline emissions) as a percent of emission standards for 100,000-mile catalysts						
Vehicle	Species	With baseline emissions	With high-sulfur emissions	After return to low-sulfur fuel		
				With LA4 preconditioning	With US06 preconditioning	Emission difference
Taurus 100K Short-term	NMHC	66.7%	76.0%	56.0%	65.3%	-1.3%
	CO	23.9%	53.0%	22.3%	22.5%	-1.4%
	NOx	38.5%	113.5%	47.0%	49.5%	11.0%
Second Altima Short-term	NMHC	54.7%	78.7%	58.7%	54.7%	0.0%
	CO	23.2%	31.2%	25.1%	21.7%	-1.5%
	NOx	30.5%	57.0%	36.0%	33.5%	3.0%
Second Altima Long-term	NMHC	54.7%	76.0%	0.0%	52.0%	-2.7%
	CO	23.2%	29.0%	0.0%	16.8%	-6.4%
	NOx	30.5%	66.0%	0.0%	32.5%	2.0%

The results presented in Tables 6 and 7 show that after each preconditioning cycle all emission rates for all vehicle/test conditions were below the applicable emission standard, whether or not complete reversibility was achieved. This is illustrated in Figures 1-4 where the percent increase in emission rates from initial to final testing with low-sulfur fuel are presented together with the final emission rates as a percent of the applicable standard. Generally the CRC results obtained on 100,000-mile aged catalysts (CRC, 1998) show similar results. In the CRC study, only NMHC for the Nissan Sentra and NOx for the Suzuki Metro were above the 100,000-mile emission standard after exposure to high-sulfur fuel and then operation on low-sulfur fuel. With the Sentra and Metro, these emissions were either at, or above, the emission standards during the initial low-sulfur testing, with the Sentra actually showing reversibility for NMHC. The Metro did not demonstrate NOx reversibility.

The effect of preconditioning on reversibility is important because the precondition tests used in the API and CRC studies are surrogates for what would happen in actual vehicle operation. The FTP has traditionally been used as the certification cycle, which was supposed to represent in-use driving. However, it has long been recognized that this cycle, developed in the 1970s, does not

Figure 1

Reversibility for 4,000-mile catalysts after short-term exposure with LA-4 preconditioning
 Percent change from baseline and percent of standard after return to low-sulfur fuel

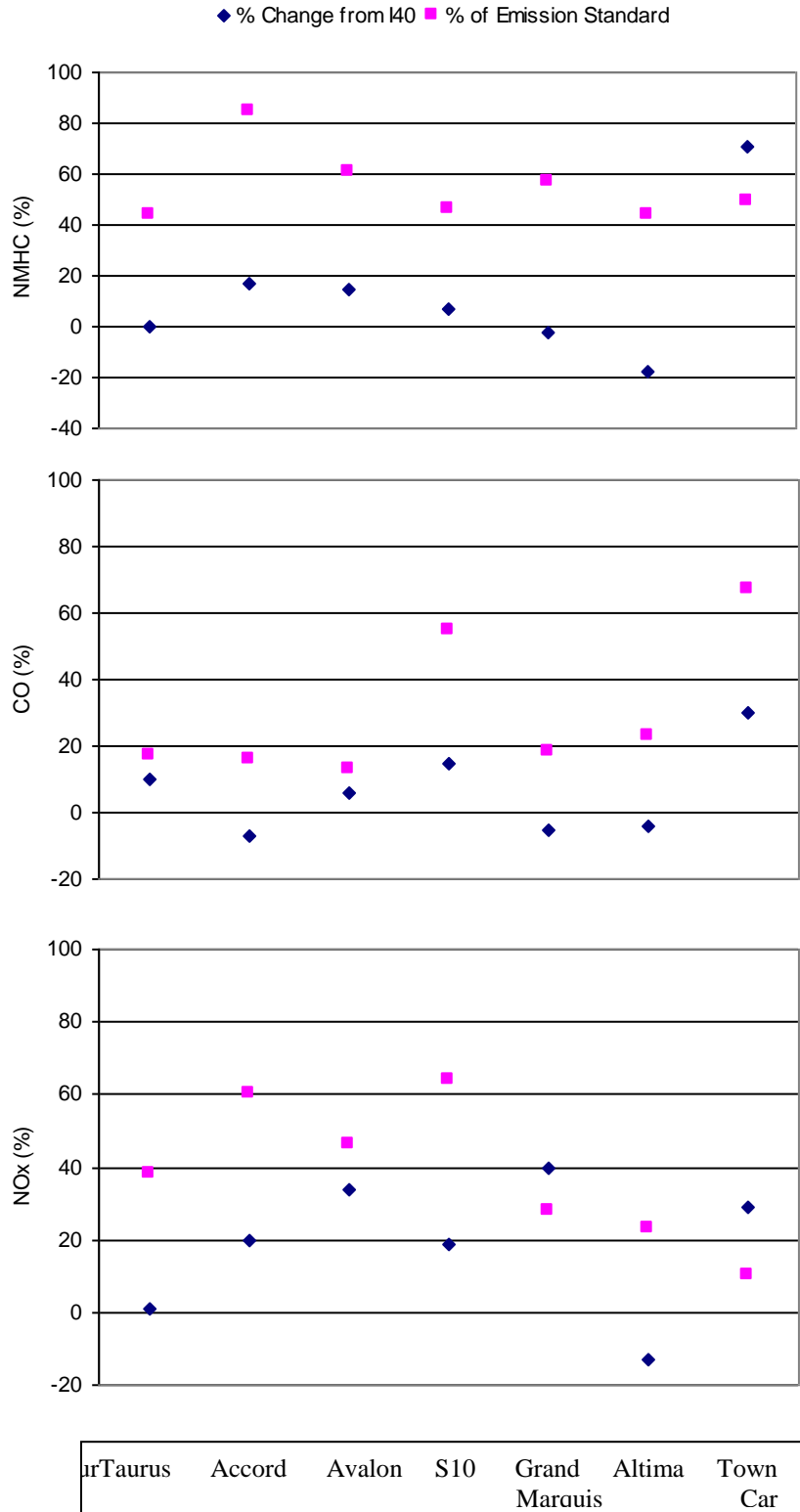


Figure 2

Reversibility for 4,000-mile catalysts after short-term exposure with US06 preconditioning
 Percent change from baseline and percent of standard after return to low-sulfur fuel

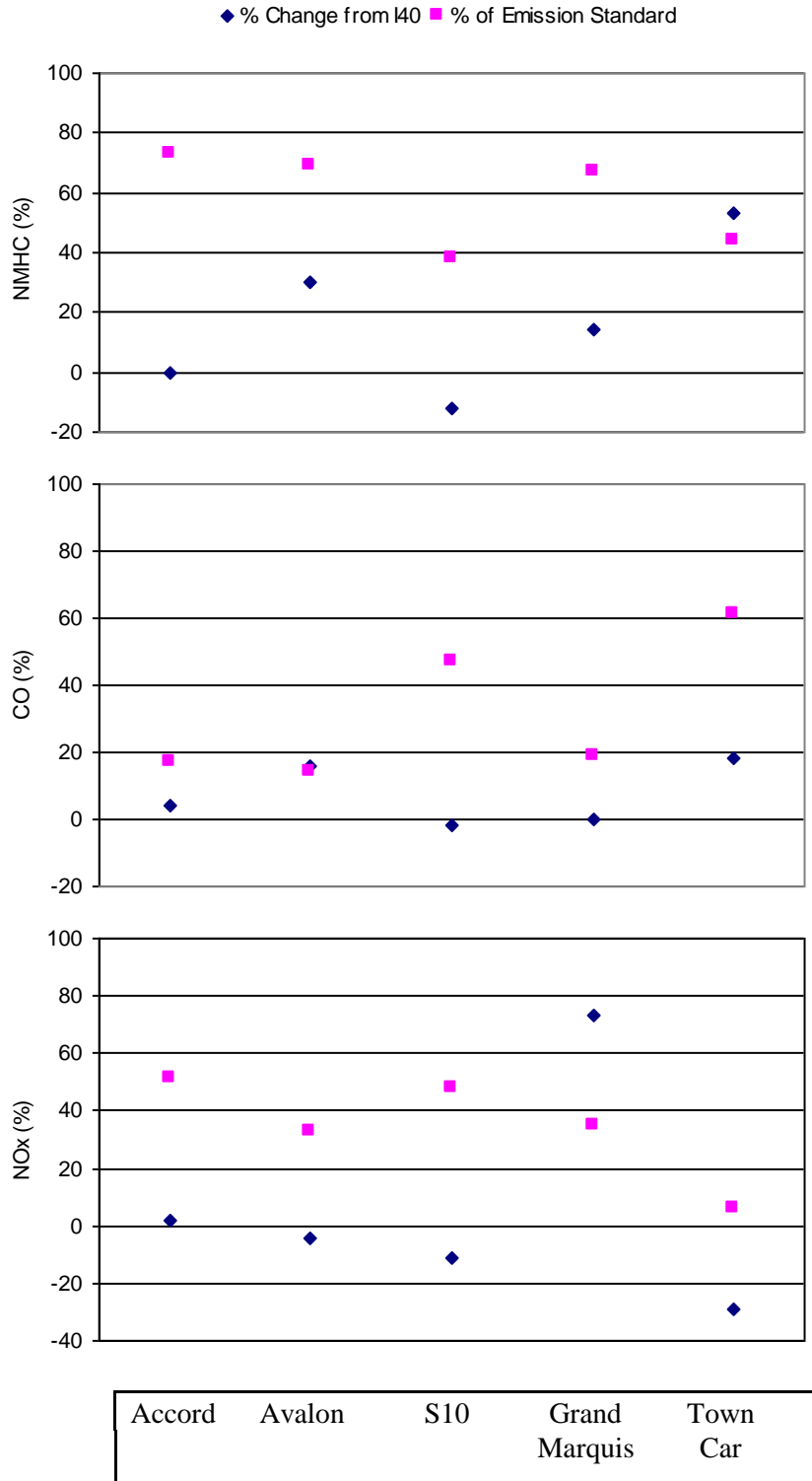


Figure 3

**Reversibility for 4,000-mile catalysts after long-term exposure
Percent change from baseline and percent of standard after return to low-sulfur fuel**

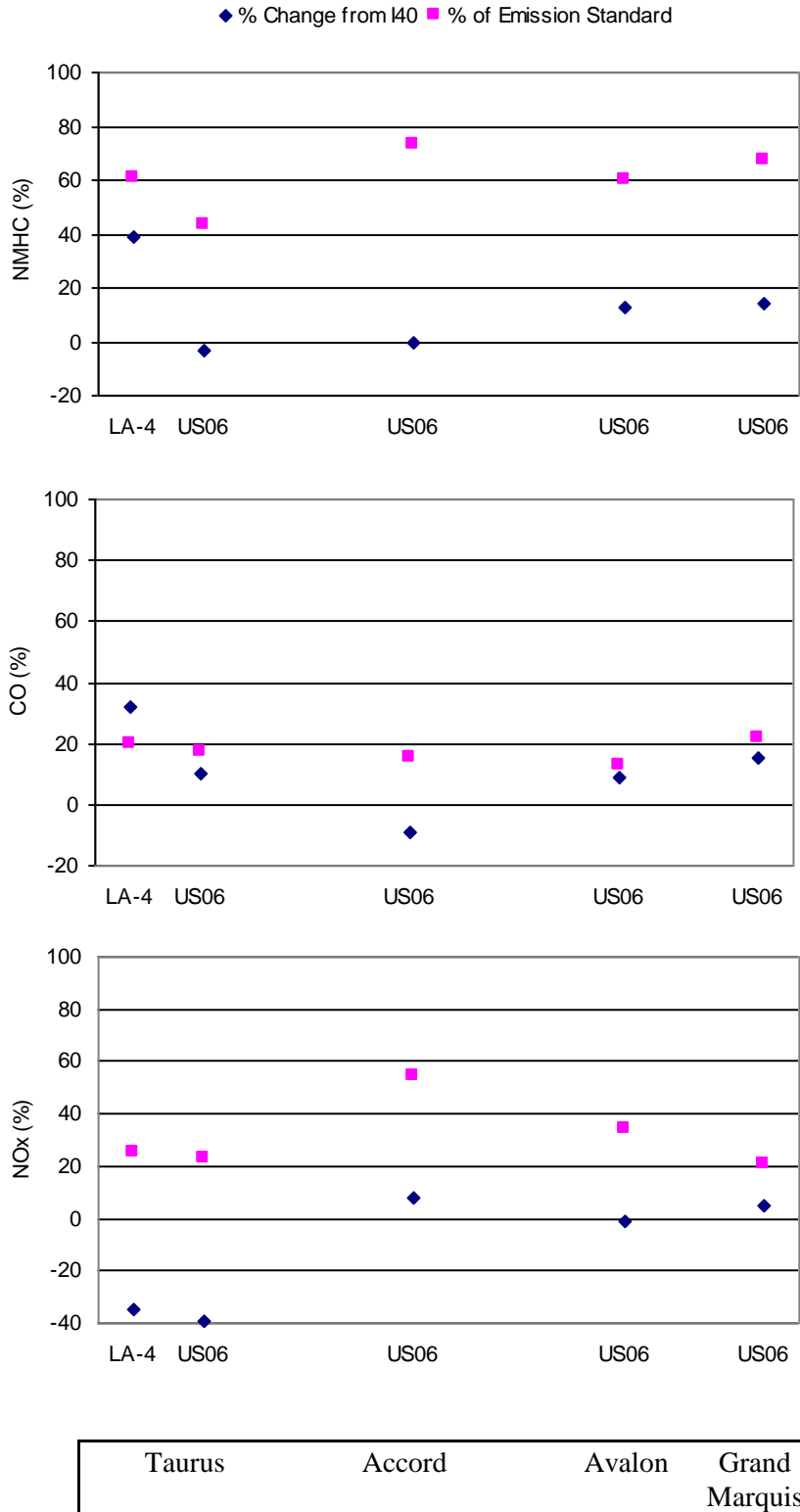
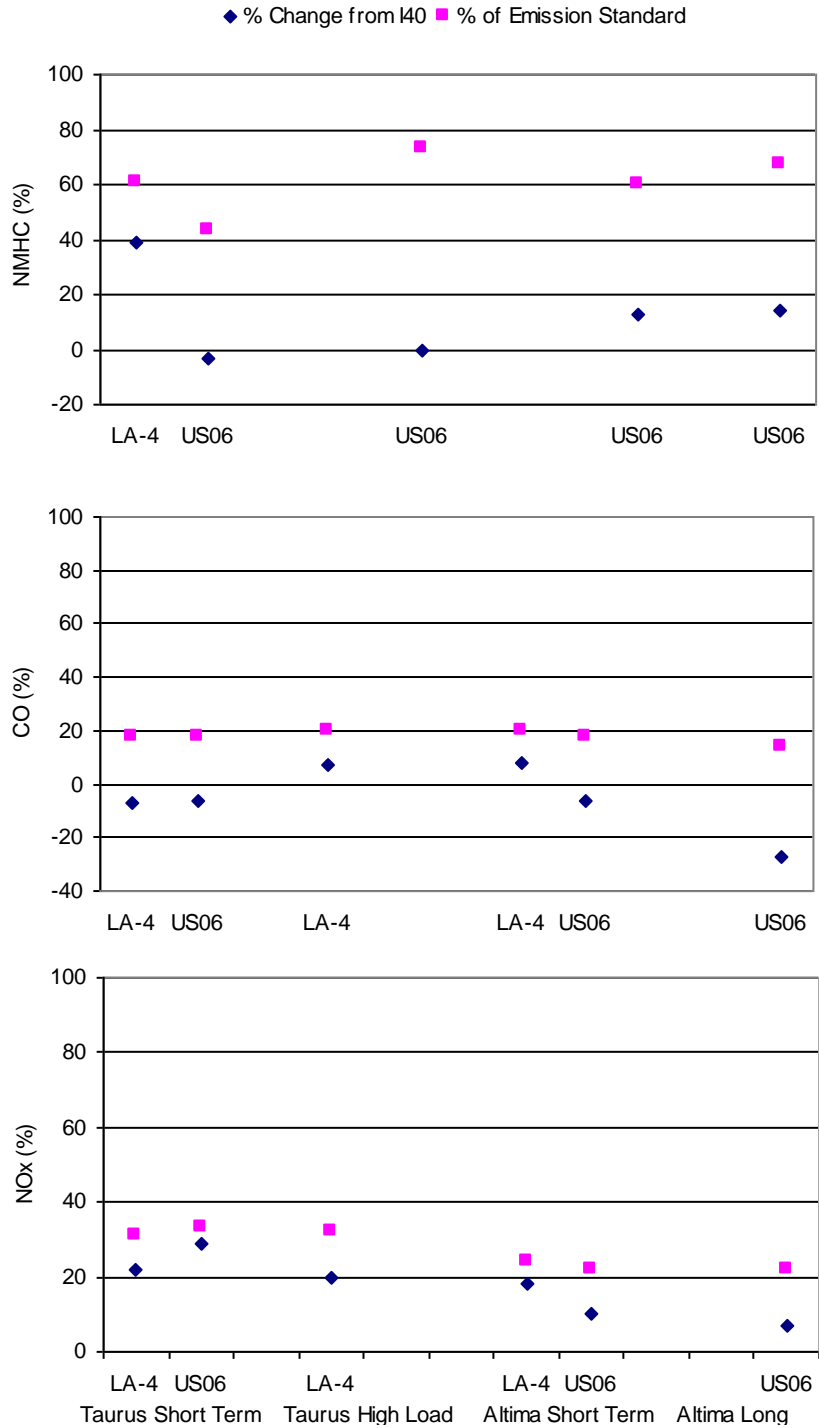


Figure 4
Reversibility for 100,000-mile catalysts
Percent change from baseline and percent of standard after return to low-sulfur fuel



represent the full extent of engine loads during normal driving. The US06 cycle (sometimes called the supplemental federal test procedure, SFTP) was developed for use by EPA as a supplemental driving cycle to account for driving modes with high engine loads that are not present in the FTP. The emissions regulations, which test vehicles over this cycle, will be phased in over model years 2000 to 2002. The US06 driving cycle is an appropriate preconditioning cycle for the reversibility studies because it represents high-load conditions that are encountered in normal driving.

Current vehicles tend to use rich operating conditions under high loads. However, the amount of rich operating conditions varies considerably among vehicles and depends on a number of design factors. When the emission regulations requiring tests under the US06 cycle are phased in, vehicle manufacturers are likely to use less rich operation to comply with the new standards. Because of this expected change in vehicle operation, it is not clear that preconditioning with current low-emission vehicles will represent the same exhaust conditions that would be encountered with Tier 2 vehicles that must meet SFTP standards. Because the effects of gasoline sulfur are known to depend on the exhaust stoichiometry, this expected change in vehicle operation implies that Tier 2 vehicles, certified to the SFTP, may not have the same reversibility effects as current vehicles.

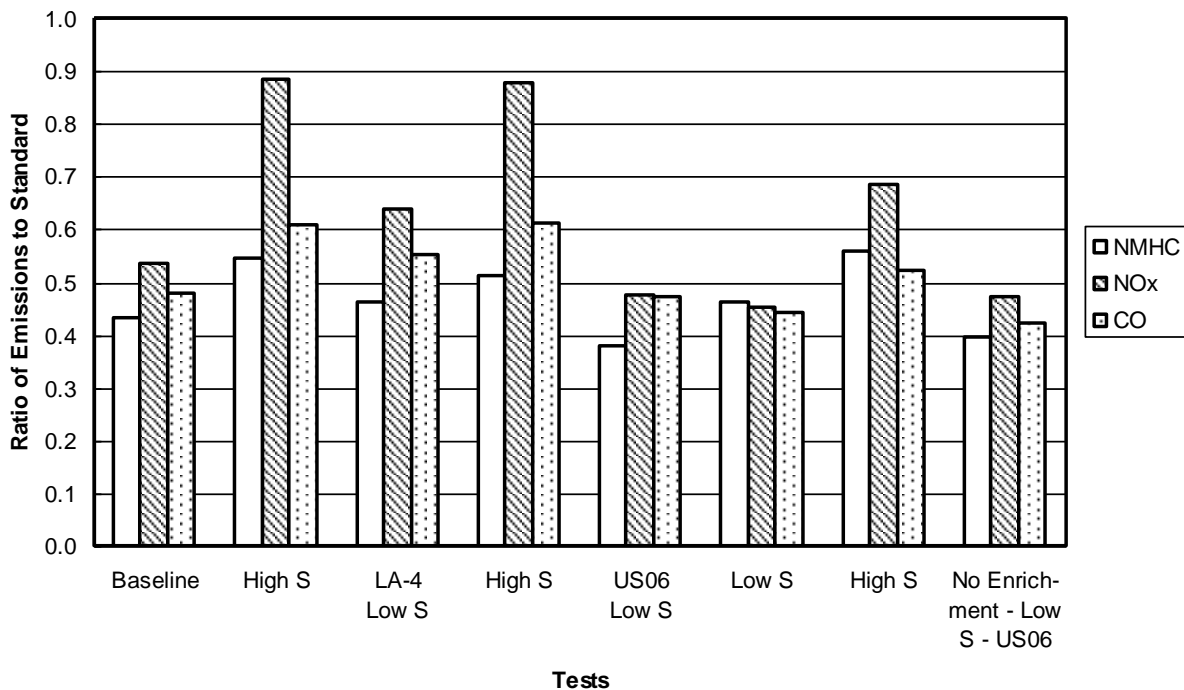
In order to test the effects of enrichment on reversibility, a set of emission tests was run on the Chevrolet S10 truck. This truck was initially tested using the normal sequence of testing. Following these tests the fuel metering control system was modified so that the signal for enriched operation was disabled. With this change, the operation during the US06 cycle, after return to operation on low-sulfur fuel, had no commanded enrichment.

The results of all the tests for the Chevrolet S10 are shown in Table 8; they are also plotted in Figure 5 as the ratio of the emissions to the emissions standards. For this Tier 1 vehicle, under normal operation, the sulfur effect was completely reversible for all pollutants with the US06 preconditioning. With enrichment disabled, complete reversibility was obtained for NMHC and CO and the NO_x was almost completely reversible. A simplified statistical analysis, described in the next paragraph, shows no significance difference between the reversibility obtained with and without the commanded enrichment for this vehicle.

Test designation and conditions	NMHC	NO _x	CO
A1-Baseline, low-sulfur	0.108	0.214	1.628
A2-High-sulfur	0.136	0.354	2.068
A3-Low-sulfur, FTP test	0.116	0.255	1.872
B1-High-sulfur	0.128	0.351	2.075
B2-Low-sulfur, US06 preconditioning	0.095	0.190	1.599
2A2-Low-sulfur	0.116	0.181	1.502
2B1 -High-sulfur	0.140	0.274	1.776
2B2-Low-sulfur, no enrichment, US06 preconditioning	0.099	0.189	1.434
Standard deviation (assumed same for all fuels)	0.00612	0.0289	0.1023
Degrees of freedom	9	9	9
Change with normal operation (B2 – A1)/A1	-11.8%	-11.1%	-1.8%
Change with no enrichment (2B2 – 2A2)/2A2	-14.7%	4.7%	-4.5%
Difference with normal operation (B2 – A1)	-0.013	-0.029	-0.025
95% Upper and lower confidence limits for B2 – A1	-0.00003 -0.025	0.036 -0.083	0.182 -0.241
Difference with no enrichment (2B2 – 2A1)	-0.017	0.009	-0.067
95% Upper and lower confidence limits for 2B2 – 2A1	-0.003 -0.031	0.074 -0.031	0.164 -0.299

Figure 5

Chevrolet S10 Reversibility Data



A simplified statistical analysis was performed on the S10 data. The standard deviation was computed using the sum of squares of the differences between each data point and the mean for the corresponding fuel. The baseline case had three data points; the remaining tests had two data points each. This standard deviation was used to compute the upper and lower confidence limits for the differences between the emissions after the return to low-sulfur fuel (with the US06 preconditioning) and the emissions for the initial low-sulfur fuel. This was done for both the normal operation and the operation with no commanded enrichment. In all differences for CO and NO_x, the confidence intervals for the differences included zero. Thus there were no statistically significant differences between the two low-sulfur operations for CO and NO_x. For NMHC, the upper confidence level was less than zero. The return to low sulfur fuel produced lower NMHC emissions at a 95% confidence level. These basic tests show that there was no statistical difference from complete reversibility for all pollutants in the data for the S10.

The 95% confidence limits for the differences with normal operation and no commanded are shown in the last and the third-from-the-last rows in Table 8. These data show that the confidence limits for the emissions differences overlap. Thus, there are no statistically significant differences between normal operation and operation with no commanded enrichment for this vehicle.

ANALYSIS

To assess factors that contribute to sulfur sensitivity and reversibility, an analysis has been done on the API study results. The vehicles tested in the API program are listed below in order of sulfur sensitivity and in order of reversibility. The results are presented for NMHC, CO, and NO_x emissions and go from high to low sensitivity and from low to high reversibility. The orders are qualitative and are based upon an analysis of the percentage increases in emission rates between the initial low-sulfur results and the high-sulfur results for the sensitivity analysis. The percentage changes in emission rates from the initial low-sulfur results and the final (after preconditioning) high-sulfur results were used to assess reversibility. It should be noted that somewhat different orders for reversibility are obtained if one uses the reversibility index. As discussed above, the reversibility index is dependent on the sulfur sensitivity. This leads to higher reversibility ranking for vehicles with higher sulfur sensitivities. The authors believe that the changes in emission rates are a more relevant measure.

NMHC

Sulfur Sensitivity (High → Low) Town Car>Taurus>Avalon≅Grand Marquis>Accord>S10>>Altima

Sulfur Reversibility (Low → High) Town Car>>Taurus≅Avalon≅Accord>Grand Marquis>S10>>Altima

CO

Sulfur Sensitivity (High → Low) Taurus>Grand Marquis>Avalon≅Town Car≅Accord>S10>Altima

Sulfur Reversibility (Low → High) Town Car>Taurus>Avalon>S10>Grand Marquis≅Accord≅Altima

NOx

Sulfur Sensitivity (High → Low) Town Car>>Grand Marquis>Accord>Avalon>S10≅Taurus≅Altima

Sulfur Reversibility (Low → High) Grand Marquis>Avalon>Town Car>Accord≅S10>Altima≅Taurus

Several generalizations are possible from these rankings of sulfur sensitivity and reversibility:

1. There appears to be a correlation between sulfur sensitivity and reversibility, with those vehicles with high sensitivities having low reversibility.
2. The Altima and S10 consistently show low-sulfur sensitivities and high reversibility.
3. The Accord and Avalon are intermediate in sensitivity and reversibility.
4. The Town Car, Taurus, and Grand Marquis generally show the highest sensitivity and lowest reversibility. Two exceptions to this are the intermediate sensitivity and reversibility of the Grand Marquis for NMHC and low sensitivity and high reversibility of the Taurus for NOx.

Table 6 summarizes catalyst and vehicle operating characteristics from the Sierra Research analysis of the API results (Sierra Research, 1998). Presented are platinum group metal

compositions, ceria content (high or low), mean and peak catalyst bed temperatures during the FTP and US06 driving cycles, and the median and standard deviations for the air/fuel ratios during the FTP and US06 cycles.

Vehicle	Catalyst Composition		Engine Displacement/Catalyst Volume	Catalyst Temperatures (°C)		Air/Fuel Ratio			
	Platinum Group Metals	Ce		FTP	US06	FTP		US06	
				mean/max	mean/max	Median	S. D.	Median	S. D.
Town Car	H. Pd/L. Rh?	H	1.76	545/625	710/800	14.36	0.1	14.31	0.56
Taurus	H. Pd/L. Rh?	H	1.24	460/550	600/650	14.36	0.52	14.36	1.57
Grand Mar.	H. Pd/L. Rh?	H	1.8	570/675	740/850	14.26	0.37	14.31	0.46
Accord	H. Pd/L. Rh?	H	1.34	560/700	720/800	14.36	0.65	14.34	1.77
Avalon	H. Pd trimetal Pt/Rh	L	1.39	570/700	690/800	14.41	0.25	14.46	1.02
		H							
S10	Pt/Rh	H	1.75	490/600	675/800	14.36	0.19	14.31	1
Altima	Pt/Rh	H	0.84	640/800	775/850	14.36	0.4	14.41	0.8

The S10 and Altima are equipped with Pt/Rh catalyst formulations. Numerous studies (Truex, 1997) have shown the sulfur tolerance of the platinum group metals to be in the order Rh > Pt > Pd. It has also been shown that Pt and Rh catalysts exhibit better reversibility than Pd catalysts. The Altima also has the largest catalyst volume to engine displacement ratio of vehicles tested. Thus, it is not surprising that these vehicles show lower sensitivity and higher reversibility. It should also be noted that the catalyst temperatures of the Altima are the highest of all vehicles tested. This will further reduce the impact of sulfur poisoning and tend to increase the reversibility.

The Town Car, Taurus, Grand Marquis, and Accord are all equipped with very high loaded Pd catalysts. The analysis also indicated the presence of low levels of Rh in these formulations. In one of the author's (TJT) experience, it is likely that these systems are Pd-only formulations and the indicated presence of low amounts of Rh are a result of analytical interference. Generally, it is expected that these formulations would have higher sulfur sensitivity and lower reversibility than the Pt/Rh formulations. There are, however, differences in the sensitivities of these vehicles that appear to be due to other factors. First, the Accord generally exhibits better sulfur tolerance and reversibility than the other high Pd catalyst-equipped vehicles. The Accord has slightly higher peak catalyst temperatures and an air/fuel calibration with significant lean and rich spiking. The latter is indicated in the actual air/fuel traces (Sierra Research, 1998) and is shown

in Table 6 by higher standard deviations of the air/fuel ratio for this vehicle. As discussed previously, higher temperatures will tend to reduce sulfur poisoning and increase reversibility, and previous work (Bennett, 1997) has shown that vehicle calibrations with significant rich and lean spiking show lower sulfur poisoning than calibrations with tight air/fuel control.

There are significant differences in sulfur sensitivities among the Town Car, Taurus, and Grand Marquis that must be due to factors other than catalyst formulation. The Grand Marquis shows less sensitivity and higher reversibility than the other vehicles for NMHC and the Taurus shows much lower sensitivity and high reversibility for NO_x. One potential explanation for the better NMHC performance of the Grand Marquis is the significantly higher catalyst temperatures compared to the Town Car and Taurus. Hydrocarbon performance is significantly enhanced with increasing catalyst temperatures. Two characteristics of the Taurus distinguish it from the Town Car and Grand Marquis: First, its catalyst temperatures are significantly lower, which may account for the poorer NMHC performance characteristics; and second, the air/fuel control is much looser. As discussed for the Accord, this latter effect may be aiding in reduced sulfur sensitivity. Finally, it should be noted that the Town Car and Grand Marquis have low catalyst-volume-to-engine-displacement ratios. This can lead to more emission 'breakthrough' during high load conditions if catalyst activity decreases. NO_x performance is generally most sensitive to catalyst volume effects.

The Avalon is equipped with high Pd-loaded Pt/Pd/Rh close-coupled catalysts and an underfloor Pt/Rh catalyst. It is also important to note that the close-coupled catalysts have low ceria loading. The presence of Rh will tend to make this system more sulfur-tolerant. In addition, ceria increases the sulfur sensitivity of three-way formulations. Thus, it might be expected that this system with lower ceria loading would be more sulfur-tolerant than the Pd-only systems. The Avalon also has high catalyst temperatures that will tend to reduce the effects of sulfur.

The above results provide further evidence supporting previous studies (Truex, 1997) that show a number of factors contribute to sulfur sensitivity and reversibility. These results imply that changes in catalyst formulations and vehicle calibration can be utilized to reduce sulfur sensitivity and improve reversibility. Recent results reported by Southwest Research Institute (1998a, 1998b) have demonstrated that changes in catalyst formulation can reduce sulfur sensitivity when tested on the same vehicle. These results, together with the range in sensitivity

and reversibility demonstrated in production vehicles, indicate that there is some flexibility available to the automotive engineer to reduce sulfur sensitivity and improve reversibility.

CONCLUSIONS

Both the API and the CRC reversibility studies confirm the effect of sulfur on catalyst systems: increases in gasoline sulfur content lead to increases in emissions of criteria pollutants due to degradation of catalyst efficiency.

Both the API and the CRC reversibility studies show that the effects of sulfur are reversible to some degree. The extent of the reversibility varies from vehicle to vehicle and, for a given vehicle, is different for different pollutants.

In both studies the amount of reversibility increased when the US06 cycle was used for preconditioning instead of the LA-4 cycle.

Complete reversibility (defined as emissions less than or equal to the baseline) could not be obtained for all vehicles. For some vehicles this could not be obtained even under the EPEFE purge cycle. For the Ford Taurus with catalysts aged to 100,000 miles, attempts to obtain complete reversibility by using high dynamometer loads in conjunction with the EPEFE cycle were successful only for HMHC and CO. The NO_x emissions were 8.5% above the baseline.

The range of sulfur sensitivity and reversibility of production vehicles together with results from independent studies designed specifically to reduce sulfur sensitivity, indicate there is some flexibility available to the automotive emission engineer for development of vehicles that demonstrate reduced sulfur sensitivity and improved reversibility.

The final fleet-average emissions after return to low-sulfur fuel in the API study, computed as arithmetic averages of the five vehicles certified to LEV or ULEV standards, were less than the baseline emissions for NO_x. The final fleet average NMHC and CO emissions were, respectively, 8.6% and 7.8% higher than the baseline. The vehicles used in this average had catalysts with approximately 4,000 miles.

The final fleet-average emissions in the CRC study, computed as arithmetic averages, were less than the baseline emissions for NMHC and CO. The final fleet average NOx emissions were 10% higher than the baseline. All vehicles in this study were certified to LEV standards with catalysts aged to 100,000 miles.

REGULATORY IMPLICATIONS

The results of the API and CRC reversibility studies show that the emissions of NMHC, NOx, and CO increase by about 10% at most after switching fuels from low-sulfur to high-sulfur and back again. These studies are complementary in that the CRC study examined vehicles with catalysts aged to 100,000 miles and the API study obtained the majority of its results on catalysts with 4,000 miles of operation.

The EPA considerations of sulfur reversibility must relate to the combined cost of the Tier 2 control program. These costs will consist of emission control costs and gasoline sulfur control costs. EPA's task is to develop the appropriate control strategy that will minimize these costs. The Tier 2 study (EPA, 1998a) indicates that the lifetime vehicle costs for the emission control system will be about \$130. The costs of sulfur control depend on the starting and ending point and range from one to four cents per gallon (EPA, 1998b). For a fuel economy of 25 miles per gallon and a lifetime mileage of 100,000 miles, this sulfur control cost range implies an undiscounted lifetime cost of \$40 to \$160 per vehicle.

In considering the overall program costs, EPA should also recognize that the reduction in gasoline sulfur should produce reduced emissions from the current vehicle fleet. The reversibility data found in the API and CRC studies supports the emission reduction from the current fleet due to reduction in gasoline sulfur. This emission reduction could be considered in computing the overall cost effectiveness of the combined vehicle standards and fuel standards for the Tier 2 vehicles.

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