Appendix B: Evidence Supporting the Irreversibility of Sulfur's Emission Impact

Fuel sulfur impacts vehicle emissions in two basic ways. One is a significant, immediate impact, which occurs within a few miles of driving. The other is a more lasting impact, ranging from 20 or more miles to potentially permanent. This lasting effect of sulfur on emissions is termed irreversibility, referring to the fact that the emission impact of high sulfur fuel does not reverse when low sulfur fuel is used.

The immediate impact of sulfur on emissions is summarized in an EPA technical report.[11] There, it was shown that operation on typical conventional gasoline containing 330 ppm sulfur increases exhaust VOC and NOx emissions from LEV and Tier 2 vehicles (on average), on average, by 40 percent for NMHC and 134 percent for NOx emissions compared to 30 ppm sulfur fuel. New data generated since the NPRM on similar LEVs and ULEVs show that when these vehicles were driven on high sulfur (330 ppm) fuel for a few thousand miles, the NMHC and NOx emission increase due to high sulfur fuel increased by 149 percent and 47 percent, respectively. In other words, instead of the previous estimated 40 percent and 134 percent increases in NMHC and NOx emissions, respectively, the newer estimates would be 100 percent and 197 percent, respectively.

In this section, we are concerned with the impact of sulfur under a broader range of conditions. In particular, we are interested in vehicles' emission response following exposure to low sulfur fuel after exposure to high sulfur fuel. We are also concerned with the potential that long term exposure to high sulfur fuel may increase emissions to a greater degree than the short term exposures simulated in most emission testing.

This section is divided into five parts. The first section describes the sensitivity of vehicle exhaust emissions to gasoline sulfur content. The second discusses the theory of how sulfur affects catalytic activity and the conditions conducive for its removal (sulfur irreversibility). The third describes the vehicle testing programs which have attempted to measure the irreversibility of the sulfur impact. The fourth presents criteria for evaluating the wide range of sulfur irreversibility data which are available. Finally, the fifth describes EPA's projections of the degree of sulfur irreversibility for various vehicle types (e.g., Tier 1 vehicle, LEVs, and Tier 2 vehicles).

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[1] "Development of Light-Duty Emission Inventory Estimates in the Notice of Proposed Rulemaking for Tier 2 and Sulfur Standards," U.S. EPA, February 1999.

A. Exhaust Emission Sensitivity to Sulfur Content

The sulfur in gasoline increases exhaust emissions of HC, CO, and NOx by decreasing the efficiency of the three-way catalyst used in current and advanced emission control systems. For the purpose of this document, we will refer to this phenomenon as “sulfur sensitivity.” Sulfur sensitivity has been demonstrated through numerous laboratory and vehicle fleet studies. These studies have demonstrated that significant reductions in HC, CO, and in particular, NOx emissions can be realized by reducing fuel sulfur levels. Sulfur sensitivity for Tier 0 and Tier 1 vehicles is marginal, with NOx emissions decreasing between 11 percent to 16 percent when sulfur is reduced from 330 ppm to 40 ppm. Sulfur sensitivity for LEV and ULEV vehicles, however, is much more significant. In the NPRM we estimated that, based on data from test programs conducted by EPA and the automotive and oil industries, LEV and ULEV vehicles could experience, on average, a 40 percent increase in NMHC and 134 percent increase in NOx emissions when operated on 330 ppm sulfur fuel (our estimate in the NPRM of the current national average sulfur level) compared to 30 ppm sulfur fuel. New data generated since the NPRM on similar LEVs and ULEVs show that when these vehicles were driven on high sulfur (330 ppm) fuel for a few thousand miles, the NMHC and NOx emission increase due to high sulfur fuel increased by 149 percent and 47 percent, respectively. In other words, instead of the previous estimated 40 percent and 134 percent increases in NMHC and NOx emissions, respectively, more realistic estimates would be 100 percent and 197 percent, respectively. The calculations resulting in these sensitivity values are described below in this section. Also, new data generated since the NPRM for late model LEV and ULEV vehicles that meet the Federal and California supplemental federal test procedure (SFTP) standards and also have very low FTP emission levels, indicate that, on average, a 51 percent increase in NMHC and a 242 percent increase in NOx emissions when operated for a short period of time on 330 ppm compared to 30 ppm could be realized.

Table A-1 lists new sulfur sensitivity data for several late model LEV and ULEV vehicles that meet the Federal and California supplemental federal test procedure (SFTP) standards and also have very low FTP emission levels when sulfur is increased from 30 ppm to 350 ppm.

Table B-1. Sulfur Sensitivity: New Data Between 30 ppm and 350 ppm

Vehicle	NMHC	NOx
DaimlerChrysler Caravan	87%	333%
Ford Expedition	81%	42%
Ford Windstar	12%	238%
Ford F-150	30%	249%
Average	51%	242%

These percentages apply to "normal emitting" vehicles, which generally are those in-use vehicles with emissions at or below twice their applicable emission standards. Higher emitting vehicles are projected to be less sensitive to sulfur, because the catalyst is not operating at peak efficiency in-use and should therefore be less affected on a percentage basis by higher sulfur levels.

We anticipate that Tier 2 vehicles will be at least as sensitive to sulfur as LEV and ULEV LDVs and possibly even more so, due to the greater stringency of the proposed Tier 2 emission standards, especially for NOx. We examined the sulfur sensitivity for vehicles in our sulfur database that were at or below Tier 2 levels with those that were above Tier 2 standards. What we found was that those vehicles meeting Tier 2 standards showed a higher degree of sensitivity to sulfur than those with higher emission levels. However, at a 95 percent confidence level, there was no statistical difference in sulfur sensitivity between the vehicles at or below Tier 2 emission standards and those above Tier 2 standards. Thus, we have only projected that Tier 2 vehicles will be just as sensitive as LEV and ULEV LDVs and not more so. Therefore, these should be considered conservative estimates for Tier 2 vehicles.

More detailed discussions of sulfur sensitivity can be found in the "EPA Staff Paper on Gasoline Sulfur Issues,"[2] published May 1, 1998, and the EPA report which developed sulfur sensitivity estimates for a range of vehicle classes for incorporation in the draft version of EPA's fleet-wide emissions model, MOBILE6. This report is titled "Fuel Sulfur Effects on Exhaust Emissions"[2] and is dated January 5, 1999.

Sulfur sensitivity has been shown to be variable and to depend upon both catalyst formulation and vehicle operating conditions, which are discussed in detail in both reports. Another variable, which was not discussed in either report, is the effect of real world vehicle aging with sulfur. Sulfur sensitivity is temperature dependent. Sulfur adheres to the catalyst

[2] "EPA Staff Paper on Gasoline Sulfur Issues," U.S. EPA, May 1998, EPA420-R-98-005

surface more thoroughly at lower catalyst temperatures (approximately 450 C to 500 C) than higher temperatures. Several vehicle manufacturers have suggested that the sulfur sensitivity results from the numerous fleet studies actually underestimate the sensitivity of sulfur on exhaust emissions, because the test cycles (FTP or LA4 cycles) used to saturate the catalyst with sulfur result in catalyst temperatures that are too high. Specifically, the argument is that most vehicles achieve catalyst temperatures over the FTP that exceed 450 C, thus not allowing complete adsorption of sulfur to the catalyst surface, whereas real-world vehicle operation in metropolitan non-attainment areas quite frequently result in catalyst temperatures at or below 450 C.

A second concern about the estimates of sulfur sensitivity used in the NPRM is that all of the vehicles in the test programs used to develop the NPRM projections of sulfur sensitivities were only exposed to high sulfur fuel for a few miles of driving prior to emission testing. This is referred to as "short-term" sulfur exposure. In addition to adsorbing onto the surface of the catalyst, sulfur can also penetrate into the precious metal layer, especially into palladium, and into the oxygen storage material. This penetration may not have fully occurred during the very few miles of operation prior to emission testing on high sulfur fuel. The short-term exposure in the test programs typically consisted of only running several emission tests (FTP or LA4). Since each FTP is approximately 18 miles in length, short-term exposure usually amounted to just under 100 miles of operation, all of which was in a controlled laboratory environment.

To address this concern, API and EPA each conducted test programs testing a combined total of six light-duty vehicles for sulfur sensitivity after short-term and long-term exposure to sulfur. The vehicles were randomly selected by both API and EPA. The long-term exposure consisted of between 1,500 and 3,000 miles of in-use operation over urban, rural and highway roads. Two of the vehicles were 1999 models, while the other four were 1998 models. All six were either LEV or ULEV vehicles. Three of the vehicles were equipped with catalyst systems aged to either 50,000 or 100,000 miles. The other three vehicles had low mileage catalyst systems aged to only 4,000 miles. Table A-2 describes the vehicles tested:

Table B-2. Vehicles Tested After Short-Term vs. Long-Term Exposure to Higher Sulfur Fuel

Make/Model	Model Year	Emission Level	Catalyst Aging (miles)
EPA Test Program			
Honda Accord	1999	ULEV	50,000
Chevrolet Cavalier	1999	LEV	50,000
API Test Program			
Nissan Altima	1998	LEV	100,000
Ford Taurus	1998	LEV	4,000
Honda Accord	1998	ULEV	4,000
Toyota Avalon	1998	LEV	4,000

All of the vehicles were tested for short-term exposure first. Each vehicle was FTP baseline[3] tested on low sulfur fuel (30 or 40 ppm). The number of tests used to establish the baseline varied from two to four. The vehicles were then tested with the high sulfur fuel (EPA at 350 ppm, API at 540 ppm). Again the number of tests ranged from two to four. Upon completion of the short-term program, each vehicle was preconditioned several times with the EPEFE sulfur purge cycle prior to beginning the long-term exposure program. Only the 1999 Honda Accord of the EPA test program reestablished a new baseline for the long-term program–the other vehicles used the original short-term baseline. All of the vehicles were then operated on the road with the high sulfur fuel from anywhere between 1,500 to 3,000 miles and tested over the FTP to establish long-term high sulfur emission levels.

Sulfur sensitivity was determined by calculating the percent increase in average emissions with the high sulfur fuel compared to the average emissions with the low sulfur fuel. For NOx emissions, all six vehicles showed greater sulfur sensitivity after long-term exposure to high sulfur fuel than after short-term exposure. For NMHC emissions, all of the vehicles except the Altima and Avalon experienced greater sensitivity for long-term exposure. Only the Altima showed lower sulfur sensitivity for CO emissions after long-term exposure. Table A-3 lists the sulfur sensitivity results for all six vehicles:

[3] Prior to baseline testing, each vehicle was preconditioned with a purge cycle based on the European Programme for Emission, Fuels, and Engine Technologies (EPEFE) sulfur purge cycle, which uses a series of ten wide-open throttle accelerations from 30 to 70 mph, in order to ensure there was no sulfur contamination prior to baseline testing.

Table B-3. Vehicle-by-Vehicle Short-Term vs. Long-Term Sulfur Sensitivity

Vehicle	*Cat. Age*	*Sulfur Aging*	*Sulfur Level*	*Tailpipe Emissions (g/mi)*			*Sulfur Sensitivity (%)*		
				NMHC	*CO*	*NOx*	*NMHC*	*CO*	*NOx*
Accord (EPA Vehicle)	50K	Short	30 ppm	0.031	0.351	0.092	12.0	36.3	69.4
			350 ppm	0.035	0.478	0.155			
	50K	Long	30 ppm	0.033	0.330	0.090	21.7	121.1	158.5
			350 ppm	0.040	0.731	0.234			
Cavalier	50K	Short	30 ppm	0.070	1.778	0.068	49.3	127.7	347.0
			350 ppm	0.105	4.048	0.303			
	50K	Long	30 ppm	0.0.70	1.778	0.068	216.6	306.4	411.8
			350 ppm	0.223	7.224	0.324			
Altima	100K	Short	40 ppm	0.041	0.788	0.061	43.9	34.3	83.6
			540 ppm	0.059	1.058	0.112			
	100K	Long	40 ppm	0.041	0.788	0.061	39.0	25.3	116.4
			540 ppm	0.057	0.987	0.132			
Taurus	4K	Short	40 ppm	0.033	0.522	0.075	54.5	59.4	34.7
			540 ppm	0.051	0.832	0.101			
	4K	Long	40 ppm	0.033	0.522	0.075	121.2	151.0	56.0
			540 ppm	0.073	1.310	0.117			
Accord (API	4K	Short	40 ppm	0.029	0.285	0.100	10.3	4.9	92.0
			540	0.032	0.299	0.192			

Vehicle	*Cat. Age*	*Sulfur Aging*	*Sulfur Level*	*Tailpipe Emissions (g/mi)*			*Sulfur Sensitivity (%)*		
				NMHC	*CO*	*NOx*	*NMHC*	*CO*	*NOx*
	4K	Long	40 ppm	0.029	0.285	0.100	41.4	63.2	145.0
			540 ppm	0.041	0.465	0.245			
Avalon	4K	Short	40 ppm	0.040	0.406	0.068	52.5	33.3	70.6
			540 ppm	0.061	0.541	0.116			
	4K	Long	40 ppm	0.040	0.406	0.068	50.0	80.8	108.8
			540 ppm	0.060	0.734	0.142			

In order to quantify the difference between short-term and long-term exposure, we averaged the low and high sulfur emissions for each pollutant for all of the vehicles and determined a straight linear fleet average emissions for both low sulfur and high sulfur fuels. The ratio of the long-term sensitivity to the short-term sulfur sensitivity was then determined. As can be seen in table A-4, the percent increases from short-term to long-term are quite significant, especially for NMHC emissions. The three vehicles with catalysts aged to 50,000 or 100,000 miles had, on average, long-term sensitivities greater than the three vehicles with 4,000 mile catalysts. Therefore, the effects of long-term exposure to sulfur presented here may be underestimated.

Table B-4. Percent Difference Between Short-Term vs. Long-Term Sulfur Sensitivity

Average	*Sulfur Sensitivity (%)*			*Ratio of the Sensitivities (long-term to short-term , in %)*		
	NMHC	*CO*	*NOx*	*NMHC*	*CO*	*NOx*
Short-Term	40.2	75.7	111.3	149.2	136.0	46.8
Long-Term	100.3	178.7	163.4			

To test whether this observed increase in sulfur sensitivity was statistically valid, we calculated the ratio of short-term sulfur sensitivity (in percent) to long-term sulfur sensitivity (in percent) for each vehicle. We then calculated the average and standard deviation of these ratios and calculated 90percent and 95percent confidence intervals. At a 95percent confidence level, the lower limits of the confidence intervals for NMHC and NOx pollutants exceeded 1.0. This indicates that at least a 95percent confidence exists that the long-term sulfur sensitivity exceeds that for short-term exposure. The same was true for CO emissions at a 90percent confidence level.

We multiplied the short term sulfur sensitivities from the larger vehicle database by the ratio of the long to short term sensitivities from the 6 vehicle database. This resulted in a sulfur sensitivity of 100 percent for NMHC and 197 percent for NOx emissions when measured at 330 ppm fuel sulfur compared to 30 ppm.

B. Theory Supporting the Reversibility and Irreversibility of Sulfur's Emission Impact

Sulfur impacts emissions from modern vehicles primarily by reducing the efficiency of the three-way catalyst. Molecules of sulfur (either in the form of sulfur dioxide or hydrogen sulfide) adsorb on the catalyst surface and basically take up space so that molecules of HC, CO and NOx cannot adsorb and react to form water, nitrogen, oxygen and carbon dioxide. With palladium catalysts, it appears that sulfur also penetrates into the metal itself, forming a reservoir of sulfur within the catalyst. Sulfur dioxide also penetrates into the oxygen storage medium of the catalyst and reduces the ability of the catalyst to manage the level of oxygen on the catalyst surface. This oxygen management function is a key component of the 98 percent plus efficiencies of today's three-way catalysts, particularly for controlling NOx emissions.

EPA summarized the basic chemical and thermodynamic mechanisms involved in sulfur's two types of interference in it staff paper on gasoline sulfur in May of 1998.[4] This paper also summarized the conditions required to remove sulfur from the catalyst once the vehicle had been exposed to high sulfur fuel. The results of a number of studies showed that generally high temperatures (in excess of 700^{o} F) are required to remove sulfur from both the surface of the catalyst and from the washcoat matrix. In addition to high temperature, a rich exhaust (absence of oxygen coupled with presence of HC and CO, or a low air-fuel ratio) or an alternating sequence of rich and lean (presence of more oxygen in the exhaust than is needed to oxidize the HC and CO present, or a high air fuel ratio) exhaust was often needed to fully regenerate the catalyst. Larger degrees of lean and rich exhaust appear to be much more conducive to sulfur removal than small changes in air fuel ratio. When these rich or alternating rich-lean conditions were not present, even higher temperatures were required to remove the sulfur from the catalyst, when such removal was successful. However, when the combination of temperature and variation in the air-fuel ratio is sufficient, the sulfur accumulated from operation on high sulfur fuel appears to be essentially eliminated and the emission impact of the high sulfur fuel is fully reversed.

[4] "EPA Staff Paper on Gasoline Sulfur Issues," U.S. EPA, May 1998, EPA420-R-98-005.

If sulfur reversibility was the only criteria involved in catalyst design, auto manufacturers could place their catalysts right up against the engine and design the onboard computer to vary the air fuel ratio from rich to lean sufficiently to regenerate the catalyst after any temporary exposure to high sulfur fuel. Engine exhaust temperatures are generally high enough at the exhaust manifold during typical driving to facilitate sulfur removal. The onboard computer is certainly capable of varying the air-fuel ratio significantly. However, other critical catalyst design criteria prevent such the use of such simple measures. First, excessive temperatures can thermally damage the catalyst and reduce its efficiency. Second, simultaneously high conversion efficiencies of HC, CO and NOx require very tight air fuel ratio control (minimal swings to either rich or lean conditions).

Regarding catalyst temperature, auto manufacturers must balance a number of conflicting criteria. One important criterion for catalyst design is that it light-off quickly. Most of the HC and CO emissions from LEV vehicles, and significant amounts of NOx emissions, occur prior to catalyst light-off. Achieving this has affected the type and amount of materials used in the catalyst and resulted in moving the catalyst closer to the engine. Many manufacturers have switched to catalysts containing palladium, which generally can withstand higher temperatures than platinum and rhodium catalysts. At the same time, catalyst manufacturers have improved the design of their platinum and rhodium catalysts so that they can withstand higher temperatures, as well. Moving the catalyst closer to the engine also increases catalyst temperature during warmed-up operation, other factors being equal. Despite improvements in the thermal durability of catalysts, sufficiently high temperatures can still cause a significant loss of catalyst efficiency.

Engine load also affects exhaust and catalyst temperature. The engine load for a given vehicle is a function of vehicle speed, rate of acceleration, vehicle weight and road grade, with higher levels of all of these factors leading to higher engine loads and catalyst temperatures. Vehicles which carry the most widely varying loads and which are driven the most aggressively will generally experience the most variation in their catalyst temperature. Manufacturers must design their catalysts to both light-off quickly and stay warm under light loads while not sustaining thermal damage under heavy loads. Light trucks and sporty vehicles probably present the most difficult challenges in this regard. For example, light trucks are most often driven with one person and minimal cargo. However, they also are used to carry numerous passengers or carry or pull heavy cargo up steep hills. The catalyst must be designed to withstand the higher temperatures of these heavier loads.

One additional factor affecting catalyst temperature is the upcoming implementation of EPA and California SFTP standards. The SFTP standards address emissions generated while the vehicle is driving aggressively (high speeds and high rates of acceleration) and while the air conditioning is turned on, both of which generate higher engine loads than exist during EPA's FTP test cycle. Manufacturers have historically designed their engines to run rich under high loads. The excess fuel decreases exhaust and catalyst temperature relative to an engine running at stoichiometry (just the right amount of air to burn the fuel). The SFTP standards will require that manufacturers reduce much of this high-load enrichment in order to reduce HC and CO emissions during these high loads. Therefore, all other factors being equal, exhaust and catalyst temperatures under extreme conditions will increase after implementation of the SFTP standards, which begin their phase-in in the 2001 model year. Thus, the SFTP standards incrementally increase the difficulty of quickly lighting-off the catalyst while still protecting it from thermal damage during extreme driving conditions. While these extreme conditions must be considered in the catalyst design process, their frequency in-use is not sufficient to rely upon for sulfur removal. For example, some vehicle owners own and tow trailers up steep hills, while others do not. Therefore, while the SFTP standards may increase temperatures under some conditions, they will not necessarily increase sulfur removal capability for the general vehicle population.

Requiring manufacturers to increase the temperature of their catalysts under light loads to improve sulfur reversibility would therefore increase temperatures under heavy loads even further. EPA has no information on the feasibility of manufacturers increasing warmed-up catalyst temperatures beyond that required by the current standards, as well as the proposed Tier 2 standards, without additional degradation in catalyst efficiency. Since the vast majority of the HC, CO and NOx emission control occurring under both the current standards and the proposed Tier 2 standards relies on the proper operation of the catalyst over the life of the vehicle, increasing catalyst temperatures to enhance sulfur reversibility risks essentially all of the benefits of EPA's exhaust emission control program (both current and proposed). Therefore, it would be imprudent to require vehicle manufacturers to design catalysts that operate at temperatures high enough to improve the reversibility of sulfur effects and also meet the proposed Tier 2 standards in-use.

Moving to the variation in air-fuel ratio, manufacturers have significantly enhanced their engines' and computers' abilities over the past few years specifically to avoid large swings in rich and lean operations. This ability to maintain tight control of the air-fuel ratio has increased catalyst efficiency significantly in the process. Designing the vehicle to have alternating rich-lean operation may improve the reversibility of sulfur effects, but would reduce catalyst efficiency and potentially prevent the achievement of both current and proposed Tier 2 exhaust emissions standards. As was the case with increasing catalyst temperature, it would be counter-productive to reverse this progress in overall emission control just to enhance the sulfur reversibility of catalyst systems.

Results from our Tier 2 technology assessment program indicate that there will be trade-offs between NMOG and NOx control in order to meet Tier 2 emission standards, especially for larger vehicles. For example, significant reductions in NOx can be achieved by improved EGR strategies that don't necessarily rely on improvements to the catalyst, whereas reductions in NMOG may rely more heavily on strategies to reduce catalyst light-off time as well as catalyst light-off performance. Since sulfur doesn't affect emissions coming out of the engine, an emission control strategy that focuses less on catalyst performance may not experience sulfur problems as readily as systems that depend more on the catalyst. Since these trade-offs will be very model-specific, it is very difficult to determine the impact emission control strategies needed to meet strict Tier 2 emission standards will have on sulfur reversibility tolerance.

Thus, the two changes in emission control design necessary to reverse sulfur, hotter catalyst temperatures and variable air-fuel ratios, both run counter to other design criteria aimed at achieving stringent emission standards in-use. Therefore, EPA believes that sulfur reversibility should be evaluated with the catalyst temperatures and air-fuel ratio control of today's cleanest vehicles, considering the impact of the future SFTP standards.

The next section evaluates the available sulfur irreversibility data from numerous sulfur irreversibility test programs.

C. Results of Sulfur Irreversibility Test Programs

We have received data from seven test programs which evaluate the irreversibility of sulfur's impact on vehicle emissions. These programs are summarized in the following seven sections.

1. Pre-SFTP LEVs

All of the data generated for the NPRM was for Tier 1, LEV, and ULEV vehicles that were not designed to meet the Federal, or California SFTP standards. The potential effect of the SFTP standards on sulfur reversibility has already been discussed above. Therefore, we are going to divide the data from the various test programs into two categories: pre-SFTP LEVs and SFTP-compliant LEV and Tier 2 vehicles. The following is a summary of the programs in the pre-SFTP category. Two of the programs were discussed in the RIA for the proposed rule. There are also two new programs that were run after the NPRM.

a. Coordinating Research Council (CRC) Sulfur Irreversibility Program

The CRC sulfur irreversibility program evaluated six 1997 LEV LDV models that were part of their original sulfur sensitivity program. The following table lists the six vehicles used in the program.

Table B-5. CRC Test Vehicles

Vehicle	*Number of Cylinders*	*Engine Displacement*
Ford Taurus	6	3.0L
Ford Escort	4	2.0L
Honda Civic	4	1.6L
Toyota Camry	4	2.2L
Nissan Sentra	4	1.6L
Suzuki Metro	4	1.3L

All six vehicles were equipped with 100K mile bench aged catalysts and oxygen sensors. Testing was performed in two phases - I and II. Phase I consisted of three FTP tests (with a single LA4 cycle run in between) with an initial baseline fuel containing 30 ppm sulfur. Three additional FTP tests (again with the single LA4 preconditioning) were run using fuel containing 600 ppm sulfur. In order to evaluate the reversibility of the effects of the higher 600 ppm sulfur from the catalyst surface of the six vehicles, all of the vehicles ran eight FTP tests using an LA4 test just prior to each FTP as a sulfur "purge" cycle. The LA4 cycle was chosen as a purge cycle because of its general representativeness of city driving. Reversibility was defined as the ratio of 1) the difference between the average of emissions with high sulfur fuel and the average of emissions from the subsequent eight tests using low sulfur fuel to 2) the difference between the average of the high sulfur results with the average of the initial baseline low sulfur results. Total mileage accumulation during purge testing was roughly 250 miles. In other words, after 250 miles of operation, emission performance stabilized and no further purging of sulfur from the catalyst surface occurred.

Phase II consisted of three FTP tests with fuel containing 600 ppm sulfur followed by two FTP tests with 30 ppm sulfur fuel with an LA4 purge cycle prior to each FTP. Six FTP tests were then performed with a US06 cycle prior to each FTP as a sulfur purge cycle. The US06 cycle was chosen as a purge cycle to simulate aggressive high speed and load operation that would encourage higher catalyst temperatures and rich A/F operation. Reversibility was determined in the same manner as in phase I (same initial 30 ppm sulfur baseline). Total mileage accumulation turned out to be roughly 200 miles.

The following table lists the results of the CRC sulfur irreversibility test program.

Table B-6. Sulfur Irreversibility: CRC Test Program (%)

		NMHC		***NOx***	
		Purge Cycle		*Purge Cycle*	
Vehicle Manufac	Models	LA4	US06	LA4	US06
Ford	Taurus	31.0	17.0	30.0	5.0
Ford	Escort	0.0	0.0	5.0	0.0
Honda	Civic	6.0	1.0	4.0	3.0
Nissan	Sentra	1.0	0.0	15.0	12.0
Toyota	Camry	0.0	2.0	50.0	0.0
Suzuki	Metro	0.0	0.0	14.0	13.0
Fleet Estimate		**3.0**	**0.0**	**16.0**	**5.0**

The fleet estimate used for the CRC data was determined by averaging the baseline low sulfur results, the high sulfur results and the final low sulfur results for all vehicles and determining reversibility as discussed above. These results indicate that on average, NMHC emissions are very reversible, regardless of purge cycle used (LA4 or US06). The Ford Taurus, however, showed only a moderate level of irreversibility for NMHC, especially with the LA4 purge cycle (31 percent). The results for NOx indicate that with the LA4 purge cycle, the average level of irreversibility is 16 percent with the Toyota Camry having irreversibility as high as 50 percent. When using the US06 purge cycle, NOx emissions were far more reversible with an average irreversibility of 5 percent. The Nissan Sentra and Suzuki Metro showed almost the exact same level of irreversibility with both purge cycles.

b. American Petroleum Institute Sulfur Irreversibility Program

The API program[5] evaluated a total of seven vehicles, four were 1998 LEV LDVs, one was a 1998 ULEV LDV, and the other two were Tier 1 vehicles (LDV and LDT1). All of the vehicles had been driven for 6,000-10,000 miles, except for the S10 pickup, which had 50,000

[5] API has completed a third-party review of the results of their test program (as well as the CRC test program). See "Reversibility of Gasoline Sulfur Effects on Low Emissions Vehicles," T.J. Truex and L.S. Caretto for API, April 7, 1999.

miles on it. API replaced the catalysts of all of the vehicles. Reversibility of the sulfur effect was measured for all of these vehicles with their new catalysts thermally aged to the equivalent of 4,000 miles (i.e., low mileage catalysts) and after only a very short exposure to high sulfur fuel. Four of these vehicles were also tested with 1,000 miles of road aging on high sulfur fuel (540 ppm) prior to reversibility testing.

The sulfur reversibility of two vehicles was also tested after short term exposure to high sulfur fuel with their catalysts thermally aged to represent 100,000 miles of driving. (However, the oxygen sensors were not aged.) Finally, one vehicle was tested after 2,000 miles of driving using high sulfur fuel with its catalysts thermally aged to represent 100,000 miles of driving.

All of the vehicles were tested in a sequence similar to the one used by CRC. The program started with testing using low sulfur fuel (40 ppm). This was followed by testing with a high sulfur fuel (540 ppm). Then, the fuel was switched back to the low sulfur fuel and the vehicle operated over either an LA4 or US06 cycle, which was used as a sulfur purge cycle. Following this purge cycle, emissions were again measured with the FTP.

One major difference between the API and CRC programs was that API generally only performed two tests at each sulfur level, including the purge cycle phase. This will underestimate reversibility since other programs have shown that emissions on low sulfur fuel after exposure to high sulfur fuel continue to decrease after two tests. Thus, statistically speaking, the API program is weaker than the CRC program. Examination of individual emission test results shows significant variability occurred.

Table B-7 lists the vehicle tested in the API program.

Table B-7. API Test Vehicles

Vehicle	*Number of Cylinders*	*Engine Displacement*
1998 Ford Taurus (LEV)	6	3.0L
1998 Honda Accord (ULEV)	6	2.3L
1998 Toyota Avalon (LEV)	6	3.0L
1998 Nissan Altima (LEV)	4	2.4L
1998 Ford Grand Marquis (LEV)	8	4.6L
1998 Ford Town Car (Tier1)	8	4.6L
1997 Chevrolet S-10 (Tier1)	6	4.3L

API screened specific vehicles for this test program by performing emission testing over both the FTP and the US06 cycle. API believed that these vehicles were nearly in compliance with future SFTP standards and therefore representative of 2000 and later emission control technology. This assumption will be discussed further below.

Table B-8 shows the sulfur irreversibility emission results for all of the vehicles when tested with low mileage (4,000 mile) catalysts.

Table B-8. Sulfur Irreversibility: API Test Program
Low Mileage Catalysts, Short-Term Exposure to High Sulfur Fuel (%)

		NMHC		***NOx***	
		Purge Cycle		*Purge Cycle*	
Vehicle Manufac	Models	LA4	US06	LA4	US06
Ford	98 Taurus	0.0	n/a *	3.8	n/a
Honda	98 Accord (ULEV)	76.9	0.0	21.7	2.2
Toyota	98 Avalon	28.6	57.1	47.9	0.0
Nissan	98 Altima	0.0	n/a*	0.0	n/a
Ford	98 Gr. Mar	0.0	19.4	15.5	28.2
Ford	98 Town Car (Tier1)	53.7	40.0	5.0	0.0
Chevrolet	97 S-10 (Tier1)	33.3	0.0	29.7	0.0
Fleet Estimate		**32.4**	**54.1**	**16.7**	**7.7**

* Vehicle not tested with US06 purge cycle.

The most obvious difference between the irreversibilities measured by API and those found by CRC is that API's average NMHC irreversibility rate when using the LA4 as a purge cycle is 32 percent, while CRC's average NMHC reversibility rate shows nearly full reversibility at three percent irreversibility. The measured NOx irreversibilities (with the LA4 purge cycle) were almost identical in the two programs, 17 percent for API compared to 16 percent for CRC. However, it should be pointed out that API only performed two tests on low sulfur fuel.

API found much lower irreversibility using the US06 cycle as a purge cycle for NOx (7.7

percent). However, the opposite was true for NMHC (54.1 percent). This 54.1 percent irreversibility is considerably higher than that found in the CRC program, where NMHC emissions were essentially fully reversible after purging with the US06 cycle.

Another difference between the API and CRC test results is the great deal of disparity between the irreversibilities measured for individual vehicles in the API program. Some vehicles were highly reversible while others were not. The CRC results appear to be more consistent from vehicle-to-vehicle. This could be a result of the fact that CRC performed eight purge/FTP combinations with low sulfur fuel after exposure to high sulfur fuel, compared to API, which only performed two purge/FTP combinations. The CRC data showed that emissions after the switch back to low sulfur fuel fluctuated up and down before reaching a more consistent level during the eight tests. It is also possible that API simply experienced greater test-to-test variability, or that the vehicles in the API program simply differed more in their inherent irreversibility.

Table B-9 shows measured irreversibility for vehicles with low mileage catalysts that were operated on high sulfur fuel (540 ppm) for 1,000 miles on the road. Four vehicles were evaluated in this manner. The Taurus was tested with the LA4 purge cycle, but not the US06, while the Accord, Avalon, and Grand Marquis all were tested with the US06 purge cycle but not the LA4. As with the low mileage catalyst data, there is a significant amount of disparity between vehicles, especially for NMHC irreversibility with the US06 cycle. Irreversibility of NOx emissions with the US06 cycle, however, are consistent and indicate that the sulfur effect is almost fully reversible with the US06 cycle. The Taurus with only short term exposure to high sulfur fuel was 100 percent reversible with the LA4 purge cycle for NMHC, but only 67.9 percent reversible with the LA4 cycle after road aging. Reversibility of NOx emissions from the Taurus was nearly complete for both short term and longer term exposure to high sulfur fuel.

Table B-9. Sulfur Irreversibility: API Test Program
Low Mileage Catalysts, 1,000 Mile Exposure to High Sulfur Fuel (%)

	1,000 Mile Exposure				*Short-Term Exposure*			
	NMHC		***NOx***		***NMHC***		***NOx***	
	Purge Cycle		*Purge Cycle*		*Purge Cycle*		*Purge cycle*	
Models	LA4	US06	LA4	US06	LA4	US06	LA4	US06
98 Taurus	32.5	0.0	2.4	0.0	0.0	n/a *	3.8	n/a
98 Accord (ULEV)	n/a	0.0	n/a	5.5	76.9	0.0	21.7	2.2
98 Avalon	n/a	25.0	n/a	0.0	28.6	57.1	47.9	0.0
98 Grand Marquis	n/a	54.5	n/a	0.0	0.0	19.4	15.5	28.2
Fleet Estimate	**32.5**	**12.0**	**2.4**	**0.0**	**6.0**	**31.0**	**22.3**	**11.6**

Table B-9 shows measured irreversibility for vehicles with catalysts bench aged to represent 100,000 miles of driving. Only two vehicles were tested with this configuration - the Taurus and the Altima. Due to problems with the fuel tank on the original Altima used in the program, a second Altima was procured and tested with a 100K catalyst system. Irreversibility of the Altima's emissions was measured after both short-term exposure to high sulfur fuel, as well as after 2,000 miles of highway driving with high sulfur fuel. This was the only vehicle in the API program that had both a 100,000 mile catalyst and extended road aging with high sulfur fuel. It was also the only vehicle with 2,000 miles of driving with high sulfur fuel instead of 1,000 like the other four vehicles with more extended use with high sulfur fuel.

Table B-10. Sulfur Irreversibility: API with 100K Aged Catalysts Test Program (%)

	NMHC		***NOx***	
	Purge Cycle		*Purge Cycle*	
Models	LA4	US06	LA4	US06
Short-term Exposure to High Sulfur Fuel				
98 Taurus	0.0	0.0	11.3	14.6
98 Altima	15.1	0.0	21.1	10.8
Fleet estimate	**0.0**	**0.0**	**12.7**	**12.7**
2,000 Mile Exposure to High Sulfur Fuel				
98 Altima	n/a	0.0	n/a	6.1

The Taurus showed very similar levels of NMHC emission reversibility (after the LA4 purge cycle) with both low mileage and high mileage catalysts (essentially fully reversible in both cases). NOx emission irreversibility increased from 3.8 percent with the low mileage catalyst to 11.3 percent with the 100,000 mile catalyst. NOx emission reversibility did not improve after purging with US06 cycles.

The first Altima tested, which had a 4000 mile catalyst, was fully reversible for both NMHC and NOx emissions with the LA4 purge cycle. The second Altima, which had a 100,000 mile catalyst showed more irreversibility, only 15.1 percent for NMHC emissions and 21.1 percent for NOx emissions. Both NMHC and NOx emission reversibility improved with purging with the US06 cycle, though NOx emissions were still not fully reversible.

The second Altima showed similar NMHC and NOx reversibility with both short-term and long-term exposure to high sulfur fuel with the US06 purge cycle. The second Altima was not tested with the LA4 purge cycle.

Table B-11. Sulfur Sensitivity: API Test Program
Low Mileage Catalysts, Short-Term Exposure to High Sulfur Fuel (g/mi)

	NMHC	***NOx***

FTP Test Sulfur Level	*30 ppm*	*540 ppm*	*540 ppm*	*30 ppm*	*540 ppm*	*540 ppm*
Sulfur Exposure	---	Short-term	1,000 Mile	----	Short-term	1,000 Mile
Vehicle	Low Mileage Catalysts					
Taurus	0.033	0.051	0.073	0.075	0.101	0.117
Accord	0.029	0.036	0.041	0.100	0.164	0.245
Avalon	0.040	0.058	0.060	0.068	0.130	0.143
Gr. Marq.	0.044	0.075	0.055	0.040	0.143	0.152
Average	0.037	0.055	0.057	0.071	0.135	0.164
	100,000 Mile Catalysts					
Altima	0.041	0.059	0.057	0.061	0.112	0.132

c. Ford Sulfur Irreversibility Program

Ford tested two vehicles, a 1999 LEV Taurus and a 1999 LEV Explorer. Both vehicles were equipped with 4K mile aged catalysts. Neither vehicle was designed to meet SFTP emission standards. The vehicles were initially tested over the FTP cycle using low sulfur fuel (35 ppm) to establish a baseline. A total of three FTPs were run. This was followed by testing another three FTPs on a high sulfur fuel (450 ppm). Then, the fuel was switched back to the low sulfur fuel and the vehicles ran a LA4 cycle immediately followed by a FTP. The LA4 cycle was used to purge sulfur from the catalyst. Ford ran between three to five of these LA4/FTP combinations for each vehicle. Ford repeated the entire procedure with the US06 cycle in place of the LA4 cycle as a purge cycle. The following table lists the results of the Ford sulfur irreversibility test program.

Table B-12. Sulfur Irreversibility: Ford Test Program (%)

		NMHC		***NOx***	
		Purge Cycle		*Purge cycle*	
Model	Vehicle Type	LA4	US06	LA4	US06
Taurus	LDV	12.0	0.0	7.0	0.0
Explorer	LDT3	91.0	70.0	n/a	n/a

The Ford results were somewhat sporadic. The Taurus was mostly reversible over the LA4 and fully reversible over the US06, whereas the Explorer was highly irreversible over the LA4 cycle. They were unable to perform any tests over the US06 for the Explorer. Our biggest concerns with the Ford data was that the vehicles were mistakenly equipped and tested with 4K catalyst systems instead of 50K or 100K aged catalysts, and the data showed an enormous amount of variability.

d. EPA Sulfur Irreversibility Test Program

After publication of the NPRM, we tested two 1999 LDVs which were supplied to us by their manufacturer. One was a LEV Chevrolet Cavalier and the other was a ULEV Honda Accord. Both vehicles were equipped 50K aged catalysts. The vehicles were initially tested over the FTP cycle using low sulfur fuel (30 ppm) to establish a baseline. We tested until the emission results stabilized, typically three to four FTPs (approximately 60 to 80 miles). This was followed by FTP testing on a high sulfur fuel (350 ppm). Again, tests were run until emission levels were stable. Upon completion of high sulfur testing, the fuel was switched back to the low sulfur fuel and the vehicles ran a combination of LA4 cycle immediately followed by a FTP. These tests were also run until emissions stabilized, not exceeding eight LA4 + FTP cycles. Since neither vehicle was SFTP-compliant, we did not perform any tests with the US06 cycle as a purge cycle.

In addition to short-term sulfur testing, we also tested the vehicles with long-term exposure to sulfur. After completion of the short-term testing, the vehicles were driven over several EPEFE purge cycles to ensure that any sulfur from the short-term testing was removed from the catalysts. The vehicles were baseline tested on low sulfur fuel as before and then driven for 2,000 to 3,000 miles on the road with high sulfur (350 ppm) fuel. FTP tests were performed at 500 mile intervals. Upon the completion of high sulfur road aging, the vehicles ran a combination of LA4 cycle immediately followed by a FTP, exactly as in the short-term testing. Again, no US06 purge cycle testing was performed.

The following Table lists the results from our test program.

Table B-13. Sulfur Irreversibility: EPA Test Program, Short-Term and Long-Term Exposure (%)

		NMHC		*NOx*	
Short-Term		*Purge Cycle*		*Purge cycle*	
Model	Vehicle Type	LA4	US06	LA4	US06
Cavalier	LEV LDV	67.0	n/a	42.0	n/a
Accord	ULEV LDV	0.0	n/a	26.0	n/a
Long-Term					
Cavalier	LEV LDV	0.0	n/a	27.0	n/a
Accord	ULEV LDV	0.0	n/a	14.0	n/a

The results for short-term exposure suggest that both vehicles were highly irreversible, especially the Cavalier. The NMHC results for the Accord are most likely an anomaly since the vehicle mistakenly had only one test performed on high sulfur fuel. The results for long-term sulfur exposure are counter-intuitive, since NMHC emissions were fully reversible compared to the low level of reversibility for the vehicles when tested after short-term exposure. NOx emissions were slightly more reversible than for short-term exposure. However, even with long-term exposure to sulfur, NOx emissions were still only partially reversible.

e. ATL Sulfur Irreversibility Program

ATL, under contract for us, tested two vehicles, a 1999 LEV Ford Windstar mini-van and a 1999 LEV Ford Taurus. Both vehicles were procured from a rental agency in California and had approximately 50K miles. Thus, they were equipped with catalysts which had been aged with 50,000 miles of in-use driving, albeit at higher annual mileage rates than typical in-use vehicles. Both vehicles had low emissions, especially the Taurus which had emissions below Tier 2 levels.

ATL used the exact same test procedure as us for our in-house testing. The vehicles were initially tested over the FTP cycle using low sulfur fuel (30 ppm) to establish a baseline. Tests were run until emission results stabilized, typically three to four FTPs (approximately 60 to 80 miles). This was followed by FTP testing on a high sulfur fuel (350 ppm). Again, tests were run until emission levels were stable. Upon completion of high sulfur testing, the fuel was switched back to the low sulfur fuel and the vehicles ran a combination of LA4 cycle immediately followed by a FTP. These tests were also run until emissions stabilized, not exceeding eight LA4 + FTP cycles. Because we were anticipating new powertrain control modules (PCM) from Ford that were to be equipped with SFTP-compliant calibrations, we did not run either vehicle over the US06 cycle. The following Table summarizes the results.

Table B-14. Sulfur Irreversibility: ATL Test Program

		NMHC		***NOx***	
		Purge Cycle		*Purge cycle*	
Model	Vehicle Type	LA4	US06	LA4	US06
Taurus	LDV	30.0	n/a	34.0	n/a
Windstar	LDT2	26.0	n/a	29.0	n/a

As can be seen, both of these vehicles were partially reversible. The level of irreversibility for both vehicles falls almost exactly in the middle of the data spread for all of the pre-SFTP vehicles.

f. Irreversibility for Long-Term Sulfur Exposure

In section A., we discussed the effect long-term exposure to sulfur has on sulfur sensitivity. We found that, based on a sample of six pre-SFTP LEV vehicles, long-term exposure to high sulfur fuel resulted in an additional sensitivity in emissions to sulfur of 149 percent for NMHC and 48 percent for NOx, above the original emission sensitivity levels when comparing emissions from a fuel sulfur level of 30 ppm to a fuel sulfur level of 330 ppm. For example, if baseline emissions were 0.10 g/mi NOx and high sulfur emissions were 0.15 g/mi NOx after short term exposure, then high sulfur emissions would be about 0.175 g/mi NOx after long term exposure. However, the data from these six vehicles indicates that when these vehicles were operated again on 30 ppm sulfur fuel with an LA4 purge cycle, the extra emissions sensitivity resulting from long-term exposure was completely recovered. In other words, all of the vehicles showed the same or lower emissions on low sulfur fuel after long-term exposure to high sulfur fuel as they did after short term exposure to high sulfur fuel. This would suggest that after long-term exposure to sulfur, emissions are capable of recovering to short-term levels with only moderate FTP-type driving. We are projecting this phenomenon to occur for both pre-SFTP and SFTP-compliant vehicles, though this data is available only for pre-SFTP vehicles. Thus, there is some uncertainty in applying it to SFTP-compliant Tier 2 vehicles, as well. However, the same is true for the data showing a larger sulfur sensitivity after long-term exposure to high sulfur fuel.

2. SFTP-compliant LEV and Tier 2 vehicles

The following three sections describe sulfur irreversibility test programs that utilize SFTP-compliant, low emitting LEVs and prototype Tier 2 vehicles. All of these programs occurred after publication of the NPRM. We are also quantifying irreversibility for NMHC and NOx emissions together instead of independently, because per our discussion above and our own experience developing the emission control strategy for the Expedition discussed below, sensitivity and irreversibility of either pollutant appears to be very dependent on the particular strategy chosen to reduce these emissions (particularly engine calibration and catalyst loading of precious metals and oxygen storage).

a. DaimlerChrysler Sulfur Irreversibility Program

DaimlerChrysler tested a prototype “Tier 2-like” 3.3L Dodge Caravan that met SFTP emission standards and was equipped with a 100K aged catalyst. DaimlerChrysler tested the vehicle over a test procedure very similar to the short-term portion of our sulfur irreversibility test program for the Cavalier and Accord. The only differences were that they tested a high sulfur fuel level of 450 ppm instead of 350 ppm, and they performed reversibility testing with the REP05 cycle in lieu of the US06 cycle for sulfur purging prior to FTP tests after operation on high sulfur fuel. The following Table lists results for the Caravan.

Table B-15. Sulfur Irreversibility: DaimlerChrysler Test Program (%)

	NMHC		***NOx***		***NMHC + NOx***	
	Purge Cycle		*Purge Cycle*		*Purge Cycle*	
Vehicle	LA4	REP05	LA4	REP05	LA4	REP05
Caravan	18.0	39.0	29.0	5.0	27.0	11.0

The Caravan was partially reversible for NMHC, NOx, and NMHC + NOx. The vehicle was more reversible after REP05 operation than LA4 operation for NOx, but not NMHC emissions. NMHC + NOx emissions indicate significant irreversibility for LA4 operation and moderate irreversibility even after REP05 operation.

b. EPA Sulfur Reversibility Program

In addition to the two pre-SFTP LEVs vehicles that we tested, we also tested a 1999 Ford Expedition SUV from our Tier 2 technology demonstration program. The vehicle was equipped with a 50K aged catalyst system. We modified the Expedition such that it met Tier 2 intermediate useful life emissions standards (bin 4 - 0.075 g/mi NMOG, 0.05 g/mi NOx) as well as federal and California SFTP standards with reasonable margins of safety. The modifications made consisted of calibration changes and an advanced catalyst system (see Chapter IV.A of the RIA for a detailed description of our Tier 2 test work with the Expedition). The vehicle was initially tested over the FTP cycle using low sulfur fuel (30 ppm) to establish a baseline. We tested until the emission results stabilized, typically three to four FTPs. This was followed by FTP testing on a high sulfur fuel (350 ppm). Again, tests were run until emission levels were stable. Upon completion of high sulfur testing, the fuel was switched back to the low sulfur fuel and the vehicles ran a combination of LA4 cycle immediately followed by a FTP. These tests were also run until emissions stabilized, not exceeding eight LA4 + FTP cycles. The entire test procedure was repeated with the REP05 cycle in place of the LA4 cycle as a purge cycle. The following Table lists the results for the Expedition.

Table B-16. Sulfur Irreversibility: EPA Test Program (%)

	NMHC		***NOx***		***NMHC + NOx***	
	Purge Cycle		*Purge Cycle*		*Purge Cycle*	
Vehicle	LA4	REP05	LA4	REP05	LA4	REP05
Expedition	78.0	91.0	21.0	0.0	65.0	70.0

The Expedition was partially reversible for NOx over LA4 conditions and fully reversible over the REP05. However, the most interesting observation was that it was highly irreversible for NMHC over all driving conditions, but especially for aggressive. The results for NMHC , although more severe for the Expedition, were similar to the Caravan in that both vehicles were more irreversible over the REP05 than the LA4 cycle. Looking at NMHC + NOx results, indicate that the Expedition was highly irreversible for all driving conditions.

c. ATL Sulfur Reversibility Program

ATL, under contract for us, tested two vehicles, a 1999 LEV Ford Windstar mini-van and a 1999 LEV Ford F-150 pick-up truck. Both vehicles were procured from a rental agency in California and had approximately 50K miles. Thus, they were equipped with catalysts which had been aged with 50,000 miles of in-use driving, albeit at higher annual mileage rates than typical in-use vehicles. Both vehicles were then equipped with new powertrain control modules (PCM) with calibrations modified to meet SFTP emission standards, courtesy of Ford. Both vehicles had low emissions, but not at Tier 2 emission levels. A third vehicle (Taurus) was procured by ATL, but a SFTP-compliant PCM was not available, so it was not tested with the other two vehicles.

ATL used the exact same test procedure as us for our in-house testing. The vehicles were initially tested over the FTP cycle using low sulfur fuel (30 ppm) to establish a baseline. Tests were run until emission results stabilized, typically three to four FTPs. This was followed by

FTP testing on a high sulfur fuel (350 ppm). Again, tests were run until emission levels were stable. Upon completion of high sulfur testing, the fuel was switched back to the low sulfur fuel and the vehicles ran a combination of LA4 cycle immediately followed by a FTP. These tests were also run until emissions stabilized, not exceeding eight LA4 + FTP cycles. The entire test procedure was repeated with the REP05 cycle in place of the LA4 cycle as a purge cycle. The following Table summarizes the results.

Table B-17. Sulfur Irreversibility: ATL Test Program (%)

	NMHC		***NOx***		***NMHC + NOx***	
	Purge Cycle		*Purge Cycle*		*Purge Cycle*	
Vehicle	LA4	REP05	LA4	REP05	LA4	REP05
Windstar	0.0	0.0	35.0	0.0	31.0	0.0
F-150	60.0	25.0	13.0	7.0	18.0	9.0

For the LA4 cycle, both vehicles experienced considerable irreversibility for NMHC, NOx, and NMHC + NOx, except for NMHC emissions with the Windstar. With the REP05 cycle, the Windstar was fully reversible for all pollutants, while the F-150 was still partially reversible.

D. Criteria for Evaluating Sulfur Reversibility Data

Projecting the degree of sulfur irreversibility for various vehicles types under representative in-use conditions is difficult due to inadequacies in much of the available data. As mentioned in the previous section, the sulfur reversibility testing would ideally have used vehicles designed to meet a range of FTP and SFTP standards, thermally aged catalyst systems prior to testing, exposed these systems to high sulfur fuel for a few thousand miles of typical driving, and used representative driving cycles to purge sulfur between emission tests.

EPA established a number of criteria for evaluating the available data in order to project likely levels of in-use sulfur irreversibility. The first criterion is to focus exclusively on testing of vehicles with thermally aged catalysts. We believe that this is essential, because catalysts prior to thermal aging contain far more surface area and oxygen storage capacity than is needed to meet low emission levels. It is possible for sulfur to deactivate a considerable portion of the surface area and oxygen storage with minor impacts on overall catalyst performance. This would not be representative of the impact of sulfur on real-world emissions over most of the vehicle's life.

Development of the subsequent criteria are more complex, because the issues of SFTP compliance, vehicles emissions performance and representative driving cycles are not as easily addressed. None of the vehicles tested were certified to either the Tier 1 or LEV SFTP emission standards. Four of the vehicles were equipped with "prototype" SFTP-compliant calibrations, meaning they met both the Tier 1 and LEV US06 standards. Of these four vehicles, only one (EPA Ford Expedition) met the SC03 standards as well as the US06 standards.

As discussed earlier, there will be considerable trade-offs in NMOG and NOx control in order to meet strict Tier 2 emission standards. There can be considerable uncertainty associated with balancing these trade-offs at very low emissions levels if the vehicle is periodically operated on high sulfur fuels, making the ability to remove sulfur from the catalyst highly uncertain. For example, a given catalyst today may be fully reversible for one pollutant and only partially reversible for another. However, because of the trade-off in NMOG and NOx performance, the modifications necessary to get that vehicle to meet both emission standards may result in the opposite effect for reversibility; i.e., full reversibility for NMOG and partial reversibility for NOx. Therefore, a very important criterion in conjunction with SFTP compliance is LEV emission performance for pre-SFTP vehicles and "Tier 2-like" emission performance for SFTP-compliant Tier 2 vehicles.

Likewise, for the bulk of the data which is for pre-SFTP LEVs, only the LA4 and US06 driving cycles were used in the test programs. The LA4 cycle was derived from driving patterns in Los Angeles in the early 1970's. However, due to physical limitations in the dynamometers in use at the time, all accelerations greater than 3.3 mph per second were reduced to this level. This, plus the fact that driving has become more aggressive over the past 25 years makes the LA4 cycle less aggressive on average than today's typical driving. However, the LA4 cycle does include driving as fast as 58 mph, so it is also not representative of light, city driving.

The US06 cycle is made up of real-world driving segments from the REP05 cycle. However, the concentration of aggressive driving is much higher than occurs in the real world. Therefore, the length of time that the catalyst is exposed to both high temperatures and rich conditions is much higher than would occur in the real world. This could easily remove more sulfur than would be removed in-use during aggressive driving.

The four SFTP-compliant vehicles used the REP05 cycle in lieu of the US06 cycle. The REP05 cycle was developed by EPA to be is representative of aggressive driving that occurs outside the LA4 or FTP cycle. All but one of the aggressive driving segments found in the US06 cycle were taken from the REP05. While each segment of the US06 cycle was taken from actual in-use driving, the timing and combination of these segments is not representative of in-use driving in the way REP05 is representative. As with the US06 cycle, however, the length of time that the catalyst is exposed to both high temperatures and rich conditions could be much higher than would occur in the real world, resulting in the removal of more sulfur than would be removed in-use even during aggressive driving. Thus, while it is likely that typical vehicles will experience the reversibility which was measured after driving over the REP05 cycle, we cannot be certain that this is the case.

As mentioned in Section B, meeting the SFTP standards will require the tightening of air-fuel mixture control and reduce the amount of rich operation in-use during aggressive driving. Both of these changes directionally reduce sulfur removal. This primarily affects the sulfur reversibility testing after preconditioning with the US06 cycle. For pre-SFTP vehicles, the US06 cycle still likely over-estimates the amount of sulfur reversibility which would occur in-use, due to its unrepresentative concentration of high temperatures and rich operation. Thus, the measured levels of sulfur reversibility after operation on both LA4 and US06 cycles will be used to project the in-use levels of sulfur reversibility for pre-SFTP vehicles.

In summary, the projections developed in the following section will:

<u>Pre-SFTP Vehicles</u>

1. Only use data from vehicles with aged catalyst systems,
2. Emphasize data from vehicles with LEV emission levels, and
3. Use data where the sulfur was purged using either the LA4 or US06 cycle.

<u>SFTP-Compliant LEV and Tier 2 vehicles</u>

1. Only use data from vehicles with aged catalyst systems,
2. Emphasize data from vehicles with emission levels appropriate for the LEV and Tier 2 standards,
3. Use data from vehicles that were modified to meet SFTP standards, and
4. Use data where the sulfur was purged using either the LA4 or REP05 cycle.

E. Projected Levels of Sulfur Irreversibility In-Use

1. Pre-SFTP Vehicles

Applying the first criterion developed in Section D. results in the retention of the CRC and EPA data (Tables B-2 and B-9), as that testing was performed on vehicles with thermally aged catalysts. It also allows the use of the API data contained in Table B-6. However, the remaining API data apply to vehicles with low mileage catalysts, which are not sufficiently representative of in-use operation. Therefore, EPA's current conclusions about irreversibility of sulfur effects for pre-SFTP vehicles do not rely on the API data except that in Table B-6.

Table B-18. Pre-SFTP Sulfur Irreversibility: Summary of Relevant Test Programs (%)

	NMHC		***NOx***	
	Purge Cycle		*Purge Cycle*	
Models	LA4	US06	LA4	US06
CRC (6 vehicles)	0.0	0.0	16.0	4.0
EPA (2 vehicles)	75.0	n/a	38.0	n/a
ATL (2 vehicles)	28.0	n/a	30.0	n/a
API (2-3 vehicles)	0.0	14.0	0.0	12.0
Fleet Estimate	14.0	0.0	20.0	5.0

For pre-SFTP vehicles (Tier 0, Tier 1 and NLEV), as described above, we decided to utilize reversibility measurements using both the LA4 and US06 driving cycles. We decided to project reversibility for these vehicles by taking the mid-point of the LA4 and US06 values for NMHC and NOx, respectively. Therefore, for these vehicles, using the average of these test results, we project that NMHC emissions are almost fully reversible at four percent irreversibility, while NOx emissions are 12 percent irreversible.

2. SFTP-Compliant LEV and Tier 2 vehicles

The DaimlerChrysler, EPA, and ATL data all met the first criterion of aged catalyst systems. The DaimlerChrysler vehicle was equipped with a 100K aged catalyst, while the vehicles from the other two programs had 50K aged catalyst systems. As for emission performance, all four vehicles were LEVs, meeting the LEV standards with considerable margins of safety. The Expedition and Caravan were both modified in an attempt to meet Tier 2 standards. Only the Expedition actually met both Tier 2 NOx and NMOG emission standards with a typical margin of safety. The Caravan was close to Tier 2 levels, but exceeded the NOx standard. The F-150 was also close to Tier 2 levels, while the Windstar exceeded Tier 2 levels by a significant margin. It should be noted, however, that all four vehicles are LDTs which were certified to substantially higher emission standards than the Tier 2 standards in their baseline configurations. Also, because these vehicles are LDTs, their catalyst temperatures are typically higher than LDVs, which is good for removing sulfur from the catalyst.

All four vehicles from the three programs met the federal and California SFTP emission standards for the aggressive driving portion (US06) with considerable margin. The Expedition also met the SFTP emission standards for the air-conditioning portion of the test (SC03) as well.

As discussed above, trade-offs between NMOG and NOx control in order to meet Tier 2 standards combined with periodic operation on high sulfur fuel will result in uncertainty in the ability to remove sulfur from the catalyst. Therefore, for SFTP-compliant Tier 2 vehicles, we feel that the most appropriate way to analyze irreversibility is to evaluate NMHC and NOx together (i.e., NMHC + NOx), rather than separately. The following Table shows the results for the four vehicles from the DaimlerChrysler, EPA, and ATL test programs.

Table B-19. SFTP-Compliant Sulfur Irreversibility:
Summary of Relevant Test Programs (%)

	NMHC + NOx	
	FTP Purge	*REP05 Purge*
Daimler-Chrysler Caravan	27.0	11.0
Ford Expedition	64.8	69.6
Ford Windstar	31.4	0.0
Ford F-150	18.3	9.1
Average	29.4	10.9
Average w/ lower weights for Caravan and Windstar	29.4	16.6

As can be seen, NMHC + NOx irreversibility is generally much lower after high speed, aggressive driving than after more average city driving. As previously discussed, the REP05 cycle represents the top 28 percent of driving with the highest speeds and hardest accelerations. Thus, most people will drive like the REP05 cycle at least part of the time; however, it is not clear whether occasional driving like the REP05 cycle will provide all of the reversibility enhancement that was provided by the entire REP05 cycle performed in sequence.

There is also still significant variability between the irreversibility of individual vehicles, with the Expedition showing the highest irreversibility by far. This is significant for determining a SFTP-compliant Tier 2 irreversibility estimate, because the Expedition is the only vehicle which complies with both the NMHC and NOx Tier 2 standards with a reasonable amount of headroom. The Windstar (@ 0.12 g/mi NOx) and the Caravan (@ 0.09 g/mi) exceed the Tier 2 NOx standard by significant margins, while the F-150 truck had NOx emissions just slightly above the 0.07 g/mi standard.

Therefore, to determine an irreversibility estimate for SFTP-compliant Tier 2 vehicles, we had to account for the differences in various vehicle's compliance with the Tier 2 standards. We accomplished this by reducing the weight given to the Windstar and Caravan. We recalculated the average irreversibility by reducing the weight assigned to the Windstar and Caravan to one-fourth and one-half of a vehicle, respectively. As shown in the table above, this has no impact on the average irreversibility after FTP driving, but reduces that after REP05 driving modestly. The REP05 cycle represents about 28 percent of all in-use driving. Due to roadway limitations, no one can drive like the REP05 cycle 100% of the time (i.e., residential areas, congested streets, etc.). Therefore, it is reasonable to project that the majority of vehicles are driven in this way at least part of the time. However, it is likely that some vehicles are never or very rarely driven this aggressively. Therefore, we project that roughly 75 percent of vehicles are driven regularly like the REP05 cycle and that 25 percent are not. Thus, we decided to weigh the irreversibility after FTP driving by 25 percent and that after REP05 driving by 75 percent. This results in an average NMHC+NOx irreversibility of 20 percent.

We also wanted to focus on the irreversibility of the Expedition, since it was the only vehicle meeting the Tier 2 standards with adequate headroom. The Expedition had irreversibility levels of 65-70 percent over the two driving cycles. Since the lower irreversibility was seen over the FTP, that figure (65 percent) seems reasonable for an estimate based solely on the Expedition. Therefore, for Tier 2 vehicles, we project that irreversibility of NMHC+NOx emissions will fall somewhere between the low level of 20 percent, based on all four vehicles, and 65 percent based on the Expedition. For emission modeling and cost effective analyses, we decided to use a midpoint estimate of 42.5 percent for Tier 2 vehicles. As for SFTP-compliant LEV vehicles, we decided to use a straight average of the four vehicles weighing the irreversibility after FTP driving by 25 percent and that after REP05 driving by 75 percent, similar to what we did for Tier 2 vehicles. This resulted in an average NMHC+NOx irreversibility of 15 percent. As mentioned above, we project that Tier 0 and Tier 1 vehicles are fully reversible.

Appendix B References

1. “Development of Light-Duty Emission Inventory Estimates in the Notice of Proposed Rulemaking for Tier 2 and Sulfur Standards,” U.S. EPA, February 1999.

2. EPA Report Number M6.FUL.001