

**A REVIEW OF APPENDIX B OF THE U.S. EPA
REGULATORY IMPACT ANALYSIS FOR TIER 2
VEHICLE EMISSION STANDARDS AND GASOLINE
SULFUR CONTROL REQUIREMENTS**

by

Melvin N. Ingalls

FINAL REPORT

Prepared for

**National Alternative Fuels Association
10800 East Bethany Drive, Suite 200
Aurora, CO 80014**

June 5, 2000

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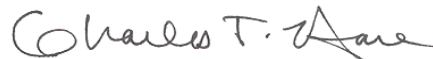
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EXECUTIVE SUMMARY

The EPA, in their February 10, 2000 Final Rule for Tier 2 vehicle emissions required a nationwide limit on the sulfur content of gasoline to 30 parts per million (ppm). During the rule making process, various organizations proposed regional and seasonal sulfur limits. The EPA rejected these proposals. The EPA questioned whether, the emissions of a vehicle operated on low sulfur fuel, then later operated on high sulfur fuel (for instance going to another region of the country), would be the same when the vehicle returned to operation on low sulfur fuel. The ability of the emissions to return their original levels is termed reversibility. If a vehicle's emissions return to their original values when low sulfur fuel is again used, after a period of using high sulfur fuel, the emissions are said to be 100% reversible.

The EPA based their rejection of regional and seasonal fuel sulfur limits on their analysis of a series of emission studies. The conclusion of their analysis was that Tier 1 vehicle emissions were reversible, but that Tier 2 vehicle emissions were not reversible. The report of the EPA analysis was contained in Appendix B of the EPA Regulatory Impact Analysis. In the present report, it is generally referred to as "Appendix B."

The purpose of the work presented herein was to review Appendix B to understand the EPA's methodology and conclusions, to determine the validity of their analysis, to identify areas where additional analysis might prove useful in understanding emissions reversibility, and to perform additional analysis.

After studying Appendix B, it was concluded that methodology used by EPA was faulty, and that the data used did not support the conclusion that emissions from Tier 2 vehicles were irreversible. Specific issues include:

- ! Emissions data from only four vehicles were used to define the Tier 2 reversibility. This is an extremely small number of vehicles to represent the entire U.S. passenger vehicle fleet. The four vehicles were an SUV, a pickup and two minivans. Again, not representative of the model distribution in the passenger vehicle fleet.
- ! The SUV emissions were weighted to represent 2/3 of the final estimate of Tier 2 emissions reversibility. Two of the tested vehicles showed full reversibility, yet they were not given proportional weight to the SUV.
- ! The SUV was a Ford Expedition modified by EPA to meet Tier 2 regulations prior to testing at the EPA lab in Ann Arbor, Michigan. It was not a production vehicle, and manufacturer's requirements for driveability and durability had not been assessed.
- ! Analysis done for the present study shows that non-methane hydrocarbon (NMHC) emissions from large engines, such as used in the SUV, tend to be less reversible than emissions from the small engines used in sedans.

Sedans make up over 50 percent of the in-use fleet, but were not included in the test data for Tier 2 vehicles.

- ! Combining NMHC emissions and oxides of nitrogen (NO_x) emissions, as was done in Appendix B, masked the fact that NO_x emissions show essentially complete reversibility for Tier 2 vehicles.

Therefore, it must be concluded that the data, discussion, and analysis in Appendix B do not substantiate the assertion that emissions from Tier 2 vehicles are highly irreversible. The additional analysis conducted for this report indicates that Tier 2 vehicle NMHC emissions may, in fact, be more reversible than Tier 1 vehicle emissions, and that NO_x emissions are essentially completely reversible for both Tier 1 and Tier 2 vehicles.

Additional understanding of emission reversibility from various levels of sulfur exposure could be obtained by an additional investigation of the underlying data from the studies referenced in Appendix B. However, due to the limited number of vehicles, and the lack of catalyst temperature data, it is not expected that this analysis will provide a definitive understanding of emission reversibility.

Therefore, it is recommended that additional testing be conducted on a representative sample of passenger vehicles, from small roadsters to large SUV's. This testing should include, in addition to the usual emissions measurements, a continuous measurement of engine exhaust and catalyst temperature during all driving. It should also include continuous measurement of sulfur compounds before and after the catalyst. This testing should provide the data necessary to reach a definitive conclusion regarding emissions reversibility, which has not been achieved by the analysis in Appendix B.

I. INTRODUCTION

A. Background

Sulfur compounds in the exhaust (which come mainly from the sulfur in gasoline) affect the catalytic converter in two ways:

- 1) Sulfur reduces the effectiveness of the converter in converting hydrocarbons(unburned fuel) and CO into CO₂, and it inhibits the reaction of CO and NO that produces N₂ and CO₂. This is a well documented effect.
 - a) The magnitude of the reduced efficiency, varies from vehicle to vehicle.
 - b) The reduction in efficiency may or may not become more pronounced with catalyst age (vehicle miles).
- 2) Under certain conditions the catalytic converter can store sulfur. The stored sulfur also reduces the catalyst efficiency. Sulfur storage and release in an automotive catalytic converter system is a function of the catalyst temperature, with more storage occurring at lower temperature. If the catalyst temperature is above a certain value, the sulfur will pass through the catalyst without being stored, indeed, at this temperature, any sulfur that was stored will be released. The air-fuel ratio in the exhaust also affects the release of stored sulfur, with more sulfur being released at air-fuel ratios richer than stoichiometric.
 - a) How much in-use vehicles store sulfur, thus reducing the catalyst efficiency, depends on many factors, and has not been adequately determined.
 - b) The ability to store sulfur may or may not become more pronounced with catalyst age (vehicle miles).

On February 10, 2000, the EPA issued their Final Rule for Tier 2 vehicle emissions and sulfur level in gasoline, reducing the legal amount of sulfur allowed in gasoline to 30 ppm. Appendix B of the EPA Regulatory Impact Analysis presented the rationale for the sulfur regulation.

In Appendix B, four issues were addressed:

- 1) Sulfur sensitivity--the tendency for emissions to increase as sulfur levels in the gasoline increase.

- 2) Sulfur reversibility--the ability of emissions from a vehicle operating on low sulfur fuel to return to the same level after the vehicle was operated on higher sulfur fuel for a time period, then operated again on the low sulfur fuel.
- 3) Reversibility as a function of the length of time vehicle is exposed to high sulfur fuel.
- 4) Sulfur sensitivity and reversibility as a function of vehicle mileage.

B. Objective

The objective of this study was to understand the EPA analysis of sulfur reversibility studies as presented in Appendix B of the EPA Regulatory Impact Analysis (RIA) Report. Because of project effort limitations. This study investigated only sulfur reversibility (Item 2), above).

C. Approach

The approach used in this study was to carefully read and understand the conclusions and analytical methodology presented in Appendix B of the RIA Report. Then, it was to identify any areas where additional analysis might provide increased understanding of sulfur reversibility. Lastly, to the extent that the project effort allowed, it was to perform any additional analysis identified.

This study was not intended to be an in-depth analysis of all of Appendix B, but rather an effort to understand the analysis of the emissions reversibility presented; then determine if additional statistical analysis would provide additional understanding of the reversibility phenomenon.

D. Definition of Terms

One of the two main points that Appendix B addresses is whether or not temporary exposure to high sulfur fuel permanently affects the vehicle emissions. That is, if a vehicle is operating on a low sulfur fuel (for example 30 ppm sulfur) and then is switched to a higher sulfur fuel (for example 300 ppm sulfur) for a period of time, will the vehicle emissions return to the initial level when it is once again operated on low sulfur fuel? To the extent that the emissions return to the initial level, the emissions are said to be reversible.

SAE paper 1999-01-1540 presents the results of a study by the Coordinating Research Council (CRC) to investigate the emissions reversibility of six vehicles. In that paper, the emission test results are used to calculate a reversibility ratio, expressed as percent, and defined as:

$$\text{Ratio (\%)} = [(\text{emissions with high sulfur} - \text{final emissions with low sulfur}) / (\text{emissions with high sulfur} - \text{initial emissions with low sulfur})] \times 100.$$

As can be seen from the formula above, this ratio is zero if the final emissions with low sulfur fuel are equal the high sulfur emissions, i.e. the emissions are not reversible at all. If the initial and final emissions with low sulfur fuel are equal, then the emissions are 100 percent reversible. Note that reversibility can be greater than 100 percent if the final emissions with low sulfur fuel are lower than the initial emissions. The SAE paper showed several vehicles where the reversibility ratios were greater than 100 percent.

Appendix B uses the term "irreversibility," also expressed in percent, but does not define how it was calculated. From comparisons of the data in Table 4 of SAE Paper 1999-01-1540, and the data in Table B-6 of Appendix B, it appears that:

$$\text{Irreversibility} = 100 - \text{Reversibility Ratio.}$$

For example, for a Ford Taurus in Table 4 of the SAE paper, the reversibility ratio for NMHC using the LA4 as a preconditioning cycle is 69. The irreversibility in Table B-6 of Appendix B for the same vehicle and conditions is 31 (which is 100 - 69). The assumption in this report is that throughout Appendix B, the definition of irreversibility is as given above.

II. APPENDIX B ANALYSIS OF SULFUR REVERSIBILITY

The test results from eight studies of sulfur reversibility were used in the analysis presented in Appendix B. These studies consisted of chassis dynamometer emission tests (FTP tests) with various preconditioning cycles, using gasoline with sulfur at a high level (usually above 300 ppm) and a low level (usually about 30 ppm). This report section summarizes the conclusions in Appendix B, and presents the methodology used to arrive at those conclusions as they are understood. A detailed discussion of the steps involved in arriving at the conclusions is presented in Section III of this report.

A. Conclusions from Appendix B

Appendix B divided the sulfur reversibility studies into two groups: (1) Pre-SFTP vehicles and (2) SFTP compliant vehicles. This division was made because the US06 cycle of the SFTP procedure requires vehicles to operate at less rich A/F ratios during hard accelerations than was the case before the SFTP procedure. This leaner operation affects the sulfur storage on the vehicle catalyst.

1. **Pre-SFTP Vehicles**

From Appendix B, page B-29: "For pre-SFTP vehicles (Tier 0, Tier1, and NLEV), as described above....we project that NMHC emissions are almost fully reversible at four percent irreversibility, while NO_x emissions are 12 percent irreversible." From page B-31: "...we project that Tier 0 and Tier 1 vehicles are fully reversible." This quote is not a typographic error, "NLEV" was left out of this statement. Apparently four percent and 12 percent are considered as "fully reversible."

2. **SFTP Compliant Vehicles**

Quoting from page B-31 "Therefore, for [SFTP-compliant] Tier 2 vehicles we project that irreversibility of NMHC+NO_x emissions will fall somewhere between the low level of 20 percent, based on four vehicles, and 65 percent based on the Expedition. For emission modeling and cost effectiveness analyses, we decided to use a midpoint estimate of 42.5 percent for Tier 2 vehicles."

Also from page B-31 "As for SFTP compliant LEV vehicles, we decided to use a straight average of the four vehicles weighting the irreversibility after FTP driving by 25 percent and that after the REP05 driving by 75 percent, similar to what we did for Tier 2 vehicles. This resulted in an average NMHC + NO_x irreversibility of 15 percent."

3. **Summary**

Table 1 summarizes the amount of emissions irreversibility estimated in Appendix B of the RIA report.

TABLE 1. SUMMARY OF EMISSIONS IRREVERSIBILITY

Emission Regulation Level	NMHC + NOx Irreversibility
Tier 1	0%
SFTP-compliant LEV	15%
SFTP- compliant Tier 2	42.5%

B. Appendix B Data Analysis

The data analysis contained in Appendix B was studied to determine the methodology used to arrive at the above conclusions. As it is understood from the explanations in Appendix B, the sections below summarize the methodology.

1. Pre-SFTP Vehicles

There were five studies in this category discussed in Appendix B. There were a total of 18 "vehicles" (17 different vehicles, but one vehicle was tested with both a low mileage and a high mileage catalyst). Four of the five studies had data from high mileage catalysts, with a total of 12 vehicles having high mileage catalysts. There were two studies that used low mileage catalysts (one study, the API study, had both low and high mileage vehicles) with a total of eight vehicles. Only the vehicles with high mileage catalysts were utilized in the analysis in Appendix B.

a. High Mileage Catalyst Data Set for Pre-SFTP Vehicles

In Appendix B, the data from the different studies were presented in individual tables and discussed by individual study, before the average data were presented and used to determine the irreversibility for the pre-SFTP vehicles. For this report, the individual vehicle data from each study were collected in one table for the convenience of the reader. Table 2 shows these data.

b. Appendix B Calculations

The data table used for the Appendix B calculations of average sulfur irreversibility was presented Table B-18 in that Appendix. For reference, the table is repeated below as Table 3. It should be noted that the Fleet Estimate in Table 3 is not an average of the four numbers above it, nor is it an average weighted by the number of vehicles in each study.

Page B-14 of Appendix B explains the calculation of the "Fleet Estimate" as follows: "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

TABLE 2. INDIVIDUAL VEHICLE SULFUR IRREVERSIBILITY FOR PRE-SFTP VEHICLES AS LISTED IN APPENDIX B, TABLES B-5, B-6, B-7, B-10, B-13, B-14

Vehicle model	Study Source	Model year	Engine disp. Liters	NMHC		NOx	
				Purge Cycle		Purge Cycle	
				LA4	US06	LA4	US06
Ford Taurus	CRC	1997 (LEV)	3.0	31.0	17.0	30.0	5.0
Ford Escort	CRC	1997 (LEV)	2.0	0.0	0.0	5.0	0.0
Honda Civic	CRC	1997 (LEV)	1.6	6.0	1.0	4.0	3.0
Nissan Sentra	CRC	1997 (LEV)	1.6	1.0	0.0	15.0	12.0
Toyota Camry	CRC	1997 (LEV)	2.2	0.0	2.0	50.0	0.0
Suzuki Metro	CRC	1997 (LEV)	1.3	0.0	0.0	14.0	13.0
Ford Taurus	API	1998 (LEV)	3.0	0.0	0.0	11.3	14.6
Nissan Altima	API	1998 (LEV)	2.4	15.1	0.0	21.1	10.8
Chevrolet Cavalier	EPA	1999 (LEV)	not given	67.0	n/a	42.0	n/a
Honda Accord	EPA	1999 (ULEV)	not given	0.0	n/a	26.0	n/a
Ford Taurus	ATL	1999 (LEV)	3.0	30.0	n/a	34.0	n/a
Ford Windstar	ATL	1999 (LEV)	not given	26.0	n/a	29.0	n/a

TABLE 3. PRE-SFTP SULFUR IRREVERSIBILITY: SUMMARY OF RELEVANT TEST PROGRAMS(%)

Study	NMHC		NOx	
	Purge Cycle		Purge Cycle	
	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 vehicles)	0.0	14.0	0.0	12.0
Fleet Estimate	14.0	0.0	20.0	5.0

results for all vehicles and determining reversibility as discussed above." The "as discussed above" describes the calculation of the CRC Reversibility Ratio. Presumably this method for calculation of fleet average was used for all studies in Appendix B.

To determine the sulfur reversibility for pre-SFTP vehicles, the data from Table 3 were utilized as follows (quoting from page B-29 of Appendix B): "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 the test results, we project that NMHC emissions are almost fully reversible at four percent, while NO_x emissions are 12 percent irreversible."

2. SFTP Compliant Vehicles

There were no production SFTP compliant vehicles available at the time the Appendix B study was performed. Therefore, the EPA chose studies that used either prototype vehicles, or vehicles that were modified by contractors or by the EPA to meet SFTP regulations. These studies were either solicited from manufacturers or contracted by the EPA. These four vehicles were used to calculate irreversibility for both SFTP compliant LEVs, and the irreversibility for Tier 2 vehicles (Tier 2 includes the SFTP).

a. Data set

Four vehicles from three studies were used to represent the SFTP compliant vehicles (both Tier 2 and SFTP compliant LEVs separately) . These vehicles are described in Table 4, which is a composite of Appendix B tables B-15, B-16, B-17, and B-19.

TABLE 4. IRREVERSIBILITY FOR SFTP COMPLIANT VEHICLES

Study	Vehicle Model	Vehicle Mod, yr.	Emission Category	Emissions Irreversibility					
				NMHC LA4	NMHC REP05	NOx LA4	NOx REP05	NMHC + NOx LA4	NMHC + NOx REP05
DC	Caravan	"Prototype"	"Tier 2 like"	18	39	29	5	27	11
EPA	Expedition	Modified 1999	"Tier 2"	78	91	21	0	65	70
ATL	Windstar	Modified 1999	CARB LEV	0	0	35	0	31	0.0
ATL	F-150	Modified 1999	CARB LEV	60	25	13	7	18.0	9.0
Unweighted Average								29.4	10.9
Average w/lower weights for Caravan and Windstar								29.4	16.6

b. Appendix B Methodology

The explanation of the calculations for average irreversibility of SFTP compliant Tier 2 vehicles was described over several pages in Appendix B. The following steps summarize the calculations as they are understood from studying the description of the calculations.

- 1) Added NMHC and NO_x emission increases together and calculated irreversibility ratios.
- 2) Reduced ratio contribution of Windstar by 75 percent to ¼ car.
- 3) Reduced ratio contribution of Caravan by 50 percent to ½ car.
- 4) Averaged LA4 irreversibility ratio and REP05 irreversibility ratio separately.
- 5) Weighted average LA4 irreversibility ratio by 25 percent and average REP05 irreversibility ratio by 75 percent and added together to get total data set average.
- 6) Averaged LA4 irreversibility ratio from Expedition with the total data set average irreversibility from (5).

Using this method weights the Expedition data at 66.7 percent of total data. In other words, 2/3 of the estimated emissions increase is based on the increase from Expedition.

For SFTP compliant LEV vehicles, the analysis was the same as given above except for three steps: the Windstar and Caravan contributions were not reduced (Steps 2 and 3 above), and the FTP increase from Expedition was not averaged in with the total data set average (Step 6 above).

III. EXAMINATION OF APPENDIX B DATA ANALYSIS

The data analysis presented in Appendix B, and summarized in Section II of this report, was examined to determine the reasoning behind the calculation procedures. This examination is presented for the pre-SFTP vehicles and the SFTP compliant vehicles separately, below.

A. PRE-SFTP VEHICLES

There were five studies of pre-SFTP vehicles discussed in Appendix B. For all of the studies, at least some vehicles were equipped with catalytic converters that had been aged for at least the equivalent of 50,000 miles. One study, by Ford, consisted of two vehicles, that were omitted from the final analysis in Appendix B because it was felt by EPA that Ford had apparently used low mileage catalysts. Thus, the results from only four of the five studies were used in the analysis in Appendix B.

1. Data Set

Where possible, the data set shown in Table 2 above, was checked against the published results of the study. Half of the vehicle results used were from a study conducted by the Coordinating Research Council (CRC). This study was the subject of SAE Paper 1999-01-1544.

While the SAE paper presents the results in terms of a reversibility ratio, the results in Appendix B are in terms of irreversibility, which, as explained in Section I of this report, is apparently 100 minus reversibility. There is one important exception however. Apparently Appendix B does not recognize reversibility greater than 100 percent. For example, the SAE paper lists the Ford Escort reversibility ratio as 137 percent. The irreversibility should then be: $100 - 137 = -37$ percent. However, the value listed in Appendix B, Table B-6, is 0.0 percent. Apparently Appendix B truncates any negative "irreversibility" to the value zero. Presumably, the same treatment was used for all test data from all studies in Appendix B. Thus, any irreversibility value of 0.0 in the Appendix B tables, must be questioned as to whether it is really zero or actually a negative value. Table 5 compares the Reversibility Ratio given in Table 4 of SAE paper 1999-01-1540 with the Irreversibility given in Table B-6 of Appendix B.

2. Appendix B Data Analysis

The difference in the listed sulfur irreversibility in Appendix B Table B-6 and the actual vehicle sulfur reversibility has been discussed above. In addition, the average values, called "Fleet Estimates," are calculated in Appendix B in an unorthodox manner. The calculation method for the Fleet Estimates was explained in Section II above. It is the irreversibility ratio calculated from the fleet average emission results rather the average of the irreversibilities calculated from each individual vehicle. This approach removes vehicle-to-vehicle differences and produces an inaccurate fleet average.

TABLE 5. COMPARISON OF SAE PAPER REVERSIBILITY AND APPENDIX B IRREVERSIBILITY FOR CRC TEST VEHICLES

Vehicle Model	Reversibility Ratio from: SAE Paper 1999-01-1540, Table 4				Irreversibility from: RIA, Appendix B, Table B-6			
	NMHC		NOx		NMHC		NOx	
	Purge Cycle		Purge Cycle		Purge Cycle		Purge Cycle	
	LA4	US06	LA4	US06	LA4	US06	LA4	US06
Ford Taurus	69	83	70	95	31.0	17.0	30.0	5.0
Ford Escort	137	122	100^a	100	0.0	0.0	5.0^a	0.0
Honda Civic	94	99	96	97	6.0	1.0	4.0	3.0
Nissan Sentra	99	111	85	88	1.0	0.0	15.0	12.0
Toyota Camry	112	98	50	114	0.0	2.0	50.0	0.0
Suzuki Metro	170	165	86	87	0.0	0.0	14.0	13.0
Fleet Estimate	101^a	108	84	95	3.0^a	0.0	16.0	5.0
^a Inconsistency.								

The CRC results reported in the SAE paper did not use the method in Appendix B to obtain a "fleet" reversibility. The method used in the CRC paper was a complex statistical calculation which essentially calculated a fleet average based on the vehicle population emissions having a log-normal distribution rather than a normal (Gaussian) distribution. Since in-use fleet emissions at a given mileage are known to be log-normally distributed, the CRC method probably produces a better estimate of the fleet mean, providing the sample tested accurately represents the in-use fleet.

Table B-18 in Appendix B (Table 3 in this report) summarizes sulfur irreversibility from the four studies used. However, the summary values listed for each study in the table, are not the "Fleet Estimate" from each study, but some different number entirely. The text in Appendix B does not explain how the summary values for each study were arrived at. The method for obtaining the Fleet Estimate given in Table B-18 is not described either, but presumably it is calculated using the same method as the other Fleet Estimates.

The description of the utilization of the data in Table B-18 states that the "reversibility for these vehicles [was calculated] by taking the mid-point of the LA4 and US06 values for NMHC and NO_x, respectively." Taking the midpoint of LA4 and US06 values means that the LA4 and US06 values were each weighted 50 percent. No justification for this weighting is given. Later in the Appendix, the SFTP compliant data were weighted 25 percent LA4 and 75 percent REP05. Since the US06 cycle is more like

the REP05 than the LA4, it is difficult to understand why the 50/50 weighting factor was used, rather than some weighting factor closer to the 25/75 that was used for the LA4 and REP05 in the SFTP compliant analysis.

The Appendix then reports that "using the average of these test results, an NMHC irreversibility of four percent, and a NO_x irreversibility of 12 percent was obtained." From an examination of Table 3 above, it is difficult to understand how these "average" irreversibility values were determined. They are apparently not consistently based on the Fleet Estimate. For NMHC, the midpoint of the LA4 Fleet Estimate of 14.0 and the US06 Fleet Estimate of 0.0 is 7.0, not "four". For NO_x, however, 12 percent irreversibility is the midpoint between the LA4 Fleet Estimate of 20.0 and the US06 Fleet Estimate of 5.0.

Also, they do not appear to be based on the weighted average of the individual studies. For both NMHC emissions and NO_x emissions, only two studies have US06 values. Thus LA4 the Fleet Estimate could be based on two studies (eight vehicles) or four studies (12 vehicles), while the US06 Fleet Estimate could only be based on two studies (eight vehicles). The current project had neither the time nor allotted effort to calculate these different possibilities. In summary, it must be concluded that the irreversibility estimates for NMHC and NO_x, given on page B-29 of Appendix B, are based on a series of calculations which have no clear path or statistical foundation from the vehicle test data to the final irreversibility values.

B. SFTP COMPLIANT VEHICLES

As discussed in Section II above, there were no production SFTP compliant vehicles available at the time the sulfur reversibility study in Appendix B was being conducted. This is important because the SFTP regulations caused a change in the engine air-fuel ratio calibration during hard vehicle accelerations.

Prior to the SFTP regulations, engines were controlled to run fuel-rich during hard accelerations to protect the catalytic converter and other engine components from overheating. The rich air-fuel ratio reduced the engine exhaust temperature and the oxidation of hydrocarbons and CO, resulting in lower catalyst temperatures during the hard accelerations. The SFTP regulations effectively prohibited operation at rich air-fuel ratios during hard accelerations. Since a rich air-fuel ratio helps purge stored sulfur, SFTP compliant vehicles might demonstrate a different level of sulfur irreversibility than non-SFTP compliant vehicles. To determine sulfur irreversibility for SFTP compliant vehicles, a total of four production vehicles that had been modified to be SFTP compliant were used.

1. Vehicle Data Set

The data set consists of only four vehicles: two minivans, one full size pickup, and one large SUV. Thus, there are no data from sedans. Since sedans make up approximately 50 percent of the vehicles sold, the lack of sedans in the data set is a serious deficiency. Two thirds of the estimated emissions increase from an episodic exposure to high sulfur fuel was based on one vehicle: the Expedition (a large SUV). As mentioned, this vehicle was not a production vehicle; it was a 1999 production Tier 1

vehicle, modified by EPA to meet the Tier 2 standards (including SFTP standards) by changing the catalysts and the engine air-fuel ratio calibration.

2. Appendix B Data Analysis

The Sulfur Irreversibility summary table for the SFTP-compliant vehicles is presented in Table B-19 of Appendix B, and repeated in Table 4 of this report. The overall value in this table is not called "Fleet Estimate," but rather "Average." It is not, however, the average of the irreversibilities of the four vehicles presented in the table. It may be a "Fleet Estimate" as calculated in the pre-SFTP vehicle section of Appendix B. Since the appendix does not specify how this "average" was obtained, and the individual emission test values necessary to calculate a "Fleet Estimate" are not included in the appendix, it is impossible to determine the source of "average" values. This fact makes the path from the individual vehicle data to the final conclusion difficult to follow.

While the procedures to obtain the final estimate of sulfur irreversibility from the "average" values in Table B-19 are explained in the appendix and outlined in Section II.B.2.b above, the steps are not a statistical analysis, but rather a series of calculations based on some intended use of the data set. It is proper to ask if the reasoning behind these calculations is sound. Each of the data computation steps is examined individually in the paragraphs below.

a. Should NMHC and NO_x Have Been Added?

The NMHC and NO_x sulfur irreversibilities were not added together for the pre-SFTP vehicles. For the SFTP compliant vehicles, the emission test results for NMHC and NO_x were added together, then a single sulfur irreversibility value was calculated for NMHC and NO_x combined. Note also, that this is not the same as adding the sulfur irreversibilities of NMHC and NO_x together, so that the NMHC + NO_x irreversibility cannot be calculated from the separate NMHC and NO_x irreversibilities in Table 4.

The reason given in Appendix B for combining the two emission species is: "...trade-offs between NMOG and NO_x 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 the most appropriate way to analyze irreversibility is to evaluate NMHC and NO_x together (i.e., NMHC + NO_x) rather than separately." It is true that the SFTP standards that are part of the Tier 2 regulations will result in less rich operation during hard accelerations. However, there is currently no data to show that this change will affect operation at lower accelerations such as are encountered on the LA4 driving cycle, or that the change will affect removal of stored sulfur during hard accelerations.

A more compelling reason might be that the SFTP standards for the US06 cycle are expressed in terms of NMHC + NO_x. Appendix B states, however, that the results of the analysis were used for emission modeling (i.e. with the MOBILE emission factor program) and cost effectiveness analysis. The MOBILE emission factor program

uses NMHC and NO_x emissions separately, so that would be a reason for keeping the emissions separate, or at least examining them both separately and combined. Using a combined sulfur irreversibility will mask differences in the individual emission sulfur reversibility, so at the very least, separate NMHC and NO_x sulfur reversibility should also be checked.

b. For Tier 2 Vehicles, Should the Influence of The Two Minivans Have Been Reduced?

For the Tier 2 vehicle calculations only, the sulfur irreversibilities from two mini-vans were not weighted equally with the Expedition (a large SUV) and the F-150 (a full size pickup truck). The reason given was that they did not meet Tier 2 FTP NO_x emission standards. In other words, they were not Tier 2 vehicles, only SFTP compliant LEV's. The reductions in weighting were substantial ($\frac{1}{4}$ and $\frac{1}{2}$ a vehicle for the Windstar and Caravan, respectively), and apparently based on the amount by which the NO_x emissions exceeded the Tier 2 NO_x standard of 0.07 g/mile. There are no data, however, to show that sulfur reversibility is a function of NO_x emission differences between LEV's and Tier 2 vehicles. But most importantly, it is not good statistical practice to use weighting factors for weighted averages that are functions of the quantity being averaged.

The Tier 2 NO_x emission standard of 0.07 g/mile is a sales-weighted, corporate average standard. Individual vehicle models can exceed 0.07 g/mile, but must be certified in one of eight "bins." The NO_x standard for Bin 5 is 0.07 grams per mile, while that for Bin 7 is 0.15 grams per mile. The Windstar and Caravan both meet the Bin 7 NO_x standard with headroom. Therefore, assuming that the Windstar and Caravan met the other FTP and SFTP standards for Bin 7, they could be Tier 2 vehicles certified in Bin 7 (providing, of course, that their respective manufacturers had other vehicles in bins with lower NO_x standards such that the sales weighted NO_x was below 0.07 g/mile). Considering all of the above discussion, it must be concluded that reducing the influence of the Windstar and Caravan for the Tier 2 calculations was not an appropriate procedure. It would have been better to leave the Caravan and Windstar out of the Tier 2 analysis.

It should be noted that the weighting of the vehicle irreversibilities was completely arbitrary for the calculation of the irreversibility for SFTP compliant LEV's, also. It was stated that the Expedition was the only vehicle to meet both Tier 2 NO_x and NMOG emission standards. Thus, it was a Tier 2 vehicle. But it was included in the irreversibility average when calculating the average for SFTP compliant LEV vehicles. The F-150 pickup was likewise counted as both a Tier 2 and a LEV vehicle. For the irreversibility calculation for SFTP compliant LEV vehicles, the Expedition and F-150 should have been excluded since they were Tier 2 vehicles.

c. Should a Weighted Average be Used for the FTP and REP05 Sulfur Reversibilities?

The FTP and REP05 sulfur reversibilities were averaged using a weighting factor of 75 percent for REP05 and 25 percent for FTP. The goal was to provide an in-use sulfur reversibility. It was stated that EPA data show, that vehicles are driven like the REP05 cycle 75 percent of the time, and like the FTP for 25 percent of the time.

Therefore, the 75/25 weighting would appear to provide the best estimate for an in-use sulfur reversibility. However, because of the problems discussed above, the actual value produced by this weighting is not the most reasonable value for in-use sulfur reversibility.

d. For Tier 2 Vehicles, Should the LA4 Increase From the Expedition Vehicle Been Averaged with the Total Vehicle Set Average?

After the weighted average NMHC +NO_x increase, with a value of 20 percent, had been obtained using data from all the vehicles, the LA4 increase from the Expedition was added to the already weighted average, and that sum divided by two. This calculation results in the Expedition accounting for 2/3 of the final Tier 2 irreversibility value.

This is an arbitrary calculation without a scientific or engineering basis to support it. The reason given for the calculation was "... to focus on the irreversibility of the Expedition, since it was the only vehicle meeting the Tier 2 standards with adequate headroom." As pointed out above, it is not good statistical practice to use weighting factors for weighted averages that are functions of the quantity being averaged.

3. Summary

For SFTP compliant vehicles (both Tier 2 and SFTP compliant LEV's), it must also be concluded that the irreversibility estimates for NMHC + NO_x, given on page B-31 of Appendix B, are based on a series of calculations which have no clear path or statistical foundation from the vehicle test data to the final irreversibility values.

IV. ADDITIONAL ANALYSIS

Since the analysis in Appendix B does not have a clear path from the vehicle test data to the conclusions about fleet average irreversibility, additional analysis might supply a better understanding of the sulfur reversibility phenomenon. In this section, the individual vehicle sulfur reversibility is used as the starting point to attempt to arrive at a better understanding of what the vehicle tests demonstrate about reversibility.

A. PRE-SFTP VEHICLES

The Appendix B analysis of the pre-SFTP vehicles presented data from five different studies, and used data from four of the studies to reach its conclusions. There was wide variation in sulfur reversibility for the individual vehicles in these studies. Yet the analysis in Appendix B did not attempt to discover the underlying cause of this large variation in reversibility; it only used arbitrary weighting procedures to obtain a final estimate of sulfur reversibility for pre-SFTP vehicles. It would seem prudent to examine the individual vehicle data to see if it is possible to discover some of the underlying reasons for the large variation.

Table 6 presents the individual vehicle results from all five of the studies presented in the Appendix B analysis of the pre-SFTP vehicles. The data shown are in terms of reversibility ratio, as was used in the CRC study presented SAE paper 1999-01-1544.

Engine exhaust temperature over a given driving cycle is, in general, dependent on the relative power output of the engine. For example, a small engine in a large vehicle would have to use a greater percentage of the maximum power available than a larger engine in the same vehicle. The higher the percentage of maximum power used, the higher the exhaust temperature. One measure of this relative engine power is the power-to-weight ratio, defined as engine power divided by vehicle weight.

Since catalyst temperature is known to affect exhaust sulfur storage, and FTP temperatures were available in the SAE paper describing the CRC study, it was decided to plot catalyst temperature against power-to-weight ratio. Since engine power was not available, engine displacement was used as an indicator of engine power. Vehicle test weight was obtained from EPA certification test results. Both maximum and average catalyst temperatures were plotted versus the displacement-to-weight ratio.

Data from the six vehicles tested in the CRC study indicated that there was a high correlation between catalyst temperatures (both maximum and average) during the FTP and the engine-displacement-to-test weight ratio (see Figure 1). Regression correlation coefficients were greater than 0.92 for both the average and maximum temperature.

TABLE 6. REVERSIBILITY RATIOS FOR ALL PRE-SFTP VEHICLES

Vehicle model	Study Source	Model year	Engine disp. Liters	NMHC		NOx	
				Purge Cycle		Purge Cycle	
				LA4	US06	LA4	US06
Ford Taurus	CRC	1997 (LEV)	3.0	69.0	83.0	70.0	95.0
Ford Escort	CRC	1997 (LEV)	2.0	137.0	122.0	100.0	100.0
Honda Civic	CRC	1997 (LEV)	1.6	94.0	99.0	96.0	97.0
Nissan Sentra	CRC	1997 (LEV)	1.6	99.0	111.0	85.0	88.0
Toyota Camry	CRC	1997 (LEV)	2.2	112.0	98.0	50.0	114.0
Suzuki Metro	CRC	1997 (LEV)	1.3	170.0	165.0	86.0	87.0
Ford Taurus	API	1998 (LEV)	3.0	100.0	100.0	88.7	85.4
Nissan Altima	API	1998 (LEV)	2.4	84.9	100.0	77.9	89.2
Chevrolet Cavalier	EPA	1999 (LEV)	2.4 or 2.2	33.0	n/a	58.0	n/a
Honda Accord	EPA	1999 (ULEV)	2.3	100.0	n/a	74.0	n/a
Ford Taurus	ATL	1999 (LEV)	3.0	70.0	n/a	66.0	n/a
Ford Windstar	ATL	1999 (LEV)	3.0	74.0	n/a	71.0	n/a
Ford Taurus	Ford	1999 (LEV)	3.0	88.0	100.0	93.0	0.0
Ford Explorer	Ford	1999 (LEV)	4.0 or 5.0	9.0	n/a	30.0	n/a

**Catalyst Bed Temperature for FTP Cycles
from SAE Paper 1999-01-1544**

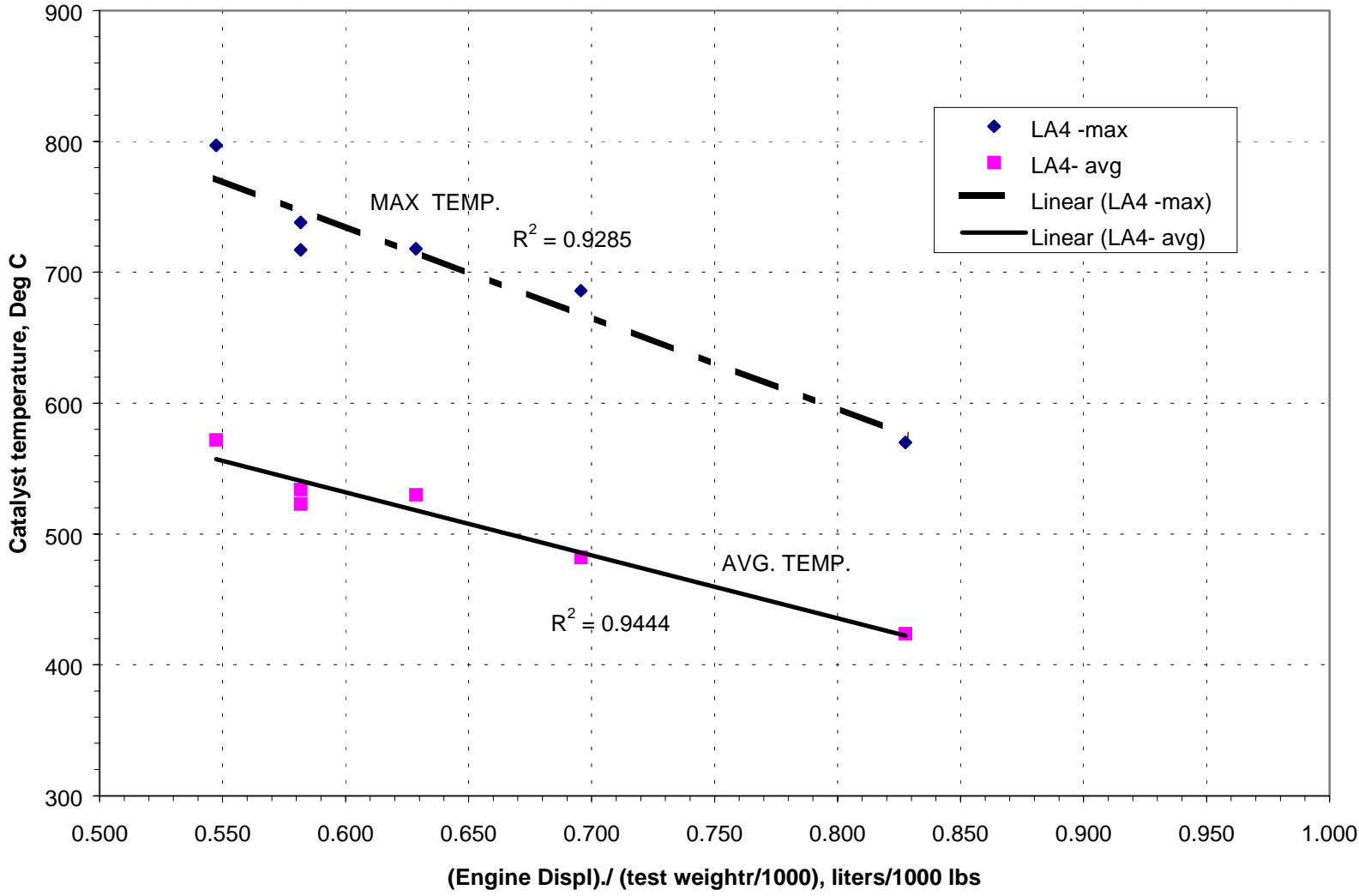


FIGURE 1. CATALYST TEMPERATURE DURING FTP VERSUS ENGINE DISPLACEMENT-TO-VEHICLE WEIGHT RATIO

It was reasoned that perhaps sulfur reversibility was a function of FTP catalyst temperature for those tests that used the UDDS cycle for preconditioning. When the sulfur reversibility ratio from each vehicle's FTP tests with the LA4 preconditioning was plotted as a function of FTP catalyst temperature, the correlation was not as good as might be expected, although there was some trend as shown in Figure 2. There are, of course, a number of other possible parameters that could influence sulfur reversibility. These influences could be determined with additional data from a well planned test program.

A visual inspection of the data in Table 6 seemed to show some correlation with engine displacement. Therefore, as a quick look at what might relate to the sulfur reversibility, individual vehicle NMHC and NO_x sulfur reversibility values for the LA4 preconditioning were plotted versus engine displacement. As many vehicles as possible were used from the five pre-SFTP vehicle studies discussed in Appendix B.

Not all vehicles had the engine displacement listed in Appendix B. The listing of LEV and ULEV vehicles in the California Air Resource Board (CARB) website was used to obtain the engine displacement for those vehicles whose displacement was not given. It should be noted that two different displacements were found for the Chevrolet Cavalier and for the Ford Explorer. LEV Cavaliers were listed with displacements of 2.2 and 2.4 liters, and the LEV Explorers with displacements of 4.0 and 5.0 liters. The larger displacement was used for plots in both cases. The plot of NMHC sulfur reversibility versus engine displacement is shown in Figure 3, and the NO_x sulfur reversibility is plotted in Figure 4.

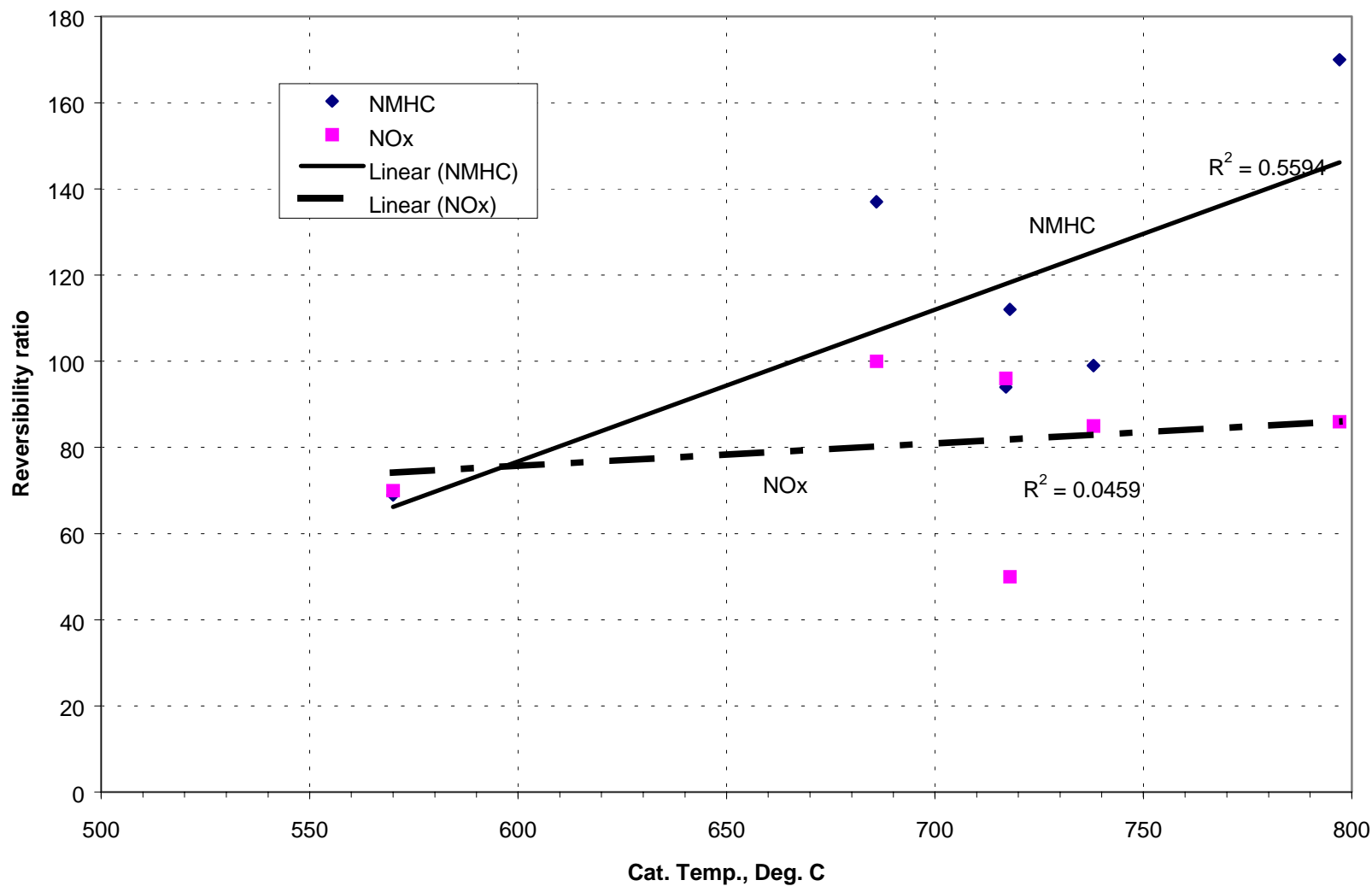
Figure 3 shows a tendency toward a linear relationship for NMHC sulfur reversibility versus engine displacement. The squared correlation coefficient, r^2 , of 0.58 indicates that there is moderate correlation between engine size and sulfur reversibility. While correlation does not guarantee cause-and-effect, there does appear to be some physical process at work here.

Figure 4 indicates some trend of NO_x reversibility with engine displacement, with an r^2 of 0.42. For NO_x, the correlation is highly influenced by the single point at 5 liters. Additional data from vehicles with a large variety of engine displacements would be required to verify this correlation.

Similar plots of emissions reversibility versus engine displacement were done for FTP tests that used the US06 cycle for preconditioning. These plots are shown in Figures 5 and 6 for NMHC and NO_x reversibility, respectively.

For NMHC, the reversibility shows a moderate linear correlation with engine displacement using the US06 for preconditioning, with an r^2 of 0.463. For NO_x however, examination of Figure 6 showed so little correlation that a regression line was not fit to the data. It appears then, that NO_x reversibility with the US06 for preconditioning is not a function of engine displacement. The average reversibility value of all of the individual vehicles in Figure 6 is 95 percent.

**MNHC and NOx Reversibility Vesus Max Catalyst Temperature
for FTP Tests from SAE Paper 1999-01-1544**



**FIGURE 2. NMHC AND NOx REVERSIBILITY FROM TESTS WITH LA4 PRECONDITIONING
VERSUS CATALYST TEMPERATURE FOR CRC VEHICLES**

NMHC Emission Resversibility with LA4 (UDDS) preconditioning

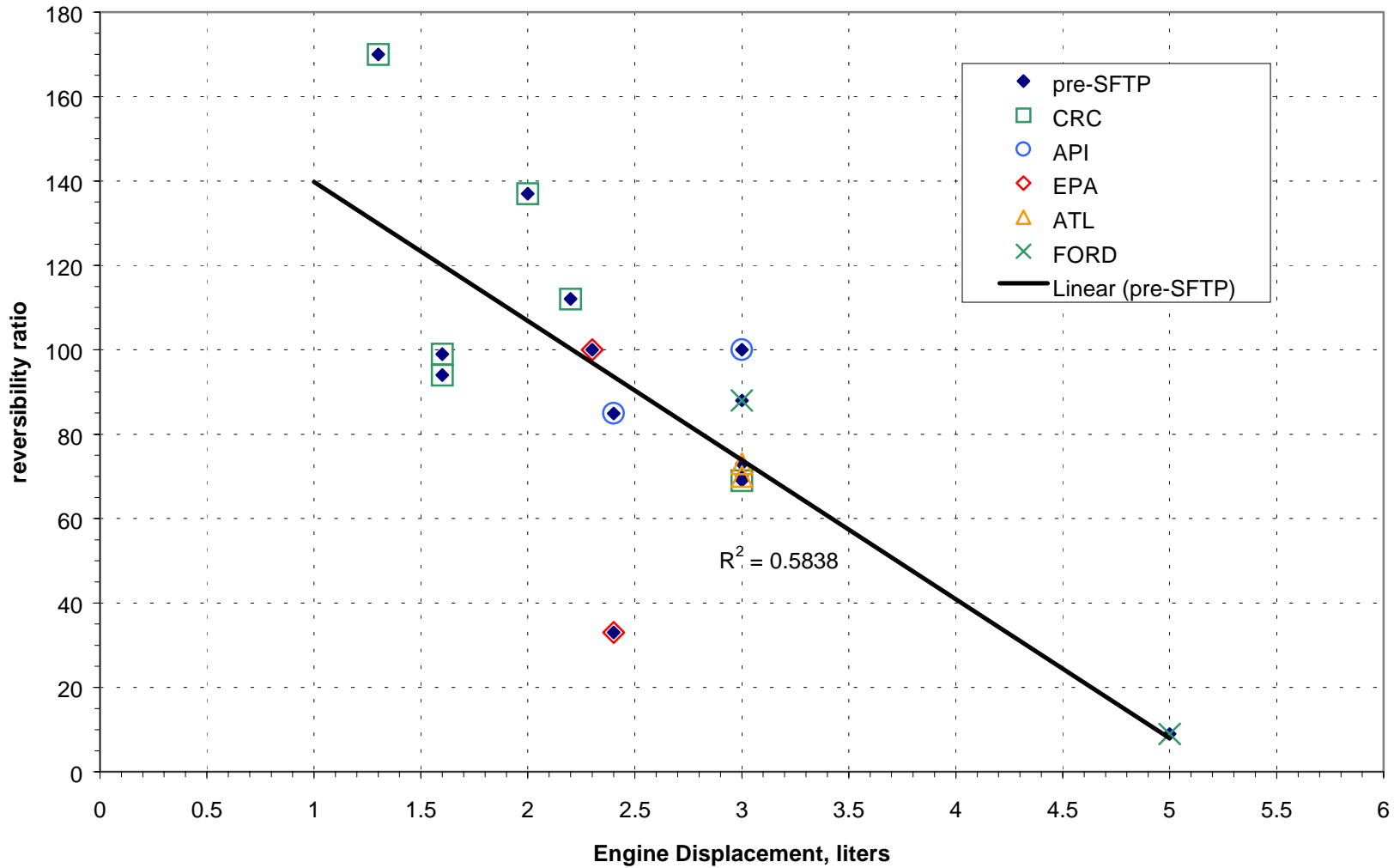


FIGURE 3. NMHC REVERSIBILITY FROM TESTS WITH LA4 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP VEHICLES

NOx Emission Reversibility with LA4 (UDDS) preconditioning

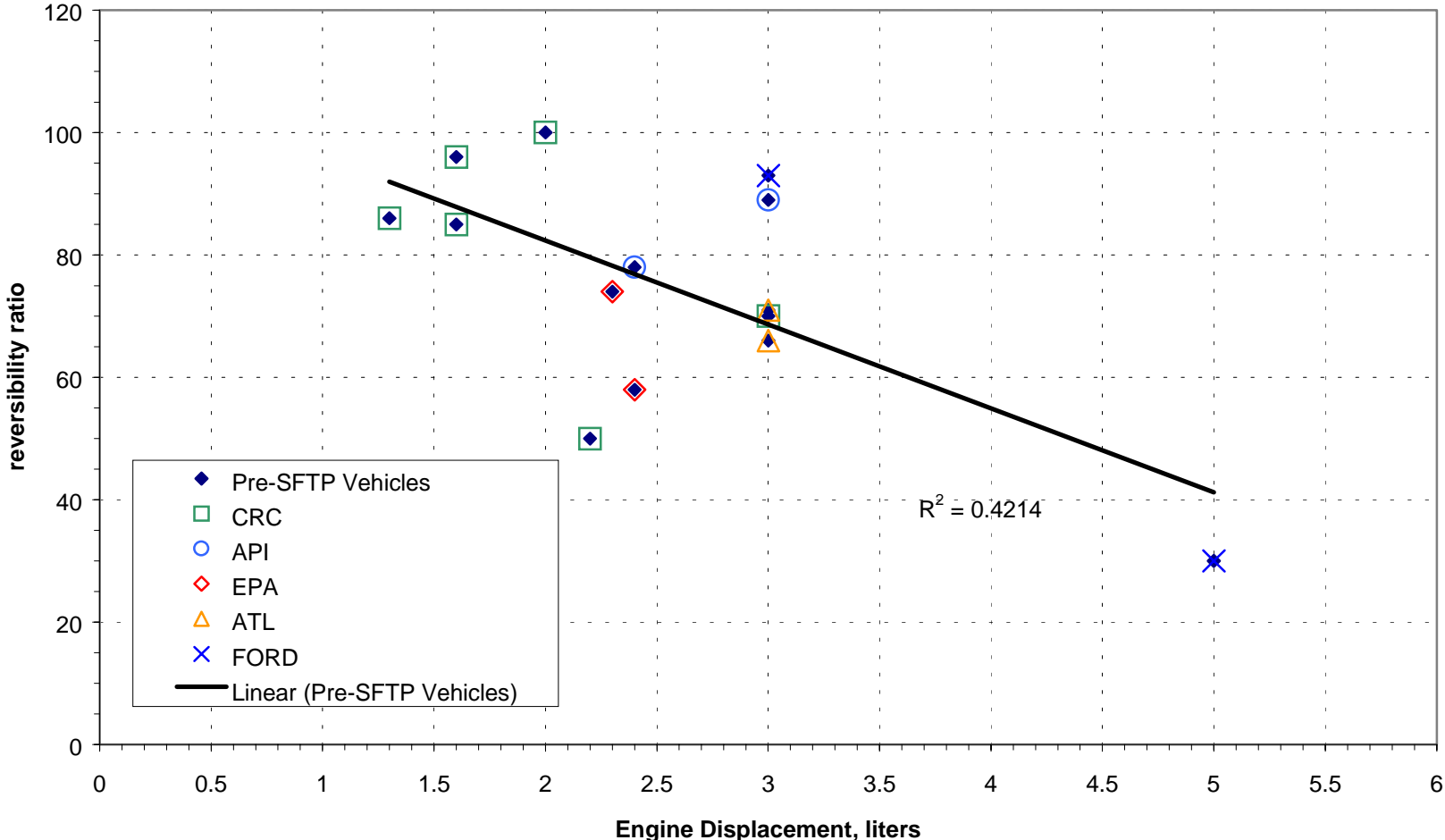


FIGURE 4. NOx REVERSIBILITY FROM TESTS WITH LA4 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP VEHICLES

NMHC Emission Reversibility with US06 Preconditioning

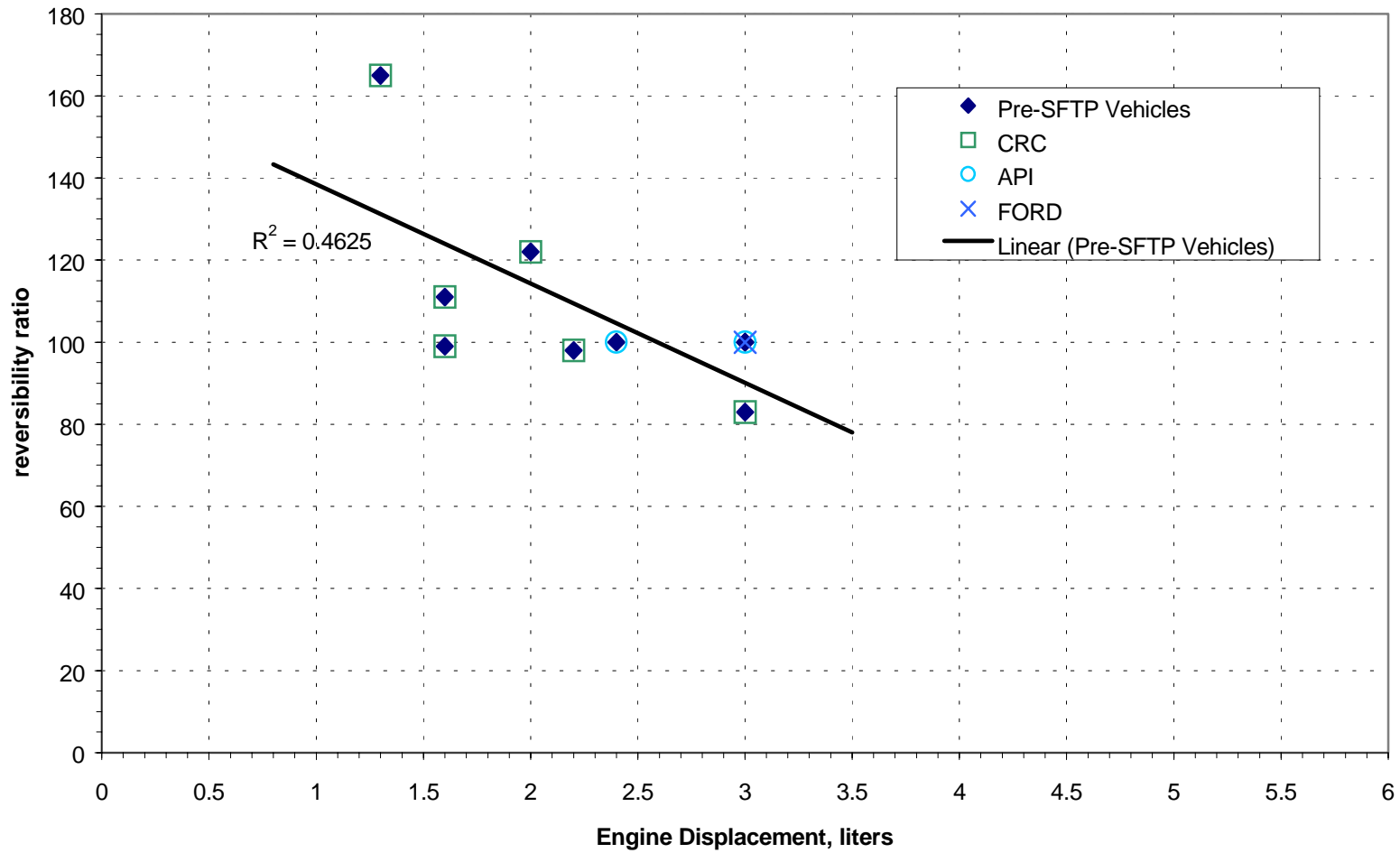


FIGURE 5. NMHC REVERSIBILITY FROM TESTS WITH US06 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP VEHICLES

NOx Emission Reversibility with US06 Preconditioning

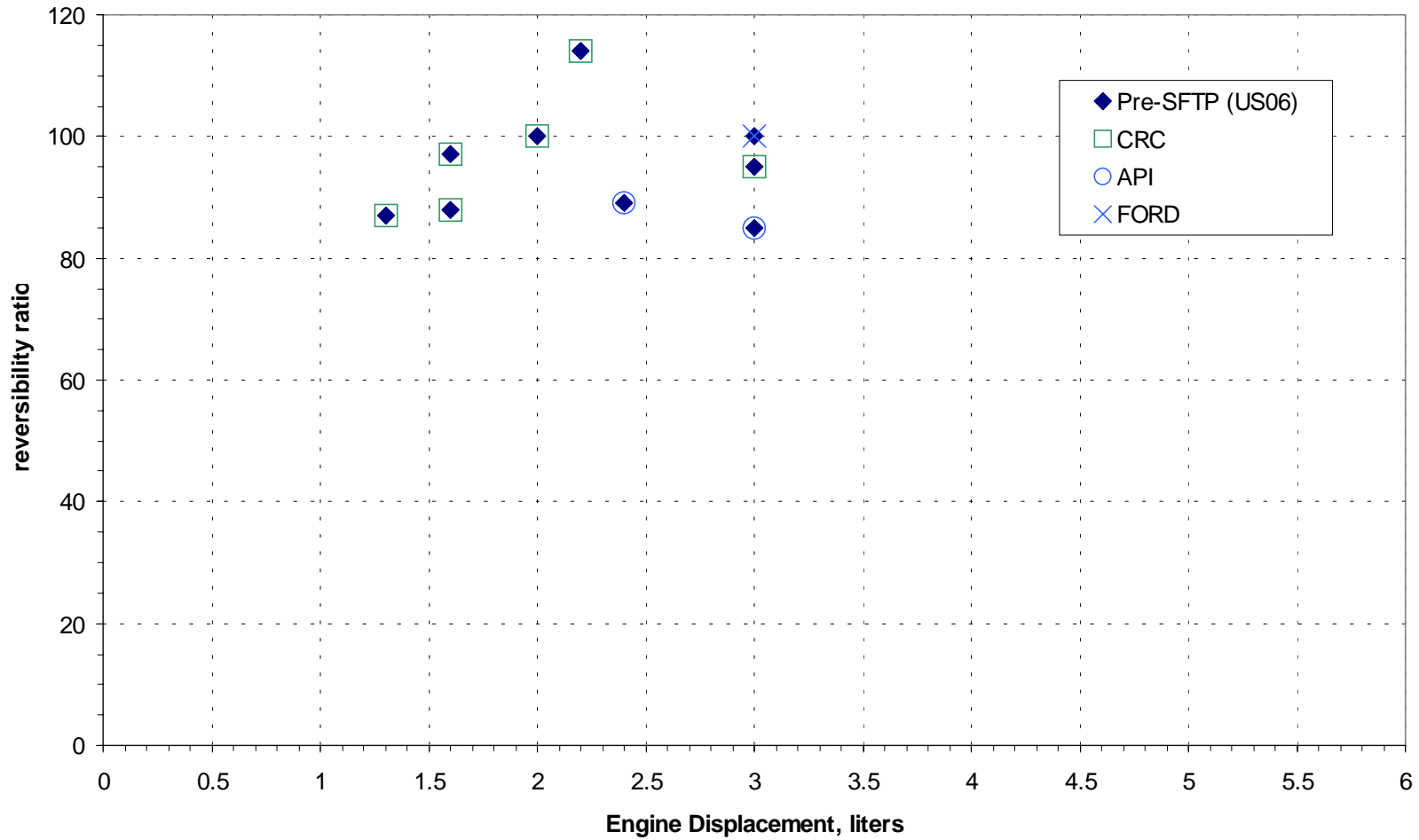


FIGURE 6. NOx REVERSIBILITY FROM TESTS WITH US06 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP VEHICLES

B. SFTP COMPLIANT VEHICLES

The Appendix B analysis of sulfur reversibility for Tier 2 vehicles relies heavily on two large vehicles: a Ford Expedition and a Ford 150 pickup truck, to essentially represent all Tier 2 vehicles. With data from so few vehicles, it would seem wise to combine the data from as many of the studies as possible.

The FTP emissions test, which utilizes the UDDS (LA4) driving cycle, does not have hard accelerations, and thus does not have the rich air-fuel ratio accelerations used in Tier 1 vehicles for hard accelerations. Thus, for tests which used the UDDS (LA4) as a preconditioning cycle, it should not matter whether the vehicle is SFTP-compliant or non-SFTP compliant, since the hard accelerations, which require different air-fuel ratio calibrations for SFTP compliant vehicles, are not included in any part of the test. The SFTP compliant data can therefore be included on the graphs previously developed for the pre-SFTP vehicles.

The SFTP compliant data from Table 4 were converted from irreversibility to reversibility values, then added to the plots of LA4 conditioning. The results are shown in Figure 7 for NMHC reversibility, and Figure 8 for NO_x reversibility.

Figure 7 shows that for NMHC, the SFTP compliant vehicles had an r^2 of 0.984, indicating an excellent linear correlation with engine displacement. The linear regression for the SFTP compliant vehicles appears to be parallel to Pre-SFTP compliant vehicles, but with higher reversibility for the same engine displacement.

Figure 8 shows that for NO_x, the SFTP compliant vehicles had only a weak correlation with engine displacement, resulting in an r^2 of 0.22. In addition, while the other regressions have had negative slopes (reversibility decreases with increasing engine size) the NO_x reversibility for the SFTP compliant vehicles had a positive slope.

The SFTP compliant vehicle reversibilities from tests that used the REP05 cycle for preconditioning were added to the plots of the Pre-SFTP reversibility for tests that used the US06 cycle for preconditioning. The results are shown in Figure 9 for NMHC reversibility, and Figure 10 for NO_x reversibility.

Since the two cycles are different, it was expected that they would produce different relationships between reversibility and engine displacement. For NMHC, the regressions show somewhat different slopes for the two sets of data. The SFTP compliant vehicles, however, have an r^2 of 0.64, again indicating a fairly good correlation between reversibility and engine displacement for the SFTP compliant vehicles. For NO_x, the SFTP compliant vehicles seem to have approximately the same level of NO_x reversibility as the Pre-SFTP vehicles. Since a straight line fit through all the data would be close to horizontal, it is obvious that the reversibility is close to a constant value, and not a function of engine displacement. The vehicle average NO_x reversibility for the SFTP compliant vehicles using the REP05 cycle for preconditioning is 97 percent, which is slight higher than the pre-SFTP average.

NMHC Emission Reversibility with LA4 (UDDS) preconditioning

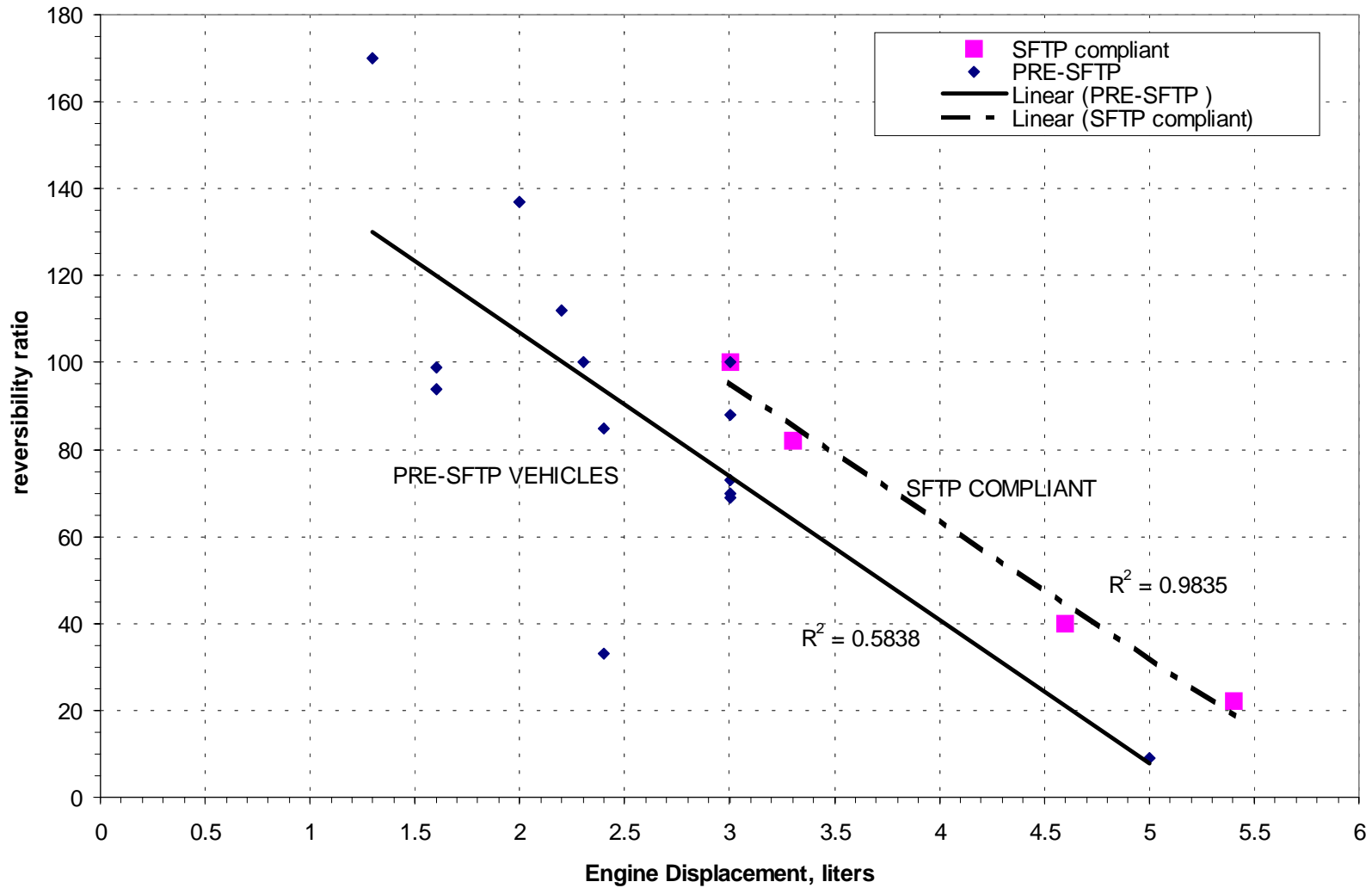


FIGURE 7. NMHC REVERSIBILITY FROM TESTS WITH LA4 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP AND SFTP COMPLIANT VEHICLES

NMHC Reversibility with US06 or REP05 cycle as Preconditioning

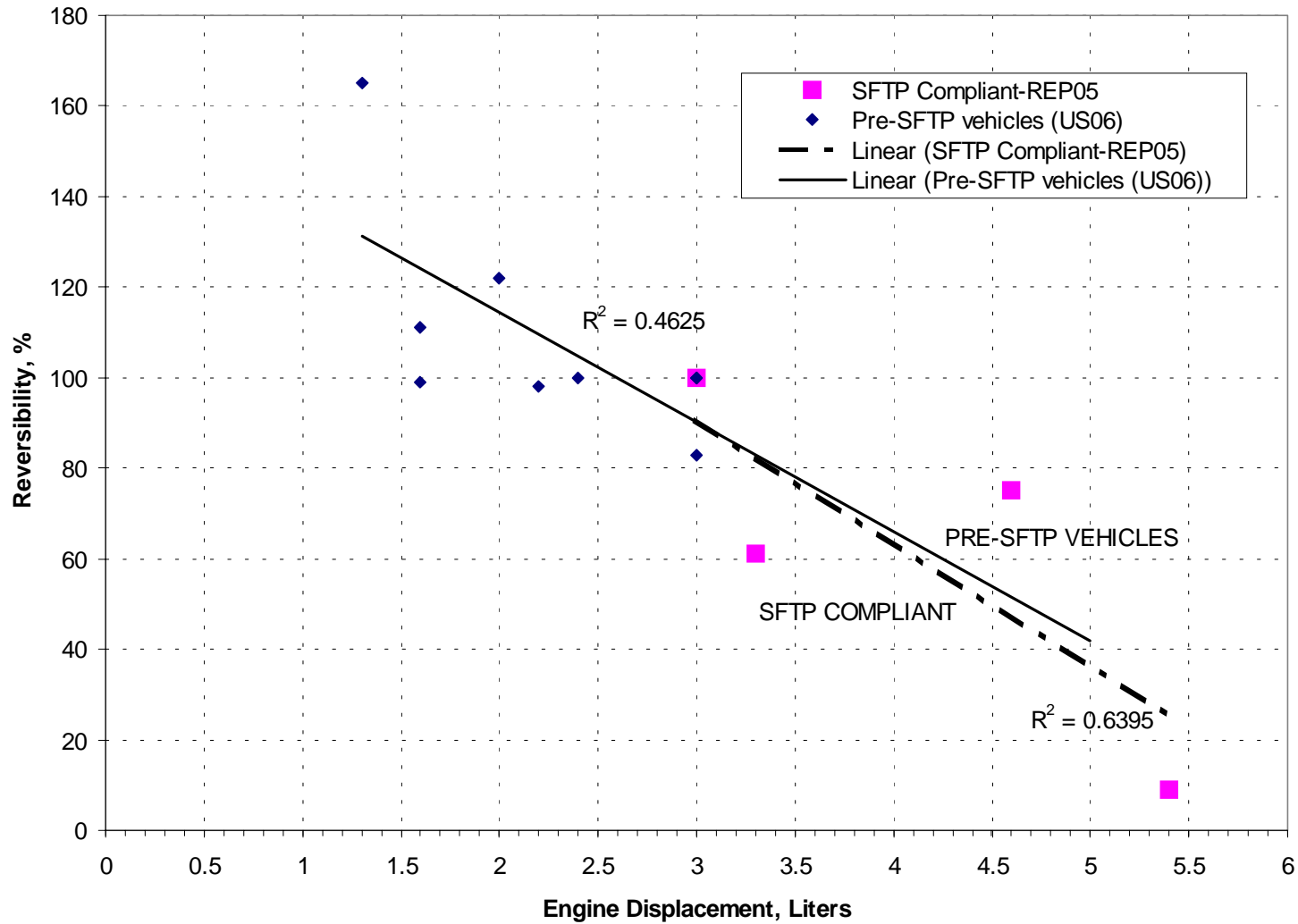


FIGURE 9. NMHC REVERSIBILITY FROM TESTS WITH US06 AND REP05 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP AND SFTP COMPLIANT VEHICLES

NOx Emission Reversibility with US06 or REP05 as Preconditioning Cycle

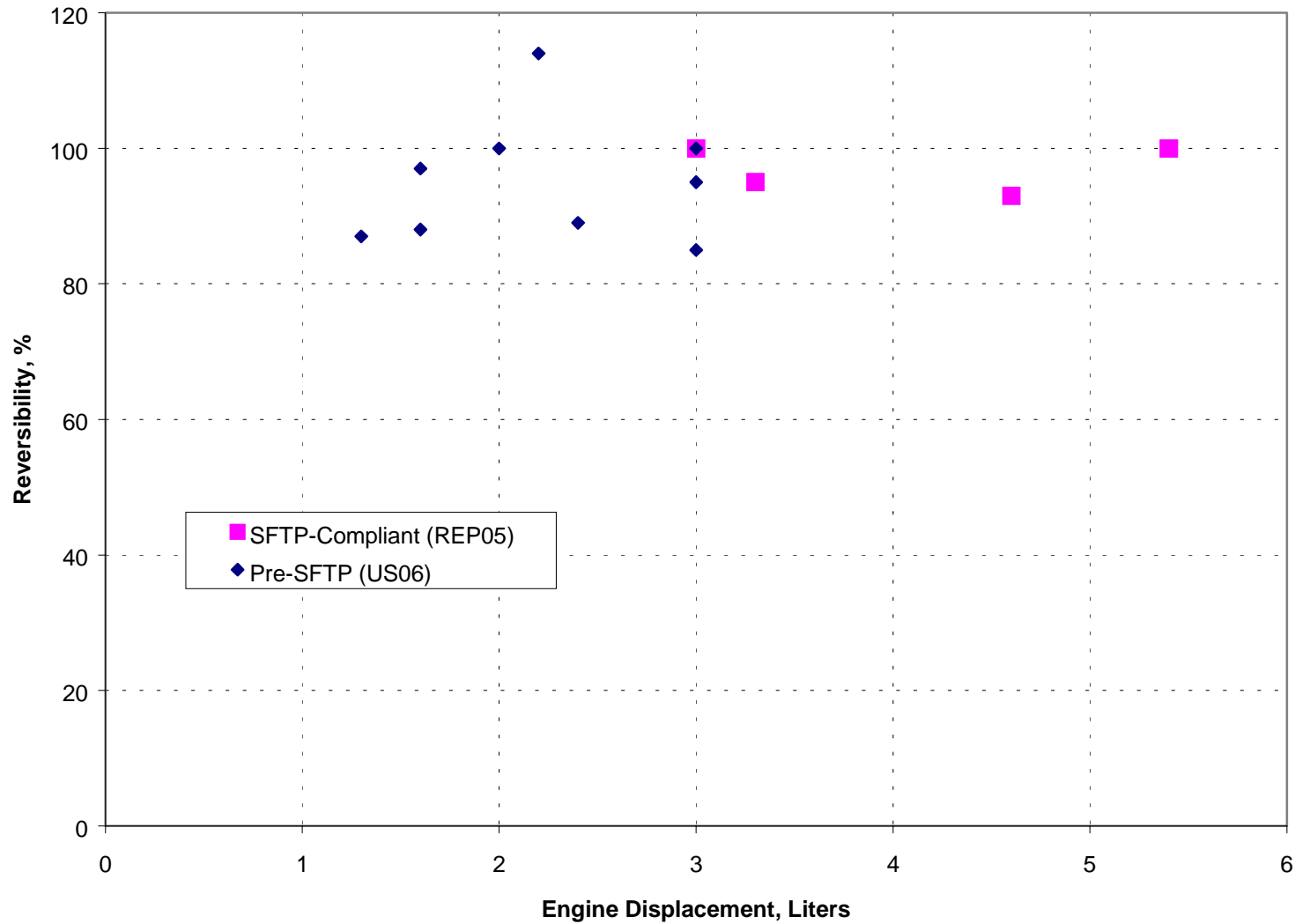


FIGURE 10. NOx REVERSIBILITY FROM TESTS WITH US06 AND REP05 PRECONDITIONING VERSUS ENGINE DISPLACEMENT FOR PRE-SFTP AND SFTP COMPLIANT VEHICLES

V. CONCLUSIONS AND RECOMMENDATIONS

From the brief data analysis in Section IV, the following conclusions in regard to emissions reversibility from sulfur exposure can be drawn.

- ! For NMHC, there is a correlation between reversibility and engine displacement for both Pre-SFTP and SFTP compliant vehicles. This correlation is better for FTP tests that used the LA4 cycle for preconditioning.
- ! For NMHC, for tests using the LA4 for preconditioning, it appears that the SFTP compliant vehicles have higher reversibility than the Pre-SFTP vehicles.
- ! For NO_x, there is a correlation between reversibility and engine displacement for Pre-SFTP vehicles using the LA4 as a preconditioning cycle. The SFTP compliant vehicles showed a much lower correlation with engine displacement using the LA4 as a preconditioning cycle.
- ! Regardless of the emission control level (Pre-SFTP or SFTP compliant), for tests using the US06 or REP05 cycle for preconditioning, the NO_x reversibility appears not to be a function of engine displacement.

Based on the limited analysis in Section IV, it appears that additional statistical analysis is necessary before the emissions reversibility from sulfur exposure for various vehicles and levels of emission control can be confidently determined. It is recommended that a complete statistical analysis be performed on the individual vehicle test results. Such an analysis should include at least the following:

- ! Analysis of variance.
- ! Correlation matrix using as many vehicle, engine and catalyst parameters as possible.
- ! Multiple regression analysis for correlated variables.

Then, using reversibilities obtained from the statistical analysis, fleet averages could be obtained using weighting factors based on vehicle population fractions and driving patterns. Additional statistical analysis will aid in the understanding of the data presented in Appendix B. However, there were only 16 vehicles used in the analysis. Additionally, the manufacturers were not represented in the test fleet in proportion to the in-use population. For example, there was only one GM car, and seven of the 16 vehicles were Ford products. It is recommended that additional vehicles be tested, and that all tests include measurements of catalyst temperature and sulfur compound concentrations before and after the catalysts.