American
Petroleum
Institute

VEHICLE EMISSIONS TESTING OF RAPIDLY AGED CATALYSTS

Health and Environmental Sciences Department
Publication Number 4667
November 1997

American Petroleum Institute

American Petroleum Institute Environmental, Health, and Safety Mission and Guiding Principles

MISSION

The members of the American Petroleum Institute are dedicated to continuous efforts to improve the compatibility of our operations with the environment while economically developing energy resources and supplying high quality products and services to consumers. We recognize our responsibility to work with the public, the government, and others to develop and to use natural resources in an environmentally sound manner while protecting the health and safety of our employees and the public. To meet these responsibilities, API members pledge to manage our businesses according to the following principles using sound science to prioritize risks and to implement cost-effective management practices:

PRINCIPLES

- To recognize and to respond to community concerns about our raw materials, products and operations.
- To operate our plants and facilities, and to handle our raw materials and products in a manner that protects the environment, and the safety and health of our employees and the public.
- To make safety, health and environmental considerations a priority in our planning, and our development of new products and processes.
- To advise promptly, appropriate officials, employees, customers and the public of information on significant industry-related safety, health and environmental hazards, and to recommend protective measures.
- To counsel customers, transporters and others in the safe use, transportation and disposal of our raw materials, products and waste materials.
- To economically develop and produce natural resources and to conserve those resources by using energy efficiently.
- To extend knowledge by conducting or supporting research on the safety, health and environmental effects of our raw materials, products, processes and waste materials.
- To commit to reduce overall emission and waste generation.
- To work with others to resolve problems created by handling and disposal of hazardous substances from our operations.
- To participate with government and others in creating responsible laws, regulations and standards to safeguard the community, workplace and environment.
- To promote these principles and practices by sharing experiences and offering assistance to others who produce, handle, use, transport or dispose of similar raw materials, petroleum products and wastes.

Vehicle Emissions Testing of Rapidly Aged Catalysts

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4667

PREPARED UNDER CONTRACT BY:

JAMES A. RUTHERFORD, CHEVRON RESEARCH AND TECHNOLOGY COMPANY
DAVID H. LAX, AMERICAN PETROLEUM INSTITUTE
CHARLES H. SCHLEYER, MOBIL RESEARCH AND DEVELOPMENT
MARK L. SZTENDEROWICZ, CHEVRON PRODUCTS COMPANY

NOVEMBER 1997

American
Petroleum
Institute

FOREWORD

API PUBLICATIONS NECESSARILY ADDRESS PROBLEMS OF A GENERAL NATURE. WITH RESPECT TO PARTICULAR CIRCUMSTANCES, LOCAL, STATE, AND FEDERAL LAWS AND REGULATIONS SHOULD BE REVIEWED.

API IS NOT UNDERTAKING TO MEET THE DUTIES OF EMPLOYERS, MANUFACTURERS, OR SUPPLIERS TO WARN AND PROPERLY TRAIN AND EQUIP THEIR EMPLOYEES, AND OTHERS EXPOSED, CONCERNING HEALTH AND SAFETY RISKS AND PRECAUTIONS, NOR UNDERTAKING THEIR OBLIGATIONS UNDER LOCAL, STATE, OR FEDERAL LAWS.

NOTHING CONTAINED IN ANY API PUBLICATION IS TO BE CONSTRUED AS GRANTING ANY RIGHT, BY IMPLICATION OR OTHERWISE, FOR THE MANUFACTURE, SALE, OR USE OF ANY METHOD, APPARATUS, OR PRODUCT COVERED BY LETTERS PATENT. NEITHER SHOULD ANYTHING CONTAINED IN THE PUBLICATION BE CONSTRUED AS INSURING ANYONE AGAINST LIABILITY FOR INFRINGEMENT OF LETTERS PATENT.

ACKNOWLEDGMENTS

THE FOLLOWING PEOPLE ARE RECOGNIZED FOR THEIR CONTRIBUTIONS OF TIME AND EXPERTISE DURING THIS STUDY AND IN THE PREPARATION OF THIS REPORT:

API STAFF CONTACT

David Lax, Health and Environmental Sciences Department

MEMBERS OF THE VEHICLE EMISSIONS TASK FORCE

J. Steve Welstand, Chairperson, Chevron Products Company

Bill Bandy, Amoco Research Center

John Eckstrom, Amoco Research Center

King Eng, Texaco, Inc.

Dennis Fiest, Shell Development Company

Ana Rodriguez-Forker, Arco Products Company

Frank S. Gerry, BP America, Inc.

Albert M. Hochhauser, Exxon Research and Engineering Company

George S. Musser, Exxon Research and Engineering Company

Rick Riley, Phillips Petroleum

Charles H. Schleyer, Mobil Research and Development

We would also like to acknowledge the following people for their contributions:

James A. Rutherford, Chevron Research and Technology Company

Mark L. Sztenderowicz, Chevron Products Company

Jeff Jetter, Honda R&D Americas, Inc.

Del Pier, Clean Air Vehicle Technology Center

Gordon Bartley, Southwest Research Institute

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

A test program was conducted to measure the effect of changing fuel sulfur content on the exhaust emissions of a 1993 Honda Civic VX certified to meet California Transitional Low Emission Vehicle (TLEV) standards. The type of exhaust aftertreatment device on this vehicle had been tested in prior programs sponsored by the Coordinating Research Council (CRC)(1)[1] and the Petroleum Environmental Research Forum (PERF)(2). The CRC study had generated debate as to how well the results represented "real world" conditions. The present test program provided an opportunity to address this question and related issues from the previous studies.

Exhaust emissions and catalyst oxygen storage (OSC) measurements were obtained on four catalysts designed for a 1993 Honda Civic VX TLEV. The measurements were made using two test fuels. One was a California emissions certification test fuel with a sulfur content of 35 ppm. This fuel was doped with additional sulfur to create a gasoline with a sulfur content of 600 ppm. The four catalysts included: (a) the original catalyst on the vehicle when purchased new; (b) two stock replacement catalysts which had been artificially aged to 100,000 miles on gasolines with 40 ppm sulfur and 1000 ppm sulfur, respectively; and (c) a "field-aged" catalyst obtained from an "in-use" 1993 Honda Civic VX TLEV with approximately 100,000 odometer miles.

The results of this test program show the following:

- The effects of sulfur on exhaust emissions of a 1993 Honda Civic certified to California TLEV standards were similar to those seen in other vehicle test programs such as those conducted by PERF and the Auto/Oil AQIRP. (1) (3) Emissions were lower on the 35 ppm sulfur fuel than on the gasoline with 600 ppm sulfur. The differences in emissions between fuels were statistically significant for the group of four test catalysts as a whole, but differences between fuels in individual catalysts were often not significant. Averaging over all catalysts, lowering fuel sulfur content from 600 to 35 ppm reduced FTP emissions by 21 to 27% depending on the pollutant.

- Exhaust emissions were lowest for the original catalyst and highest for the field-aged, 100,000 mile in-use catalyst (M9). The differences in emissions between the original catalyst and M9 were statistically significant for all pollutants over the FTP.

[1] Numbers in ( ) denote references listed at the end of the report.

- Fuel sulfur content did not have an effect on the long-term emissions performance of catalysts which had been artificially aged using the RAT-A cycle. Catalysts M7 and M8 were aged for 100 hours on a dynamometer using the RAT-A cycle for 100 hours on 40 and 1000 ppm sulfur fuels, respectively. There was no difference in overall emissions or sulfur effects between these two catalysts.

- Rapid catalyst aging did not have a large effect on sulfur response compared to in-use aging. All catalysts responded directionally the same to sulfur and there was no difference in the magnitude of the sulfur effect among the four catalysts.

- An identical catalyst from a Honda TLEV was tested in the CRC Sulfur/OBD-II laboratory reactor program. A comparison of the data generated from the two programs suggests that laboratory results may (a) overstate sulfur effects as measured from a vehicle and (b) represent hot vehicle performance better than cold operation. Reducing fuel sulfur content from 600 to 40 ppm in the CRC laboratory reactor program lowered the Honda TLEV HC and NO_x emissions by 57% or more than twice the percentage effect seen over the FTP in the present study. However, the sulfur effects on HC that were observed during the warmed-up phases of the FTP (Bags 2 and 3) of the present study were similar to those measured in the CRC lab reactor program under steady-state, warmed-up conditions.

- Gasoline sulfur content did not have a significant effect on catalyst oxygen storage capacity. Differences in OSC between the original and the aged catalysts were much larger than any differences attributable to fuel sulfur content. OSC was roughly twice as high in the original catalyst compared to the three aged catalysts, all of which had similar OSC.

Section 1

INTRODUCTION

Over the past several years, interest in evaluating the effect of fuel sulfur content on motor vehicle emissions has prompted the initiation of a number of test programs which have focused on advanced technology vehicles.

In 1993, for example, the Petroleum Environmental Research Forum (PERF) sponsored a study to evaluate the effect of fuel sulfur content on exhaust emissions from low-mileage production vehicles designed to meet California's Transitional Low Emission Vehicle (TLEV) standards. (1) One of the TLEVs tested as part of that program was a 1993 Honda Civic VX.

An identical catalyst from a 1993 Honda Civic VX TLEV model also was tested as part of a recent study sponsored by the Coordinating Research Council (CRC). (2) The CRC project was designed to measure the effect of fuel sulfur level on the conversion efficiencies and oxygen storage capacities of various rapidly aged automobile emissions control catalysts. The measurements in that program were performed using a steady-state bench reactor because three of the four catalyst formulations that were tested were prototypes for which no suitable vehicle platforms were available at the time for FTP emissions tests. Equivalent fuel sulfur levels were obtained in the CRC program by varying the content of the SO_2 feedgas to the bench reactor. However, this raised the question as to whether the results of steady-state emissions tests performed in a laboratory bench reactor were truly representative of those which would occur under in-use transient conditions as measured by the Federal Test Procedure.

Since identical catalysts were used in the CRC and PERF studies, the 1993 Honda Civic VX TLEV model provided an opportunity for a further program to compare sulfur effects in "real world" conditions on a vehicle which had accumulated a history of emissions testing to those observed in a steady-state bench reactor. It also provided a means to determine if the catalyst aging procedures in the CRC program impacted the sulfur responses differently from vehicle aging of catalysts. This program was performed under contract to the American Petroleum Institute (API) by Chevron Research and Technology Co.

Section 2
TEST VEHICLES, CATALYSTS AND FUELS

TEST VEHICLES

Two vehicles were used in this test program and are described in Table 2-1. The first vehicle was a 1993 Honda Civic VX that was certified as a California Transitional Low Emissions Vehicle (TLEV). It is the same vehicle that was used in Petroleum Environmental Research Forum (PERF) Project 93-12. (1) At the time of the PERF testing, the odometer on this vehicle showed between 4,000 and 5,000 miles. In the current program, accumulated mileage on the 1993 Honda Civic VX was between 10,000 and 11,000 miles.

The 1993 Honda Civic VX was instrumented to permit exhaust samples to be drawn upstream of the catalyst and to measure temperature and oxygen content of exhaust before and after the catalyst. Since the vehicle was not equipped for California on-board diagnostics (OBD II), this included installation of a second exhaust gas oxygen sensor.

Table 2-1: Description of Test Vehicles

Model Year	1993	1996
Model	Honda Civic VX	Honda Civic LX
California Emissions Standard Certification	TLEV	LEV (OBD II)

The second vehicle was a 1996 Honda Civic LX loaned to the project by Honda R&D Americas, Inc. (HRA). This vehicle was an OBD II certified California Low Emissions Vehicle (LEV) and was used as a platform for obtaining catalyst oxygen storage measurements. The same catalysts tested on the 1993 model also were tested in this vehicle. HRA modified the exhaust manifold and catalyst plumbing on the 1996 test vehicle to enable use of a tool for diagnosing catalyst oxygen storage and release times.

TEST CATALYSTS

Four catalysts designed for use on a production 1993 Honda Civic VX model were tested in this program. (See Table 2-2.) The "original" catalyst was the stock catalyst originally installed on the 1993 vehicle and used in the prior PERF study. It was included in the current program primarily to provide a connection to the PERF study and to determine whether normal aging had influenced its tolerance for sulfur. Two new catalysts were provided by HRA. These were stock replacements for the original catalyst. They were aged by Southwest Research Institute using the RAT-A cycle for 100 hours. One catalyst was aged using California Phase 2 Certification gasoline. The other was aged using the same gasoline with sulfur level raised to 1000 ppm. (See Appendix A for a description of the aging procedure used by SwRI.) HRA also provided a catalyst which they had obtained from a customer. This catalyst had been taken from a 1993 Honda Civic VX which had accumulated 107,000 odometer miles in customer service.

Table 2-2: Test Catalysts

Catalyst Code	Catalyst Description
ORIG	OEM Catalyst used in PERF study
M7	Replacement catalyst aged 100 hrs on 40 ppm S on RAT-A cycle
M8	Replacement catalyst aged 100 hrs on 1000 ppm S on RAT-A cycle
M9	100k catalyst aged in field in customer use

TEST FUELS

Two test fuels were used in this program. The base fuel was a California Phase 2 Certification gasoline containing about 35 ppm sulfur. The second test fuel was made by spiking the base fuel with di-*tert*-butyl disulfide (DTBS) to achieve a level of about 600 ppm sulfur. Inspection results are listed in Table 2-3.

Table 2-3: Test Fuel Analyses

Fuel Property	Fuel Code	
	FR12652	**FR24491**
Sulfur, ppm	35	600
API Gravity	60.1	not measured
Aromatic, Vol. % (uncorrected FIA)	25.8	not measured
Olefin, Vol. % (uncorrected FIA)	5.4	not measured
Paraffin, Vol. % (uncorrected FIA)	68.8	not measured
Hydrogen, Mass Fraction (NMR)	.1365	not measured
D86 T_{10}, ° Fahrenheit	139	not measured
D86 T_{50}, ° Fahrenheit	205	not measured
D86 T_{90}, ° Fahrenheit	294	not measured
MTBE, Vol. %	10.8	not measured

Section 3
TEST DESIGN AND PROCEDURES

MEASUREMENTS ON THE 1993 HONDA CIVIC VX (TLEV)

The 1993 Honda Civic VX was driven on a chassis dynamometer according to the Urban Dynamometer Driving Schedule (UDDS) of the Federal Test Procedure for vehicle certification as specified in 40 CFR § 86. Emissions were collected and analyzed using a Constant Volume Sampler (CVS) system and other standard emissions testing equipment. The test procedure included most elements of the FTP, with the following exceptions of note:

1. There were no measurements of evaporative emissions.
2. There were no diurnal heat builds prior to testing.
3. An extended preconditioning procedure was used to minimize fuel carryover effects.
4. "Engine out" emissions were measured on a second-by-second basis while diluted tailpipe emissions were collected simultaneously.

A detailed test protocol is provided in Appendix B.

Engine-out and tailpipe emissions of total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and carbon dioxide (CO_2) were reported for each of the three phases (bags) of the FTP. Tailpipe measurements of methane (CH_4) and non-methane hydrocarbons (NMHC) also were reported for each FTP phase. Mass-mean catalyst efficiencies for HC, CO, and NO_x were computed from the data for each completed test phase. In addition, fuel economy for each test phase was computed from the exhaust emissions measurements and other test data and was reported.

The temperature of the exhaust gas entering and exiting the catalytic converter was measured and recorded at a rate of approximately 10 Hz during the course of each emissions test. The 1993 Honda Civic VX was modified through the addition of thermocouples or other devices for the purpose of making these temperature measurements.

In the standard OEM configuration, the 1993 Honda Civic VX incorporates an exhaust gas oxygen sensor (EGO) upstream of the catalyst. For this program, the vehicle was modified to include a second EGO sensor located downstream of the catalyst. Following each FTP emissions test, the voltage signal outputs of both this sensor and the original equipment EGO sensor were recorded at a frequency of 10 Hz for a period of at least 3 minutes with the vehicle on the dynamometer and operating at a steady-state cruise speed of 35 mph.

Each catalyst/fuel combination was tested twice. The testing order was balanced to minimize the potential for bias in the results. The order of fuel/catalyst pairings for tests conducted on the 1993 Honda Civic VX is shown in Table 3-1.

Table 3-1: Test Sequence for 1993 Honda Civic VX

No.	Catalyst	Fuel Code
1	ORIG	FR12652
2	ORIG	FR24491
3	M7	FR24491
4	M7	FR12652
5	M8	FR12652
6	M8	FR24491
7	M9	FR24491
8	M9	FR12652
9	M9	FR12652
10	M9	FR24491
11	M8	FR24491
12	M8	FR12652
13	M7	FR12652
14	M7	FR24491
15	ORIG	FR24491
16	ORIG	FR12652

MEASUREMENTS ON THE 1996 HONDA CIVIC LX (LEV)

Measurements of oxygen storage capacity (OSC) were performed for each catalyst/fuel combination while each catalyst was installed in turn in the 1996 Honda Civic supplied by HRA. This test vehicle was instrumented by HRA to allow the OSC information generated by the vehicle's on-board diagnostic catalyst monitoring function to be examined and recorded according to instructions supplied by HRA. (See Appendix C.) The preconditioning protocol was the same as that used for the emissions tests described above except that the overnight soak was deleted and no emissions data were collected during the FTP driving cycle.

Following vehicle refueling and preconditioning, triplicate OSC measurements were conducted for each catalyst/fuel combination. The order of testing of each catalyst/fuel combination was balanced and randomized to minimize the potential for bias in the results. The order of fuel/catalyst pairings for tests conducted on the 1996 Honda Civic LX is shown in Table 3-2.

Table 3-2: Test Sequence for 1996 Honda Civic LX

No.	Catalyst	Fuel Code
1	M9	FR24491
2	ORIG	FR12652
3	M8	FR12652
4	M7	FR24491
5	M9	FR12652
6	M7	FR12652
7	M8	FR24491
8	ORIG	FR24491

Section 4
TEST RESULTS

Table 4-1 lists FTP test results from the 1993 Civic. "Sequence" is the order in which the tests were performed. "Test ID" is a unique test identifier. "Catalyst" and "Fuel ID" codes are as described previously in Tables 2-2 and 2-3, respectively.

The bag measurements from the first test with the original catalyst and 600 ppm S fuel (Test ID H9703031) appear to be faulty. This test was reviewed by the laboratory and no operational or recording problems were found. However, a replicate test was performed with this catalyst and fuel combination (Test ID H9704049). Bag measurements from the replicate test appear consistent with the rest of the experiment and the modal measurements from the two tests are very similar.

Table 4-2 lists the modal mass emissions from the same tests discussed above. These are "bag equivalent" numbers from the tailpipe and engine out modal emissions measurements. They include tailpipe equivalents, engine out bag equivalents, and mass-mean catalyst efficiencies.

Figure 4-1 presents an example of the measurements of temperature before and after the catalyst during the first 200 seconds of the first emissions test. An example of the oxygen sensor voltage measurements before and after the catalyst during the 3 minute cruise at 35 mph following the FTP is shown in Figure 4-2. All of the temperature traces throughout each emissions test and the oxygen sensor traces for each cruise following each emissions test are contained in Microsoft® Excel spreadsheets and are available from API[1] upon request. These data have been reviewed and appear generally consistent with anticipated results and from test to test. The only aberration is the after- catalyst temperature on the test with TestID H9703034. This starts the beginning of the test at about 200° centigrade rather than at the ambient temperature after the soak. This test was reviewed and no operational or technical faults were found which might have explained this abnormality.

[1] Available from Information Specialist, HESD, API.

Table 4-3 displays the oxygen storage capacity measurements for each catalyst/fuel combination tested on the 1996 Honda. The table lists the average time in seconds for the vehicle to go through an oxygen storage and release cycle. This average was taken over ten closely controlled cycles. The higher the number of seconds, the greater the oxygen storage capacity of the catalyst. HRA reviewed these data and found them to be generally reasonable. The third measurement with catalyst M8 and fuel FR24491 appeared to be anomalous. However, the laboratory reported that this measurement was accurately recorded.

Table 4-1: 1993 Honda Civic VX Tailpipe Bag Emissions

				FTP Composite (gpm)					Bag 1 (grams)				Bag 2 (grams)				Bag 3 (grams)			
Sequence	Test ID	Fuel ID	Catalyst	THC	CO	NO_x	NMHC	MPG	THC	CO	NO_x	NMHC	THC	CO	NO_x	NMHC	THC	CO	NO_x	NMHC
1	H9703031	FR12652	Original	0.151	1.328	0.401	0.1111	45.222	1.410	7.011	2.575	1.211	0.344	3.688	0.960	0.203	0.287	5.485	1.577	0.166
2	H9703034	FR24491	Original	0.121	1.032	0.298	0.0833	45.517	1.217	5.843	1.784	1.038	0.229	2.276	0.721	0.079	0.250	5.021	1.255	0.157
3	H9703037	FR24491	M7	0.124	1.454	0.391	0.0845	45.596	1.261	7.052	2.708	1.103	0.213	3.655	0.843	0.051	0.275	7.132	1.537	0.168
4	H9703040	FR12652	M7	0.096	1.099	0.342	0.0720	45.299	1.118	6.146	2.303	0.973	0.126	2.063	0.719	0.058	0.174	6.060	1.450	0.094
5	H9703043	FR12652	M8	0.094	1.407	0.334	0.0700	44.522	1.213	9.048	2.208	1.066	0.069	2.291	0.887	0.000	0.184	7.478	1.113	0.098
6	H9704001	FR24491	M8	0.109	1.417	0.427	0.0793	44.947	1.129	6.341	2.898	0.960	0.191	3.797	0.986	0.095	0.230	7.027	1.642	0.136
7	H9704004	FR24491	M9	0.177	1.884	0.566	0.1316	45.481	1.824	9.580	3.696	1.640	0.334	5.823	1.357	0.153	0.329	7.094	2.207	0.198
8	H9704011	FR12652	M9	0.127	1.321	0.366	0.0973	46.525	1.647	7.663	3.038	1.506	0.096	2.586	0.740	0.000	0.238	6.912	1.168	0.122
9	H9704014	FR12652	M9	0.131	1.639	0.408	0.1012	45.141	1.615	8.344	2.902	1.449	0.095	3.107	0.989	0.006	0.311	9.593	1.360	0.202
10	H9704017	FR24491	M9	0.172	1.955	0.570	0.1163	45.552	1.755	10.636	3.562	1.512	0.340	5.948	1.477	0.118	0.314	7.010	2.151	0.158
11	H9704021	FR24491	M8	0.113	1.389	0.502	0.0720	45.278	1.137	6.730	3.425	0.962	0.199	3.819	1.205	0.035	0.254	6.358	1.839	0.144
12	H9704024	FR12652	M8	0.093	1.120	0.333	0.0604	45.130	1.126	6.588	2.197	0.962	0.110	2.819	0.831	0.000	0.162	4.612	1.207	0.053
13	H9704035	FR12652	M7	0.095	1.211	0.287	0.0717	45.605	1.221	8.044	1.954	1.075	0.099	3.082	0.660	0.031	0.124	4.286	1.101	0.055
14	H9704039	FR24491	M7	0.130	1.588	0.401	0.0978	45.552	1.327	7.956	2.692	1.174	0.217	3.954	0.873	0.109	0.303	7.776	1.661	0.190
15	H9704044	FR24491	Original	0.116	1.172	0.346	0.0905	45.587	1.299	8.104	2.295	1.148	0.177	2.839	0.956	0.091	0.207	4.129	1.085	0.144
16	H9704049	FR12652	Original	0.074	0.643	0.245	0.0588	45.581	1.015	5.274	1.988	0.900	0.054	1.027	0.510	0.019	0.087	2.553	0.774	0.044

Table 4-2: 1993 Honda Civic VX Modal Bag Equivalents

				FTP Composite (gpm)			Phase 1 (gpm)			Phase 2 (gpm)			Phase 3 (gpm)		
Sequence	Test ID	Fuel ID	Catalyst	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
1 Tailpipe	H9703031	FR12652	Original	0.073	0.648	0.168	0.271	1.261	0.374	0.022	0.443	0.119	0.019	0.568	0.104
Engine	H9703031	FR12652	Original	2.209	6.284	1.179	2.050	6.210	1.658	2.377	6.993	1.018	1.584	5.010	1.119
Cat Eff*	H9703031	FR12652	Original	97	90	86	87	80	77	99	94	88	99	89	91
2 Tailpipe	H9703034	FR24491	Original	0.110	0.904	0.215	0.321	1.452	0.437	0.053	0.486	0.123	0.058	1.279	0.220
Engine	H9703034	FR24491	Original	2.157	6.487	1.225	2.082	6.078	1.744	2.421	6.922	0.985	1.714	5.975	1.288
Cat Eff	H9703034	FR24491	Original	95	86	82	85	76	75	98	93	87	97	79	83
3 Tailpipe	H9703037	FR24491	M7	0.811	1.365	1.702	3.173	1.731	5.110	0.189	1.017	0.698	0.199	1.748	1.024
Engine	H9703037	FR24491	M7	7.720	5.528	6.067	13.85	5.621	14.48	6.923	5.625	3.567	4.579	5.274	4.427
Cat Eff	H9703037	FR24491	M7	89	75	72	77	69	65	97	82	80	96	67	77
4 Tailpipe	H9703040	FR12652	M7	0.106	1.248	0.283	0.324	1.852	0.561	0.052	0.862	0.168	0.042	1.521	0.290
Engine	H9703040	FR12652	M7	2.073	6.581	1.359	2.155	6.415	2.067	2.276	6.867	1.033	1.629	6.167	1.440
Cat Eff	H9703040	FR12652	M7	95	81	79	85	71	73	98	87	84	97	75	80
5 Tailpipe	H9703043	FR12652	M8	0.089	1.378	0.282	0.330	2.373	0.547	0.017	0.725	0.196	0.043	1.857	0.244
Engine	H9703043	FR12652	M8	2.066	6.847	1.346	2.109	7.193	1.973	2.264	7.021	1.059	1.658	6.256	1.413
Cat Eff	H9703043	FR12652	M8	96	80	79	84	67	72	99	90	81	97	70	83
6 Tailpipe	H9704001	FR24491	M8	0.372	1.201	1.017	1.333	1.540	2.699	0.122	0.907	0.508	0.117	1.501	0.707
Engine	H9704001	FR24491	M8	4.745	5.565	3.841	6.972	5.508	7.910	4.660	5.787	2.586	3.222	5.189	3.131
Cat Eff	H9704001	FR24491	M8	92	78	74	81	72	66	97	84	80	96	71	77
7 Tailpipe	H9704004	FR24491	M9	0.320	1.917	0.777	0.995	2.561	1.647	0.151	1.702	0.471	0.128	1.837	0.695
Engine	H9704004	FR24491	M9	3.314	6.209	2.278	3.730	6.340	3.729	3.612	6.502	1.707	2.438	5.557	2.258
Cat Eff	H9704004	FR24491	M9	90	69	66	73	60	56	96	74	72	95	67	69
8 Tailpipe	H9704011	FR12652	M9	0.123	1.384	0.314	0.457	2.064	0.759	0.025	0.816	0.159	0.056	1.941	0.270
Engine	H9704011	FR12652	M9	2.061	6.296	1.350	2.154	6.389	2.044	2.243	6.405	1.054	1.647	6.019	1.383
Cat Eff	H9704011	FR12652	M9	94	78	77	79	68	63	99	87	85	97	68	80

* Mass-mean catalyst efficiency, %.

Table 4-2: 1993 Honda Civic VX Modal Bag Equivalents (Continued)

				FTP Composite (gpm)			Phase 1 (gpm)			Phase 2 (gpm)			Phase 3 (gpm)		
Sequence	Test ID	Fuel ID	Catalyst	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
9 Tailpipe	H9704014	FR12652	M9	0.133	1.676	0.352	0.483	2.436	0.738	0.025	1.021	0.235	0.071	2.337	0.280
Engine	H9704014	FR12652	M9	2.161	6.886	1.405	2.183	6.751	2.010	2.406	7.035	1.133	1.682	6.710	1.459
Cat Eff	H9704014	FR12652	M9	94	76	75	78	64	63	99	85	79	96	65	81
10 Tailpipe	H9704017	FR24491	M9	0.165	2.022	0.504	0.489	2.985	0.914	0.082	1.703	0.349	0.077	1.896	0.486
Engine	H9704017	FR24491	M9	2.201	6.694	1.393	2.256	7.107	1.993	2.423	7.028	1.143	1.738	5.751	1.411
Cat Eff	H9704017	FR24491	M9	93	70	64	78	58	54	97	76	69	96	67	66
11 Tailpipe	H9704021	FR24491	M8	1.596	1.307	8.304	6.474	1.755	33.56	0.340	1.039	1.623	0.284	1.475	1.831
Engine	H9704021	FR24491	M8	25.86	5.511	30.92	86.57	5.896	123.1	11.66	5.626	6.544	6.827	5.003	7.260
Cat Eff	H9704021	FR24491	M8	94	76	73	93	70	73	97	82	75	96	71	75
12 Tailpipe	H9704024	FR12652	M8	0.092	1.161	0.265	0.313	1.829	0.535	0.032	0.911	0.176	0.037	1.127	0.227
Engine	H9704024	FR12652	M8	2.111	6.454	1.358	2.221	6.945	2.030	2.290	6.709	1.051	1.689	5.600	1.427
Cat Eff	H9704024	FR12652	M8	96	82	81	86	74	74	99	86	83	98	80	84
13 Tailpipe	H9704035	FR12652	M7	0.095	1.357	0.256	0.338	2.206	0.506	0.030	1.028	0.160	0.036	1.336	0.250
Engine	H9704035	FR12652	M7	2.133	6.792	1.385	2.106	7.149	1.919	2.441	7.198	1.085	1.575	5.762	1.550
Cat Eff	H9704035	FR12652	M7	96	80	82	84	69	74	99	86	85	98	77	84
14 Tailpipe	H9704039	FR24491	M7	0.131	1.732	0.364	0.371	2.301	0.675	0.069	1.389	0.246	0.066	1.946	0.351
Engine	H9704039	FR24491	M7	2.158	6.951	1.391	2.156	7.050	2.116	2.425	7.312	1.079	1.655	6.196	1.431
Cat Eff	H9704039	FR24491	M7	94	75	74	83	67	68	97	81	77	96	69	75
15 Tailpipe	H9704044	FR24491	Original	0.112	0.950	0.250	0.335	1.996	0.558	0.056	0.515	0.124	0.051	0.980	0.254
Engine	H9704044	FR24491	Original	2.061	6.289	1.248	2.111	6.780	1.841	2.271	6.485	0.959	1.628	5.548	1.348
Cat Eff	H9704044	FR24491	Original	95	85	80	84	71	70	98	92	87	97	82	81
16 Tailpipe	H9704049	FR12652	Original	0.071	0.650	0.203	0.275	1.418	0.488	0.016	0.355	0.117	0.019	0.626	0.150
Engine	H9704049	FR12652	Original	2.107	6.393	1.316	2.049	6.557	1.948	2.398	6.824	1.025	1.601	5.456	1.387
Cat Eff	H9704049	FR12652	Original	97	90	85	87	78	75	99	95	89	99	89	89

* Mass-mean catalyst efficiency, %.

Table 4-3: 1996 Honda Civic LX Oxygen Storage Measurements

Sequence	Catalyst	Fuel ID	Seconds
1	M9	24491	1.99
1	M9	24491	1.92
1	M9	24491	2.04
2	Orig	12652	4.52
2	Orig	12652	4.63
2	Orig	12652	4.52
3	M8	12652	2.19
3	M8	12652	2.03
3	M8	12652	2.10
4	M7	24491	2.16
4	M7	24491	2.08
4	M7	24491	2.07
5	M9	12652	1.96
5	M9	12652	1.97
5	M9	12652	2.01
6	M7	12652	2.46
6	M7	12652	2.48
6	M7	12652	2.11
7	M8	24491	2.49
7	M8	24491	2.54
7	M8	24491	0.04
8	Orig	24491	4.61
8	Orig	24491	4.65
8	Orig	24491	4.51

Figure 4-1: Cold Start Temperatures
Test ID H9703031
(Original Catalyst, Low Sulfur Fuel)

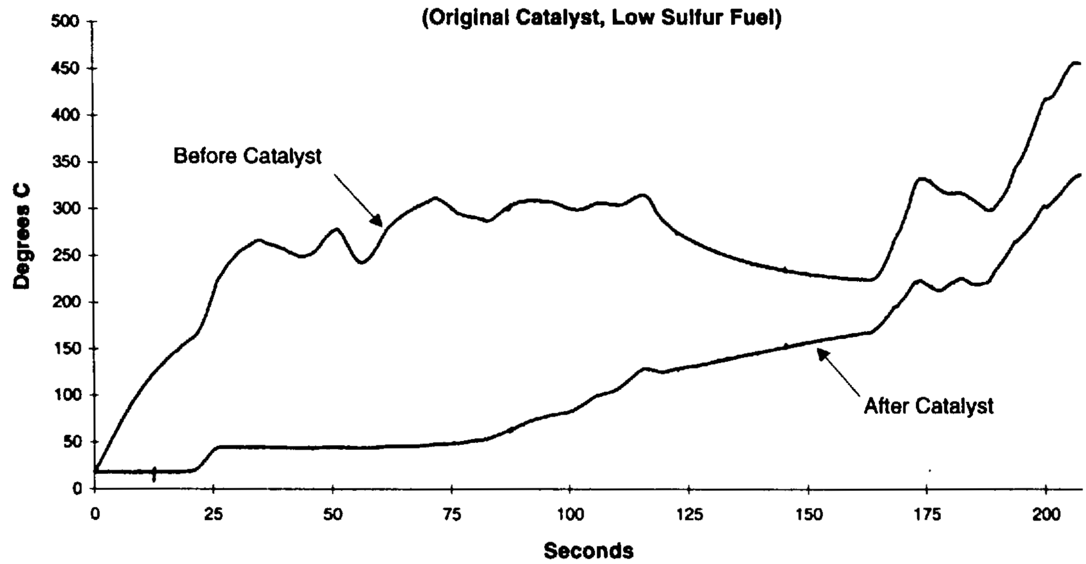
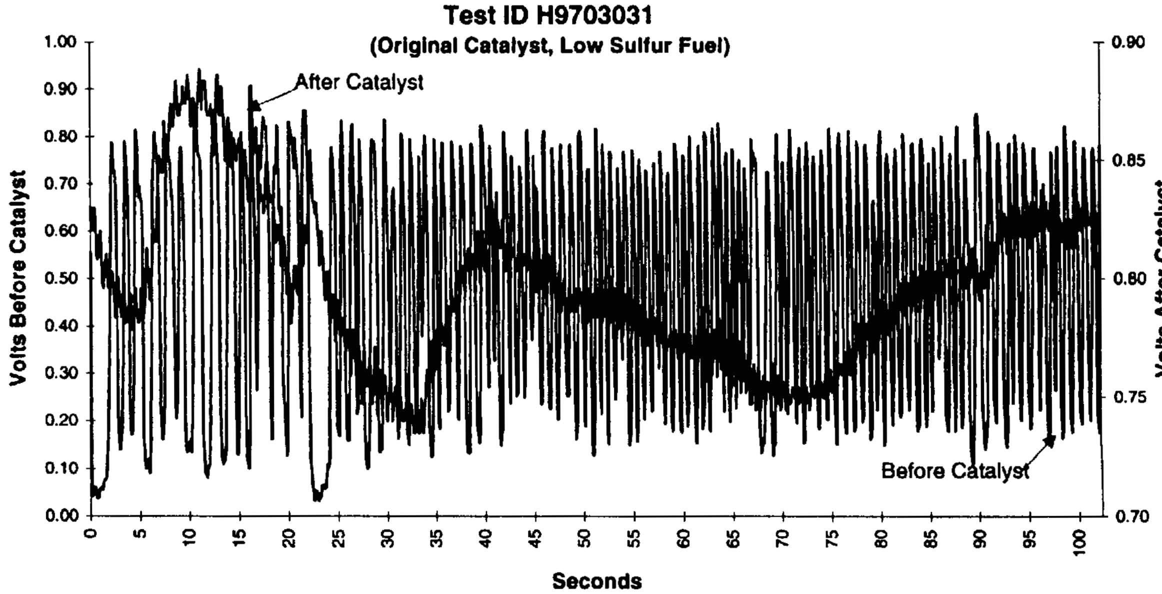


Figure 4-2: Exhaust Gas Oxygen Sensor Voltages
Test ID H9703031
(Original Catalyst, Low Sulfur Fuel)



Section 5
DATA ANALYSIS AND DISCUSSION

The emissions data presented in Section 4 were analyzed using a regression model, which included fuel, catalyst and fuel/catalyst interaction effects. Emissions data from the first test (H9703031) were not included in the statistical analysis due to the problems discussed earlier in Section 4. The two fuels and four catalysts were modeled as class variables.

Mean emissions and 95% confidence intervals for each fuel/catalyst combination are listed in Table 5-1 for the FTP and for the individual bags in the FTP. Mean FTP emissions for each fuel/catalyst combination also are plotted in Figure 5-1. The 95% confidence intervals in this figure were developed using the Tukey-Kramer multiple comparison procedure to test for significant differences among means classified by fuel type (e.g., 600 ppm sulfur versus 35 ppm sulfur). Where there is no overlap of confidence intervals between pairs of fuels, the observed difference in means is statistically significant.

The gram/mile reductions in FTP emissions observed in switching from the 600 to the 35 ppm sulfur fuel are listed in Table 5-2 and plotted in Figure 5-2. (Note that all CO measurements in Figure 5-2 have been divided by 10 to facilitate plotting on the same scale as the other pollutants shown in the figure.) The bottom of Table 5-2 also contains a summary of the sulfur effects in the PERF program which tested 10 vehicles (6 different models) certified to California TLEV standards on 25, 300 and 600 ppm sulfur fuels (1).

The effects of sulfur on Honda TLEV exhaust emissions were similar to those seen in other programs. Emissions were lower on the 35 ppm sulfur fuel than on the gasoline with 600 ppm sulfur. The differences in emissions between fuels were statistically significant for the group of four test catalysts as a whole, but differences between fuels in individual catalysts were often not significant. Averaging over all catalysts, lowering sulfur from 600 to 35 ppm reduced FTP emissions by 21 to 27% depending on the pollutant.

The effects of sulfur on emissions were similar, both in magnitude and on a percentage change basis, to those observed in the PERF TLEV program. The magnitude of the effect of sulfur on NO_x was larger in the present study, but NO_x emissions from the Honda TLEV were much larger than fleet average NO_x emissions in the PERF TLEV project. In addition, sulfur effects in both the PERF TLEV project and in this project were comparable to those observed in the Auto/Oil Air Quality Improvement Research Program for Tier 0 and in Tier 1 vehicles, given the uncertainty in the data. (1)(3)

Exhaust emissions were lowest for the original catalyst and highest for the field-aged, 100,000 mile in-use catalyst (M9). The differences in emissions between the original catalyst and catalyst M9 were statistically significant for all pollutants over the FTP. Differences among the three aged catalysts were smaller than the differences in emissions between the original catalyst and M9.

As described earlier in Section 2, catalysts M7 and M8 were aged for 100 hours on an engine dynamometer using the same accelerated aging procedure (the RAT-A cycle) employed in the CRC Sulfur/OBD-II laboratory reactor program. M7 was aged on a 40 ppm sulfur fuel and M8 was aged on gasoline with 1000 ppm sulfur. There was no difference in overall emissions or sulfur effects between these two catalysts. This indicates that fuel sulfur content does not have an effect on long-term catalyst emission performance over the RAT-A cycle.

As shown in Figure 5-2, the direction of the emissions response to fuels with lower sulfur was the same (i.e., lower) for all four catalysts tested. The differences in the magnitudes of the sulfur effect among the four catalysts were not statistically significant—as evidenced by the fact that the error bars shown in Figure 5-2 overlap to a large extent. This indicates that rapid catalyst aging does not have a large effect on sulfur response when compared to in-use aging.

An identical catalyst from a Honda TLEV was tested in the CRC Sulfur/OBD-II laboratory reactor program. Data from the present program can be used to compare a vehicle emission response to sulfur over FTP transient driving conditions to a sulfur response based on a laboratory reactor operated under steady-state conditions. Figure 5-3 compares the percent reduction in emissions in switching from 600 to 35 ppm sulfur in this program to that observed in moving from 600 to 40 ppm sulfur in the CRC program. Emissions in this program are averaged over the two catalysts which were rapidly aged using the same protocol employed by CRC (M7 and M8), and they are shown separately for each Bag of the FTP. Emission effects for the CRC program were estimated from reported catalyst efficiencies, which are directly related to emissions because feed gas composition was held constant.

The effects of fuel sulfur on emissions over the entire FTP in the present study were smaller than those observed in the CRC Sulfur/OBD-II program. In the CRC program, reducing feedgas sulfur content from 600 to 40 ppm lowered NMHC and NO_x emissions from the Honda TLEV catalyst (aged to the equivalent of 100,000 miles) by 57%. This was more than twice the percentage effect seen over the FTP in the present study. The CRC program tested catalysts in a laboratory reactor operated under steady-state, warmed-up conditions. Emissions under these conditions are typically quite low and result in a magnification of sulfur effects when emissions responses are evaluated on a percentage basis. The sulfur effects on NMHC emissions in the CRC program are of the same order of magnitude as those seen in Bags 2 and 3 of the FTP in the present study.

As described previously, measurements of oxygen storage capacity were performed for each catalyst/fuel combination in a 1996 Honda Civic. OSC measurements did not have replicates, so fuel and catalyst interaction effects could not be included in the statistical model. Multiple measurements were averaged over each fuel and catalyst. The anomalous result for catalyst M8 and the high sulfur fuel (discussed previously in Section 4) was treated as an outlier and excluded from statistical analysis. The OSC data were then analyzed using a statistical model that included fuel and catalyst effects.

The average OSC for each catalyst/fuel combination is plotted in Figure 5-4. The mean OSC for each fuel over all of the test catalysts also is shown in this figure. Differences between the original and the aged catalysts are much larger than any differences between the two fuels. OSC is roughly twice as high in the original catalyst when compared to the three aged catalysts, all of which had similar OSC. Gasoline sulfur content does not have a significant effect on the oxygen storage capacity of the four catalysts tested in this study, and average OSC is almost the same for the low and high sulfur fuels.

Table 5-1: Mean Emissions and 95% Confidence Intervals For Honda TLEV

(Grams per Mile)

Catalyst	Pollutant	FTP 35 ppm S	FTP 600 ppm S	Bag 1 35 ppm S	Bag 1 600 ppm S	Bag 2 35 ppm S	Bag 2 600 ppm S	Bag 3 35 ppm S	Bag 3 600 ppm S
M7	THC	0.096±0.005	0.127±0.005	1.170±0.084	1.294±0.084	0.113±0.032	0.215±0.032	0.149±0.048	0.289±0.048
	NMHC	0.072±0.011	0.091±0.011	1.024±0.108	1.139±0.108	0.045±0.043	0.080±0.043	0.075±0.049	0.179±0.049
	NO_x	0.315±0.051	0.396±0.051	2.129±0.373	2.700±0.373	0.690±0.193	0.858±0.193	1.276±0.225	1.599±0.225
	CO	1.155±0.219	1.521±0.219	7.095±1.860	7.504±1.860	2.573±0.634	3.805±0.634	5.173±2.009	7.454±2.009
M8	THC	0.094±0.005	0.111±0.005	1.170±0.084	1.133±0.084	0.090±0.032	0.195±0.032	0.173±0.048	0.242±0.048
	NMHC	0.065±0.011	0.076±0.011	1.014±0.108	0.961±0.108	0.000±0.043	0.065±0.043	0.076±0.049	0.140±0.049
	NO_x	0.334±0.051	0.465±0.051	2.203±0.373	3.162±0.373	0.859±0.193	1.096±0.193	1.160±0.225	1.741±0.225
	CO	1.264±0.219	1.403±0.219	7.818±1.860	6.536±1.860	2.555±0.634	3.808±0.634	6.045±2.009	6.693±2.009
M9	THC	0.129±0.005	0.175±0.005	1.631±0.084	1.790±0.084	0.096±0.032	0.337±0.032	0.275±0.048	0.322±0.048
	NMHC	0.099±0.011	0.124±0.011	1.478±0.108	1.576±0.108	0.003±0.043	0.1360.043	0.162±0.049	0.178±0.049
	NO_x	0.387±0.051	0.568±0.051	2.970±0.373	3.629±0.373	0.865±0.193	1.417±0.193	1.264±0.225	2.179±0.225
	CO	1.480±0.219	1.920±0.219	8.004±1.860	10.108±1.860	2.847±0.634	5.886±0.634	8.253±2.009	7.052±2.009
Original	THC	0.074±0.007	0.119±0.005	1.015±0.118	1.258±0.084	0.054±0.046	0.203±0.032	0.087±0.069	0.229±0.048
	NMHC	0.059±0.011	0.087±.016	0.900±0.152	1.093±0.108	0.019±0.060	0.085±0.043	0.044±0.070	0.151±0.049
	NO_x	0.245±0.051	0.322±0.072	1.988±0.528	2.040±0.373	0.510±0.273	0.839±0.193	0.774±0.318	1.170±0.225
	CO	0.643±0.219	1.102±0.309	5.274±2.630	6.974±1.860	1.027±0.896	2.558±0.634	2.553±2.842	4.575±2.009
ALL	THC	0.098±0.003	0.133±0.002	1.246±0.047	1.369±0.042	0.088±0.018	0.238±0.016	0.171±0.027	0.270±0.024
	NMHC	0.074±0.006	0.094±0.006	1.104±0.060	1.192±0.054	0.017±0.024	0.091±0.021	0.089±0.028	0.162±0.025
	NO_x	0.320±0.028	0.438±0.025	2.322±0.209	2.883±0.187	0.731±0.108	1.052±0.097	1.118±0.126	1.672±0.113
	CO	1.135±0.122	1.486±0.109	7.048±1.040	7.780±0.930	2.250±0.354	4.014±0.317	5.506±1.123	6.443±1.005

95% confidence intervals are shown

Table 5-2: Reduction In Honda Tlev Ftp Emissions In Switching From High To Low Sulfur Fuel (600-->35 Ppm) And Comparison To Results From Perf Tlev Program

Catalyst	Pollutant	Grams per mile	Percent Reduction
M7	THC	**0.032 ± 0.012**	24.8%
	NMHC	0.019±0.027	21.2%
	NO_x	0.082±0.125	20.6%
	CO	0.366±0.538	24.1%
M8	THC	**0.018±0.012**	15.8%
	NMHC	0.010±0.027	13.8%
	NO_x	**0.131±0.125**	28.2%
	CO	0.140±0.538	9.9%
M9	THC	**0.046±0.012**	26.1%
	NMHC	0.025±0.027	19.9%
	NO_x	**0.181±0.125**	31.9%
	CO	0.440±0.538	22.9%
Original	THC	**0.045±0.015**	37.6%
	NMHC	0.028±0.034	32.3%
	NO_x	0.077±0.152	23.9%
	CO	0.459±0.659	41.7%
ALL	THC	**0.035±0.004**	26.2%
	NMHC	**0.021±0.008**	21.9%
	NO_x	**0.118±0.038**	26.9%
	CO	**0.351±0.164**	23.6%
PERF TLEV, 600-->25 ppm			
	NMHC	0.028	19.1%
	NO_x	0.025	15.1%
	CO	0.193	26.9%

95% confidence intervals are shown. Significant differences are bolded

Figure 5-1
Honda TLEV FTP Emissions

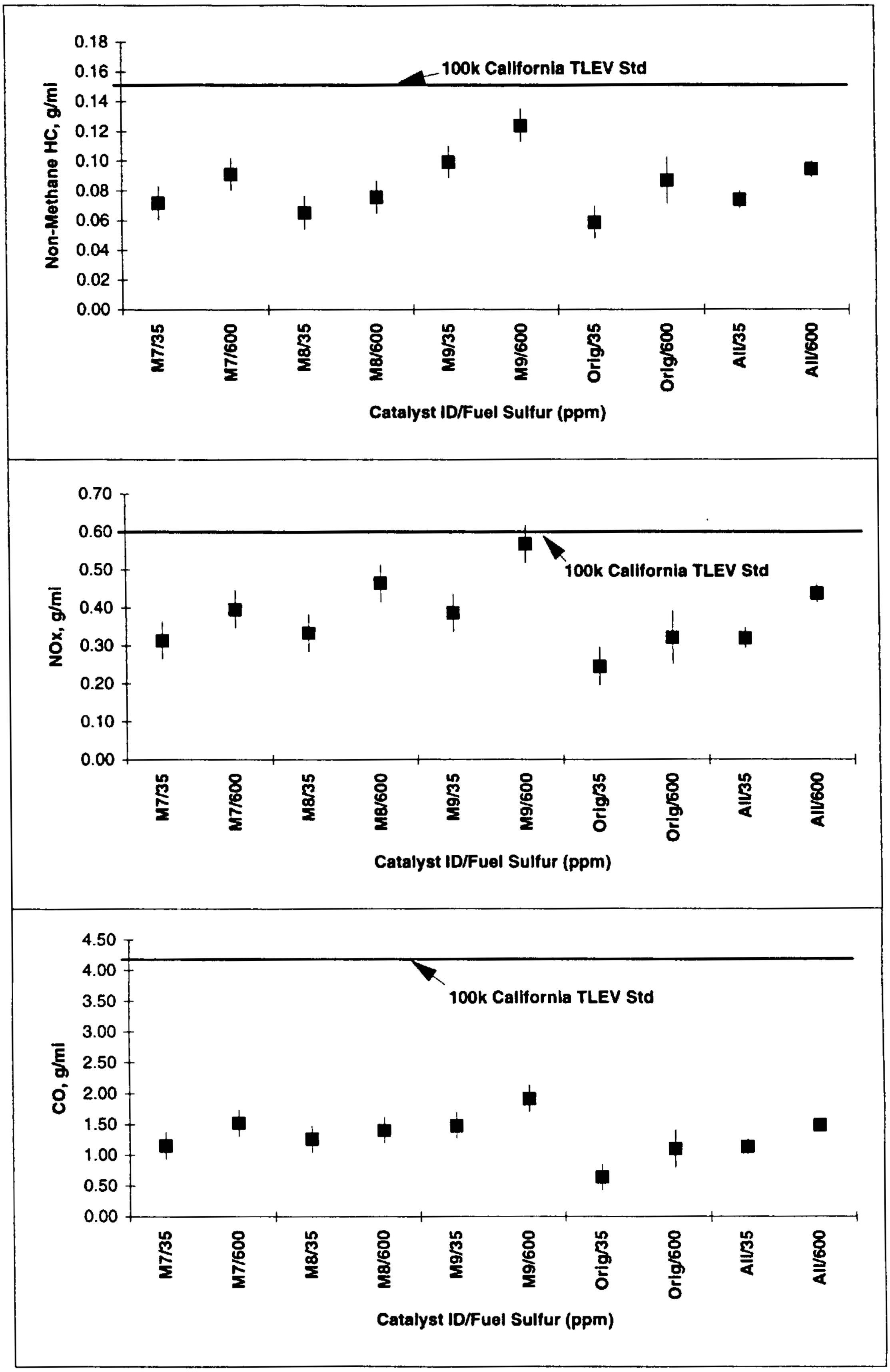


Figure 5-2
Effect of Sulfur on Honda TLEV Emissions
(Reduction in FTP Emissions 600-->35 ppm S)

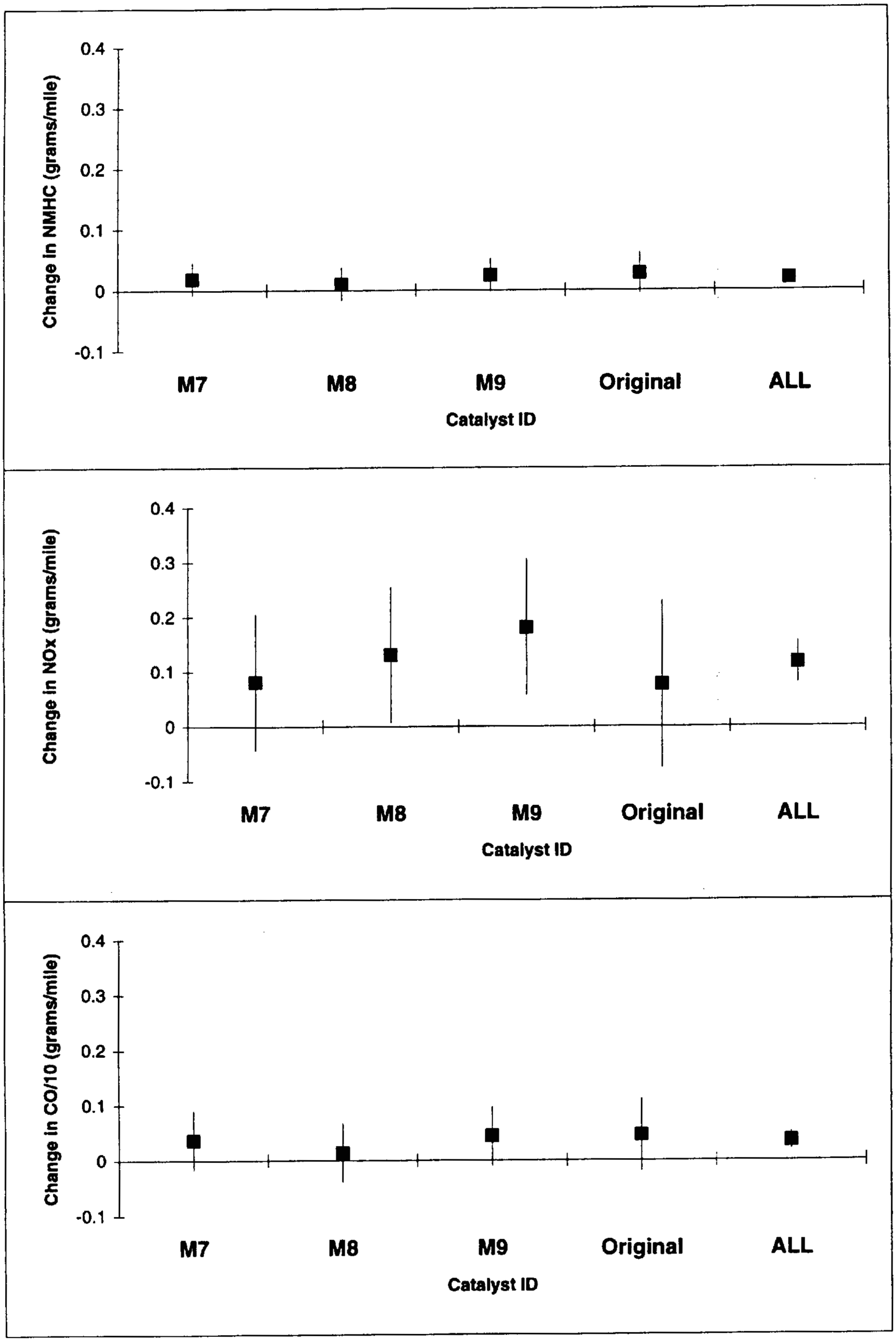


Figure 5-3
Comparison of Honda TLEV Sulfur Response in API and CRC Programs
(Percent Reduction in Emissions 600-->35/40 ppm S)

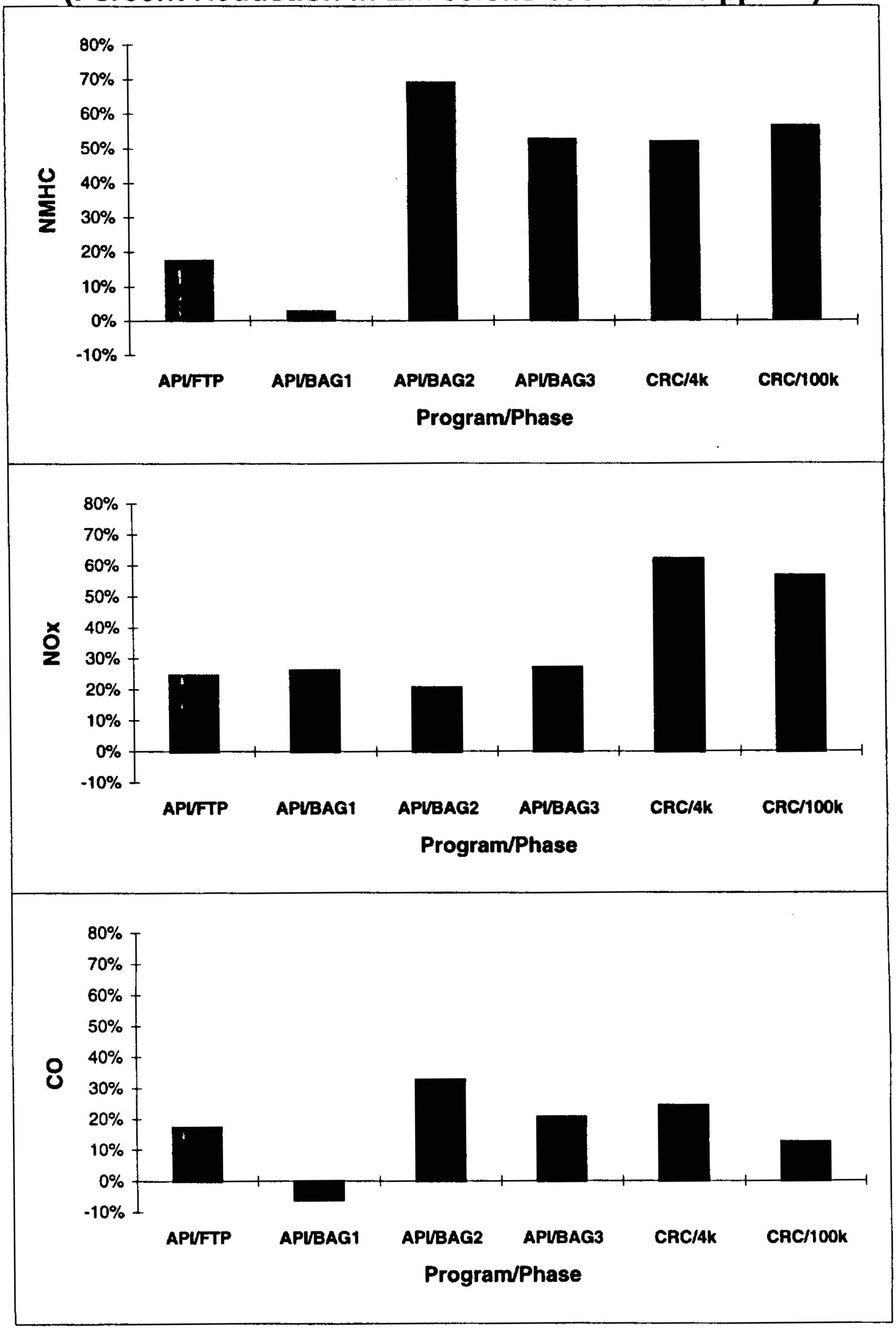
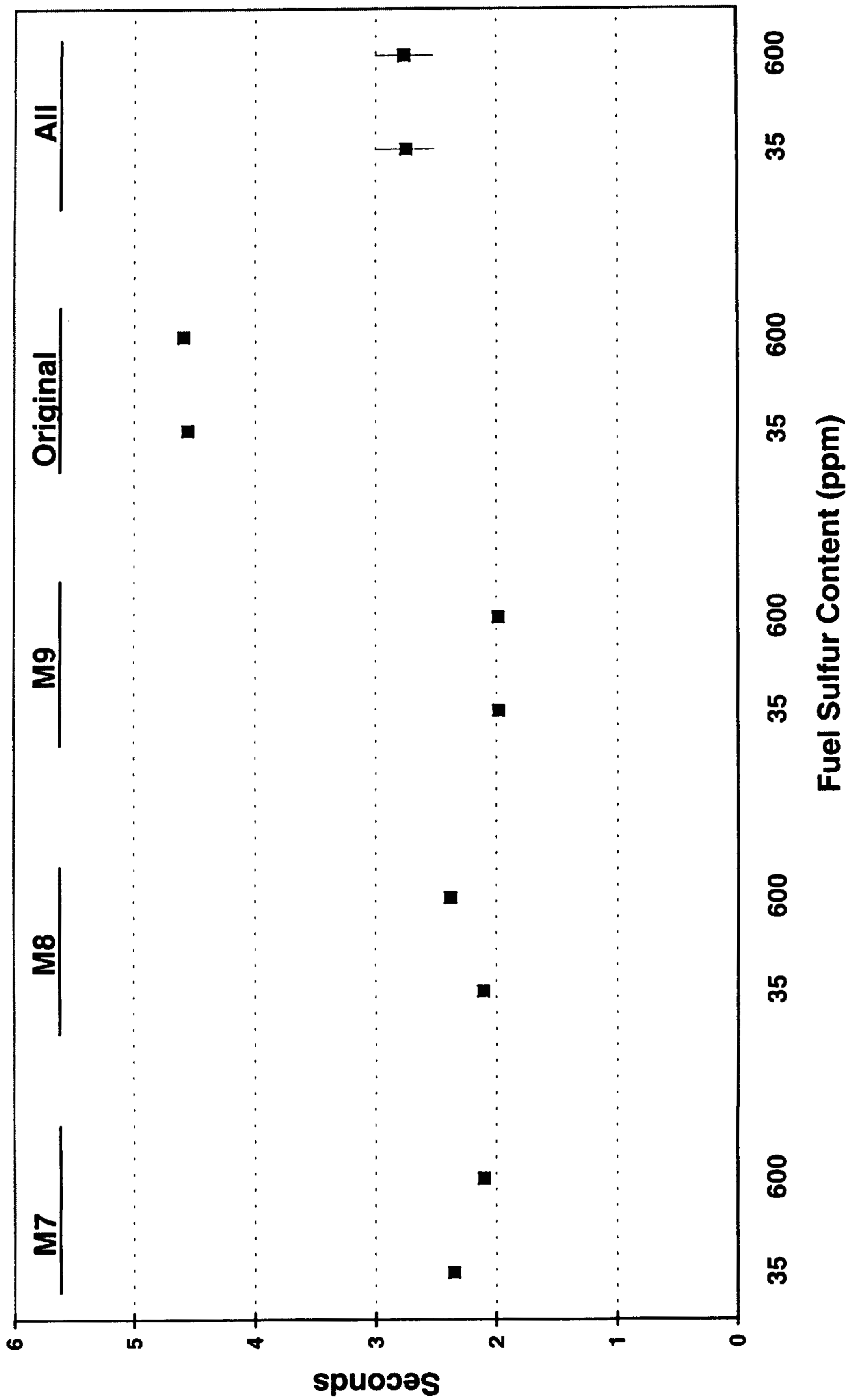


Figure 5-4
HONDA TLEV Oxygen Storage Measurements



Section 6

SUMMARY

The results of this test program show the following:

- The effects of sulfur on exhaust emissions of a 1993 Honda Civic certified to California TLEV standards were similar to those seen in other vehicle test programs such as those conducted by PERF and the Auto/Oil AQIRP. (1) (3) Emissions were lower on the 35 ppm sulfur fuel than on the gasoline with 600 ppm sulfur. The differences in emissions between fuels were statistically significant for the group of four test catalysts as a whole, but differences between fuels in individual catalysts were often not significant. Averaging over all catalysts, lowering fuel sulfur content from 600 to 35 ppm reduced FTP emissions by 21 to 27% depending on the pollutant.

- Exhaust emissions were lowest for the original catalyst and highest for the field-aged, 100,000 mile in-use catalyst (M9). The differences in emissions between the original catalyst and M9 were statistically significant for all pollutants over the FTP.

- Fuel sulfur content did not have an effect on the long-term emissions performance of catalysts which had been artificially aged using the RAT-A cycle. Catalysts M7 and M8 were aged for 100 hours on a dynamometer using the RAT-A cycle for 100 hours on 40 and 1000 ppm sulfur fuels, respectively. There was no difference in overall emissions or sulfur effects between these two catalysts.

- Rapid catalyst aging did not have a large effect on sulfur response compared to in-use aging. All catalysts responded directionally the same to sulfur and there was no difference in the magnitude of the sulfur effect among the four catalysts.

- An identical catalyst from a Honda TLEV was tested in the CRC Sulfur/OBD-II laboratory reactor program. A comparison of the data generated from the two programs suggests that laboratory results may (a) overstate sulfur effects as measured from a vehicle and (b) represent hot vehicle performance better than cold operation. Reducing fuel sulfur content from 600 to 40 ppm in the CRC laboratory reactor program lowered the Honda TLEV HC and NO_x emissions by 57% or more than twice the percentage effect seen over the FTP in the present study. However, the sulfur effects on HC that were observed during the warmed-up phases of the FTP (Bags 2 and 3) of the present study were similar to those measured in the CRC lab reactor program under steady-state, warmed-up conditions.

- Gasoline sulfur content did not have a significant effect on catalyst oxygen storage capacity. Differences in OSC between the original and the aged catalysts were much larger than any differences attributable to fuel sulfur content. OSC was roughly twice as high in the original catalyst compared to the three aged catalysts, all of which had similar OSC.

REFERENCES

1. Sztenderowicz, M. L., Bandy, W. J. III, Most, W. J., Jetter, S., Sprik, T. L., Doherty, H., and Eng, K. D., "Effects of Fuel Sulfur Level on Emissions from Transitional Low Emission Vehicles", Society of Automotive Engineers Technical Paper No. 952561, 1995.

2. Gerry, F. S., Gorse, R. A. Jr., Bandy, W. J., Beck, D., Burns, V., Doherty, H., Herwick, G., and Rutherford, J., *CRC Sulfur/OBD-II Laboratory Research Program: Executive and Technical Final Reports,* Coordinating Research Council Report No. 602, February, 1997.

3. Auto/Oil Air Quality Improvement Research Program, *Program Final Report*, January 1997.

Appendix A

CATALYTIC CONVERTER AGING WITH TWO FUEL SULFUR LEVELS

SOUTHWEST RESEARCH INSTITUTE

6220 CULEBRA ROAD • POST OFFICE DRAWER 28510 • SAN ANTONIO, TEXAS, USA 78228-0510 • (210) 684-5111 • TELEX 244846

May 21, 1996

TO: American Petroleum Institute
1220 L St. NW
Washington DC 20005

ATTN: Mr. David Lax

SUBJECT: SwRI Proposal 08-18784B, "Aging of Honda Converters at Two Fuel Sulfur Levels using the CRC Protocol."

I. INTRODUCTION

This proposal was prepared in response to a request from Dr. Bill Bandy of Amoco Corporation, made on November 29, 1995. It was first revised to reflect a change in proposed funding organization. This second revision reflects a change in the requested scope of the work. The Department of Emissions Research (DER) of Southwest Research Institute (SwRI) proposes to perform catalytic converter aging at two fuel sulfur levels, following the aging protocol developed for the CRC project, and described in the SwRI Proposal 08-18010A. Two pre-canned converters will be supplied by Honda. The converters will be aged as described below, and returned to the supplier for evaluation.

II. STATEMENT OF WORK

The DER at SwRI will perform catalytic converter aging at two fuel sulfur levels on a stationary dynamometer. A total of two (2) converters will be aged in the test program. The proposed sequence, duration, number of catalysts aged and fuel sulfur level is shown in Table 1.

TABLE 1. TEST MATRIX

Step	Converter No.	Aging Description	Aging Duration (hrs)	Fuel Sulfur Level ppm
1	1	RAT-A(800°C)	100	40
2	2	RAT-A(800°C)	100	1000

The aging engine is a 7.5L V-8 Ford engine equipped with multiport fuel injection and an exhaust splitter system custom built for this aging protocol. Converters will be aged following the Rapid Aging Engine Test Cycle (RAT A) described in Table 2.

TABLE 2. RAPID AGING ENGINE TEST CYCLE

Step	Description
1	Closed loop, stoichiometric operation for 40 seconds, catalyst inlet temperature of 800°C, measured 6 inches upstream of the catalyst face. Catalyst space velocity = 81,000 hr^{-1}
2	Power enrichment mode, 3 percent carbon monoxide for 6 seconds
3	Power enrichment with air injected at converter inlet to provide 3 percent carbon monoxide, 3 percent oxygen for 10 seconds
4	Closed loop, stoichiometric operation with air injection at the converter inlet to provide 3 percent oxygen for 4 seconds

The fuel used is California Phase II certification fuel. The sulfur level is specified at 35 - 40 ppm and unmodified fuel is used for the low sulfur aging. The high sulfur fuel aging uses the same fuel, doped with thiophene to a sulfur level of 1000 ppm.

Also included in this revision, is a request to obtain continuous temperature readings at 0, 50, and 100 hours. DER will collect two temperatures (catalyst inlet and catalyst bed) for a total of 600 seconds. This time interval equates to ten full aging cycles. The data acquisition will commence at the start of a cycle. The temperature data will be stored on a 3.5 inch computer disk, in the form of delimited ASCII files, and shipped with the catalysts.

Appendix B

DETAILED TEST PROTOCOL

1993 HONDA CIVIC VX (TLEV)

Each test on the 1993 Honda Civic VX consisted of a FUEL CHANGE and PRECONDITIONING sequence, a FTP EMISSIONS TEST, and an OXYGEN SENSOR MEASUREMENT which followed immediately after the FTP. Descriptions of each of these elements are given below.

Four different catalysts were used on the test vehicle over the course of testing.

FUEL CHANGE and PRECONDITIONING

The fuel change procedure involved a complete drain of the existing fuel from the tank, two three-gallon flushes (fill and drain) with the new fuel, and a final fill to 40% of the fuel tank capacity as listed in the owner's manual.

For a repeat test or a test using the same fuel as the previous test, the two three-gallon flushes were omitted. The fuel was simply drained and refilled to 40% of tank capacity.

The preconditioning procedure followed shortly after the final fill. The preconditioning drive consisted of one Highway Fuel Economy Test (HWFET) drive cycle, a short key-off period, followed by a single Urban Dynamometer Driving Schedule (UDDS) driving cycle (which is Bags 1 and 2 of the FTP, often referred to as the LA-4 cycle). The vehicle was then soaked overnight at 75 °F with the hood in the open position, for at least 12 but not more than 24 hours.

FTP EMISSIONS TEST

The emissions test included driving the vehicle according to the 1975 FTP protocol, beginning with the cold start following the soak period. The test was configured to collect Dilute Bags, as well as Raw Engine-Out Second-by-Second emissions and Engine-Out Bag Equivalents. Dilute emissions measurements included HC, CO, NO/NO_x, CO_2 and CH_4 (methane). Engine-out emissions included all of the above except CH_4. In order to compute Bag Equivalent Engine-Out emissions, the "CO_2 Trace" analyzer was run, and the output was stored on a second-by-second basis.

The temperatures at the inlet and outlet of the catalyst also were recorded for each complete FTP test. This was accomplished by plugging the two catalyst thermocouples into a data recorder and starting the recorder just prior to the start of the test.

OXYGEN SENSOR MEASUREMENTS

Immediately following each FTP, catalyst oxygen sensor measurements were made. This was done as follows:

1. The car was left running for 3-5 minutes following the completion of the FTP and the vehicle speed was set to cruise at a steady 35 mph.

2. After this 3-5 minute period, the output voltage of both oxygen sensors was recorded for 3 minutes (180 seconds) at 10 Hertz (samples per second) and the data were tabulated in a spreadsheet.

1996 HONDA CIVIC LX (LEV)

Measurements of oxygen storage capacity were made for each catalyst/fuel combination with the four catalysts used in testing the 1993 vehicle installed in a 1996 Honda Civic supplied by Honda Research of America (HRA) and the two fuels used in testing the 1993 vehicle. The 1996 vehicle was instrumented by HRA to allow the OSC information generated by the vehicle's on-board diagnostic catalyst monitoring function to be examined and recorded as described in the procedure provided by HRA. The preconditioning protocol was the same as that used for the emissions tests on the 1993 vehicle except that the overnight soak was deleted and replaced by a 10 minute key-off period preceding the FTP. No emissions or temperature data were collected during the FTP driving cycle. Triplicate measures of OSC were made according to the instructions provided by HRA.

VEHICLE TEST PROTOCOL SUMMARY

The following procedure was used for preconditioning and testing the two vehicles in this program. It is similar to the procedure used in the Auto/Oil Phase I sulfur study:

- Drain fuel
- 3 gallon fill - new fuel (room temperature)
- Idle 2 minutes
- Drain fuel
- 3 gallon fill - new fuel (room temperature)
- Idle 2 minutes
- Drain fuel
- 40% fill - new fuel (room temperature)

Note: The preceding is estimated to provide fresh fuel in a tank that contains no more than 1% by volume of the previous fuel, assuming no more than 1.0 gallon of residual fuel in the vehicle fuel system and 4.8 gallons for the 40% fill. If these assumptions are not valid, recalculation of the fuel flush volume and the required number of flushes required may be needed.)

- Highway Fuel Economy Test preconditioning
- Engine off 5 minutes
- Idle 1 minute
- Engine off 1 minute

1993 Honda Civic VX TLEV:

- LA-4 preconditioning
- Vehicle soak 12-24 hrs. @ 75±3 °F)
- FTP emissions test (75 °F), with catalyst temperature recordings
- Set speed to 35 mph in 4th gear
- Wait 3-5 minutes
- Record before/after catalyst oxygen sensor voltages for 180 seconds

1996 Honda Civic LX LEV:

- LA-4 preconditioning
- Engine off 10 minutes
- FTP cycle (75 °F), without any emission measurements or catalyst temperature recordings
- Immediately following the FTP, conduct triplicate catalyst oxygen storage measurements using the procedure specified by HRA (See Appendix C.)

Appendix C

OXYGEN STORAGE CAPACITY MEASUREMENTS WITH THE 1996 VEHICLE

Honda R&D of North America, Inc. supplied the following instructions for performing oxygen storage capacity measurements with the 1996 Honda Civic LX:

1. Set the vehicle speed to 50 MPH in 4th gear for 10 minutes to bring the engine and the catalyst to operating temperature.

2. Reduce the vehicle speed to 35 MPH. The hexadecimal display of the ECU monitor should have a value between 35 and 39. At this time it is very important to maintain a constant vehicle speed.

3. After the vehicle speed has been maintained at 35 MPH for approximately 2 minutes, the ECU will begin the OSC test. The ECU monitor will initially reset the OSC timer to 0. Then, it will cycle between rich and lean ten times. The average time of the ten cycles is the OSC number. Log this value in the data table. If the vehicle speed fluctuates too much, the ECU monitor will reset the timer to begin OSC testing from the beginning.

Do not repeat this test cycle more than three times. If the test needs to be repeated, start the procedure from the beginning.

American
Petroleum
Institute

1220 L Street, Northwest
Washington, D.C. 20005
202-682-8000
http://www.api.org

Order No. I46670