Technical Report

A Resistively Heated Catalytic Converter With Air
Injection For Oxidation Of Carbon Monoxide And
Hydrocarbons At Reduced Ambient Temperatures

by

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September 1989

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I. Summary

A resistively-heated metal monolith catalytic converter together with a belt-driven air pump was evaluated on a gasoline-fueled vehicle. The purpose of this work was the oxidation of carbon monoxide (CO) and hydrocarbon (HC) emissions at 20° F ambient conditions.

CO emissions were reduced to 3.9 grams per mile over the Federal Test Procedure (FTP) cycle with resistive heating of the converter for 1-1/2 minutes and excess air added in front of the catalyst for 3 minutes at the start of the test. This was a 68 percent increase in efficiency from CO measured in the absence of catalyst resistive heating and excess air addition. Bag 1 CO from the FTP cycle was reduced to 63.5 grams with catalyst resistive heating/air addition, an increase in efficiency of almost 70 percent from the no-resistive heating/no-air addition catalyst operating scheme.

Bag 1 HC was reduced to 2.88 grams with the catalyst resistive-heating/air-addition scheme referred to above. This was a 67 percent increase in efficiency from no-heat/no-air catalyst configuration levels. HC emissions were reduced to 0.20 grams per mile over the FTP with catalyst resistive heating/air addition.

II. Introduction

The motor vehicle certification process adopted in the United States requires the measurement of emissions over the Federal test procedure (FTP) cycle.[1] The ambient temperature range allowed for this testing is 68°F to 86°F; test cell temperatures at the EPA test facility in Ann Arbor, generally range between 72°F and 77°F.[2]

Motor vehicle hydrocarbon and carbon monoxide emissions, however, are sensitive to a number of variables, to include ambient temperature. Black et all. [3] measured emissions from nine high sales volume 4-cylinder engine equipped vehicles; these vehicles had accumulated driving mileages ranging from 2,800 to 61,600 miles. Mean total hydrocarbons over the FTP ranged from 0.21 g/mi at 70°F to 0.59 g/mi at 20°F with this fleet. CO levels ranged from 2.46 g/mi at 70°F to 7.50 g/mi at 20°F. Commercial summer and winter unleaded gasolines were used for this 70°F and 20°F testing, respectively. Black and others documented similar trends for non-catalyst gasoline, catalyst-equipped gasoline and methanol engines in an earlier study.[4] Other authors have also documented this phenomena.[5,6]

Light-duty automotive emissions of CO are of particular concern to the U.S. EPA. The National Ambient Air Quality Standards (NAAQS) for CO are 10 mg/m^3 (9 ppm) over 8 hours, and 40 mg/m^3 (35 ppm) over a 1-hour time period.[7] During 1987, 59 cities or metropolitan areas exceeded the CO standards on one or more days.[8] These metropolitan regions represented a population of over 86 million people. It has been observed that 90 percent of these violations occurred on days when the ambient temperature dropped below the 68°F floor specified in the transient driving requirements in certification regulations.[9] An earlier study [10] also noted that 83 percent of the exceedances of the NAAQS for CO had been occurring outside of the temperature range of 68°F to 86°F at that time.

The relative importance of increases in Bag 1 CO emissions to weighted FTP averages due to colder ambient conditions has been demonstrated by the U.S. EPA. A small fleet of in-use vehicles was tested over the FTP cycle at 75°F, 50°F, and 20°F ambient conditions.[8] Bag 1 CO levels increased 529 percent from 75°F levels when the vehicles were tested at 20°F. Similar increases in CO over the Bag 1 portion of the FTP were noted in earlier EPA studies.[6,11] The stabilized and hot transient portions of the FTP show increases in CO at lower ambient temperatures; these increases, as a fraction of 20°F test levels versus 75°F test levels are less than half of those determined from Bag 1 testing. Bag 1 CO emission levels are also comparatively much higher than CO from the stabilized and hot transient portions of the FTP at 75°F and lower ambient conditions.[6,8,11]

Higher Bag 1 CO emissions at lower ambient temperatures may be caused by several factors. First, drivetrain friction is greater at colder temperature. An engine therefore must convert more energy to obtain similar acceleration and constant speed at lower ambients until the difference in frictional resistance between 75°F and the colder ambient conditions is overcome. Fuel distribution, wall wetting, etc. may become problems of greater concern as ambient temperature decreases because of increasingly poorer fuel atomization. An increased period of fuel enrichment may be necessary to overcome driveability problems caused by poorer fuel distribution and inefficient combustion at lower temperatures. Catalytic converters also may take longer to "light-off," or come to effective operating temperature at lower ambients.

A resistively heated metal monolith catalyst has been evaluated on both methanol and gasoline-fueled vehicles [12,13,14]. Camet Inc., a subsidiary of W.R. Grace, provided this catalyst for our evaluation. This catalyst can be heated to a temperature of 1000°F in a very short period of time prior

to cold starting; catalyst specifications and power requirements have been provided in a previous paper.[12] This catalyst, therefore, may improve cold start CO emissions at reduced ambient conditions by reaching light-off temperature faster than a typical light-duty vehicle catalyst.

One part of the testing described in [13] above was an evaluation of the resistively heated converter on a gasoline-fueled vehicle at 20°F ambient conditions. The catalyst was evaluated in four different modes. First, the converter was tested in a three-way catalyst configuration; no resistive heating was applied nor was extra air added in front of the catalyst (oxidation-catalyst mode) during this testing. The catalyst was then resistively heated during Bags 1 and 3; again, no additional air was added in front of the catalyst. The catalyst was preheated for 10 seconds prior to cold start in Bag 1; resistive heating continued for 30 seconds following cold start. No resistive heating was applied during Bag 2. Resistive heating was applied for 5 seconds prior to hot start in Bag 3; heating continued for 20 seconds following hot start.

Two different resistive-heating/oxidation-catalyst simulation strategies were evaluated. The first strategy involved the same heating scheme as given above; air at 30 psi (2.4 SCFM) was added in front of the catalyst during the simultaneous resistive-heating/engine-running portions of Bags 1 and 3. The second strategy involved increasing the post-start resistive heating period in Bag 1 to 50 seconds. Air at 30 psi was added during the resistive-heating/ engine-running portions of Bag 1 and 3.

At 20°F Bag 1 CO emissions were approximately 100 times greater than those from Bag 3 when no heat or air was applied to the catalyst. A comparison of Bag 3 CO levels between 20°F and 72°F ambient testing conducted during that project indicated that the catalyst was operating with similar efficiencies over this portion of the FTP under those widely different ambient temperature conditions. Clearly, a strategy to substantially lower FTP emissions of CO at 20°F ambient conditions would have to lower these Bag 1 emissions occurring at cold start and during catalyst warm up.

Heating the catalyst without the addition of bottled air did not lower emissions of CO over the FTP at 20°F. The catalyst was preheated for 10 seconds prior to engine start and for 30 seconds following start during Bag 1. Average CO emissions over Bags 1 and 3 were not reduced by resistive heating. Weighted FTP average emissions for CO were also unchanged from no-heat/no-air mode testing. Though only a small number of tests were conducted, resistive heating during the early part of Bag 1 without the addition of excess air appeared to provide very little emissions benefit over the no-heat/no-air configuration.

The use of resistive heating and the simultaneous addition of excess air appeared to cause a slight reduction in emissions of CO. When air at 2.4 SCFM was added during catalyst heating/engine operation CO emissions fell to 175.6 grams over Bag 1; this compares to 190.5 grams for the no heat/no air configuration. This represents an almost 9 percent increase in CO efficiency over Bag 1. Weighted FTP efficiencies increased over 7 percent for CO through the use of this heating/air addition strategy.

Increasing the amount of time the catalyst was resistively heated during Bag 1 while adding air at 2.4 SCFM during the simultaneous heating/engine-running period was then evaluated. The Bag 1 preheat time was kept at 10 seconds; the time that the catalyst was resistively heated after cold start was increased to 50 seconds, an increase from the 30-second post-start heating time of the previous configuration.

The increased heating period did not lower CO emissions below levels from the previously tested configuration. CO weighted FTP average emissions were essentially unchanged from levels with the catalyst in the no-heat/no-air mode. CO emissions over Bags 1 and 3 were also unchanged from levels measured with the no-heat/no-air configuration.

CO by percent in undiluted exhaust (ahead of the CVS) was continuously monitored during the Bag 1 portion of the tests, which utilized the 10/50 heating scheme and addition of air over the catalyst at 2.4 SCFM. CO was measured at 9 percent of undiluted exhaust during the first 3 minutes of Bag 1 at 20°F ambient conditions. CO concentration dropped sharply during the period of 180 to 240 seconds into a test; after approximately 4 minutes of engine operation, CO had fallen to a stable value much less than 1 percent. The level did not change after that time. Any reduction of CO during this 3-4 minute period could substantially reduce weighted FTP CO emissions.

The goal of the testing described here was to lower emissions of CO and HC over the first 3-4 minutes of the FTP cycle at 20°F ambient conditions. This was to be accomplished by resistively heating the catalytic converter and through the use of air added in front of the catalyst in conjunction with the resistive heating. The catalyst would be resistively heated for a longer period of time than in the configurations previously tested; [13] air would be added in front of the catalyst with a belt-driven air pump, rather than from a bottle of compressed air.

III. Description of Test Program

The work discussed in Section VI of this report was conducted in two separate phases.

We were concerned that our earlier work [13] showed only a slight improvement in CO emissions at lower ambients with resistive catalyst heating and air addition during the Bag 1 portion of the FTP. Our earlier work utilized bottled air for the air added in front of the catalyst; this was done for sake of convenience. It is possible, however, that the amount of air added during Bag 1 was insufficient to fully oxidize excess CO and HC emissions during engine warm up. Conversely, the addition of excess air at 20°F might have had an undesired cooling effect on the resistively heated catalyst at cold start.

The first part of this project therefore involved a rough calculation of the amount of excess air necessary to oxidize CO and HC emissions from the test vehicle during cold start and engine warm up at 20°F ambient conditions. An average engine speed over the initial portion of Bag 1 for the test vehicle was determined. A belt-driven air pump was mounted on the vehicle and pump flowrate at different engine speeds was measured. A valve to divert part of this excess air to the atmosphere was added to the system; pump output curves for various settings of this diverter valve were then generated. A diverter valve setting was chosen that provided air at the necessary flowrate and average engine speed calculated above.

The second part of this work involved the evaluation of the catalyst over the FTP cycle with various resistive heating/air-addition schemes. The catalyst configurations tested are given in Table 1; the catalyst was evaluated in the same underfloor location as in our earlier work [13]. Each test here was conducted after an overnight soak at 20°F conditions.

Figure 1 is a diagram of the Bag 1 and Bag 2 portions of the FTP cycle. The Bag 1 or cold transient portion of the test consists of the first 505 seconds of the cycle. The 90 and 180 second time intervals corresponding to catalyst resistive heating and air pump use referred to in Table 1 are noted on Figure 1.

IV. Vehicle Description

The test vehicle was a 1987 Volkswagen Golf 4-door sedan, equipped with automatic transmission, continuous fuel injection (Bosch CIS), and radial tires. The 1.78-liter engine had a rated maximum power output of 85 horsepower at 5,250 rpm. The vehicle was tested at 2,500 lbs inertia weight and 7.7 actual dynamometer horsepower. Approximately 13000 odometer miles had been accumulated on this vehicle prior to the start of this work.

Table 1

Catalyst Resistive Heating/Air-Addition Schemes
Catalyst As Originally Supplied

Catalyst Configuration	Resistive Heating	Excess Air Supplied
Baseline	None	None
Number 1	10/50, Bag 1*	None
Number 2	None	3 minutes, Bag 1**
Number 3	10/80, Bag 1	3 minutes, Bag 1
Number 4	10/170, Bag 1	3 minutes, Bag 1

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*   Signifies heating for 10 seconds prior to vehicle start, 50 seconds following vehicle start.

**   Signifies addition of air during the 3 minutes of Bag 1 immediately following cold start.

Figure 1
Driving Trace, Bags 1 And 2 Of The FTP Cycle
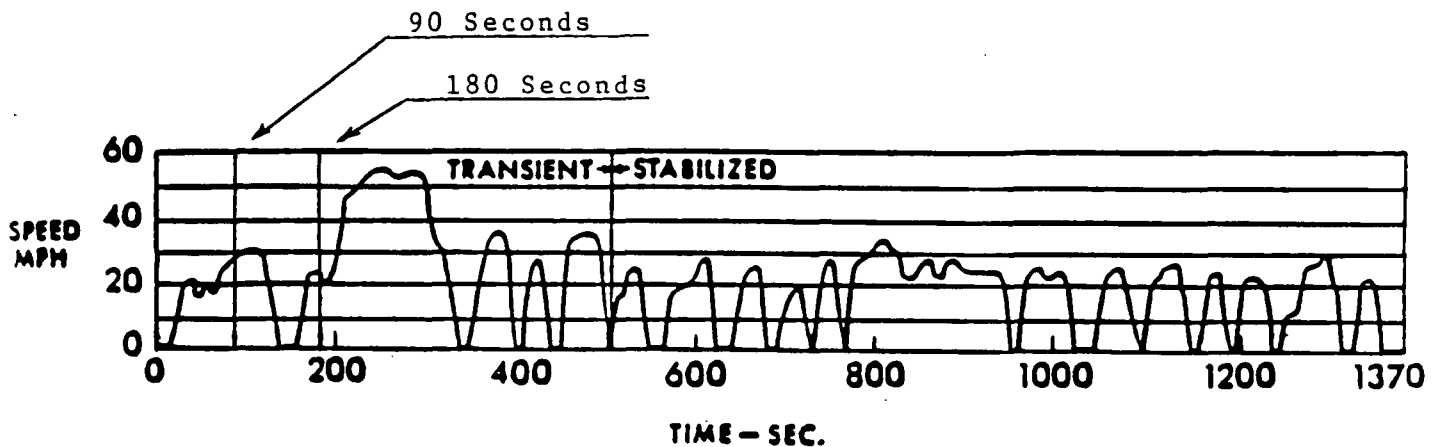
A more detailed description of the vehicle is provided in Appendix A.

V. Test Facilities and Analytical Methods

Emissions testing was conducted on a Labeco Electric single-roll chassis dynamometer, using a direct-drive variable inertia flywheel unit and road load power control unit. The Philco-Ford CVS has a nominal capacity of 350 CFM. The EPA cold test cell has the capability to cold soak a vehicle to 20° F conditions and to supply 20° F air to the engine during the FTP cycle.

Exhaust HC emissions were measured with a Beckman Model 400 FID. CO was measured using a Horiba Model AIA 23 infrared detector, while NOx emissions at 20°F were determined by chemiluminescent technique using a Beckman Model 951A NOx analyzer.

VI. Discussion

A. Selection of Air Pump Flow Rates

As previously mentioned, our earlier work with this resistively heated converter [13] resulted in only a slight improvement in CO emissions at 20°F conditions with resistive heating and air addition in front of the catalyst. We were concerned, however, that the amount of air added was insufficient to fully oxidize excess CO and HC emissions occuring during cold start. We wished to keep the amount of air added during the catalyst warm-up period to a minimum; any additional air at 20°F flowing over the catalyst might have an undesired cooling effect.

The air pump we utilized for this work was a belt-driven vane pump of the type generally referred to as the Saginaw air pump.[15] The pump's output was therefore determined experimentally. The test vehicle was not originally equipped with this pump. The engine alternator was removed and the pump mounted in its place. The battery was recharged during vehicle operation on the chassis dynamometer by a battery charger.

A five-step procedure was used to determine how much air to flow over the catalyst. This procedure called for making simplifying assumptions; these assumptions were made in the interest of saving time and effort. The procedure is outlined and explained below.

1.   Determine the period of the FTP cycle of interest as the time period during which "excess" CO emissions are produced from the test vehicle.

2.   Calculate how much additional air must be added over the catalyst to completely oxidize excess CO (and HC) emissions. Express this requirement as a flowrate.

3.   Determine the range of engine speeds over the period of interest. By weighting engine speeds against time, estimate an average engine speed over the time period of interest.

4.   Map the output of the air pump as a function of engine speed and diverter valve setting.

5.   Choose the diverter valve setting which provides the calculated air flowrate at the average engine speed determined above.

The period of higher CO emissions in Bag 1 was determined in a qualitative manner. The difference in CO emission levels between Bag 1 and 3 of the FTP from the test vehicle at 20°F was assumed to be related to cold start. Therefore, the "excess" CO emissions of interest to us could be expressed as the difference between Bag 1 and 3 levels. The same assumption was made concerning HC emissions. Tailpipe CO emissions from the test vehicle over Bag 1 at 20°F were then continuously sampled using a Sun Emissions Analyzer. CO concentrations were very high at cold start; after approximately 3.2-4.0 minutes of driving the Bag 1 cycle, however, the concentration had declined in a step-change manner. The concentrations measured after this step-change varied only slightly during the remainder of Bag 1; this behavior was noted on several tests. We attributed the step-change reduction in emissions to catalyst light-off, and defined the first 3.2 minutes of Bag 1 as the period of high CO production for the test vehicle.

Because our air pump was belt driven, its output was a function of engine speed. The vehicle was run over Bag 1 of the FTP with continuously measured engine speed. A rough measure of engine speed versus time interval over the 3.2-minute period of interest was made, and an average engine speed of 1,413 rpm was determined.

The excess CO and HC emissions were assumed to occur during the first 3.2 minutes of Bag 1. Using an empirical ratio of CH 1:1.85 for HC, an additional air requirement of 5.4 SCFM was calculated. Stoichiometric conversion of CO and HC was postulated; any cooling effect on the catalyst caused by the addition of air was therefore minimized.

Figure 2 contains the curves generated when air pump flow was mapped with respect to engine speed and diverter valve setting. A hand-operated valve was used to divert some of the pump output to the atmosphere; the valve-open notation in Figure 2 refers to the position of the actuator. The airflow to the catalyst was measured by flowing it through a rotameter. An allowance for backpressure in the exhaust pipe was not made; airflow in front of the catalyst may have been slightly lower because of this. In order to obtain 5.4 SCFM at 1,413 engine rpm, it was necessary to open the valve to the one-third open position.

B. Discussion of Test Results

The primary goal of this experimentation was the reduction of CO emission levels from the test vehicle over the FTP cycle at 20°F ambient conditions. Figure 3 presents CO emission levels over the FTP for several resistive-heating/air-addition schemes for the Camet catalyst. Figure 4 presents Bag 1 CO emissions in grams for the same heat/air schemes.

Heating the catalyst in the absence of air from the air pump provided virtually no additional CO emissions reduction. The level of CO emissions was roughly 12 grams per mile in both heated and unheated catalyst configurations. The no heat/no air scheme had slightly lower weighted FTP average CO emissions; this was due in large part to a single test during which CO emissions were measured at 10 grams per mile. Bag 1 CO levels were also similar in both cases, with the final no heat/no air test accounting for much of the difference. The significance of Bag 1 to the weighted FTP average is apparent when Bag 2 and 3 averages are considered; for the no-heat/no-air configuration here, Bag 2 and 3 CO emissions were 1.2 grams each.

The addition of air greatly reduced Bag 1 CO emissions even in the absence of catalyst resistive heating. Bag 1 CO was reduced roughly 50 percent, to 105 grams, through the addition of air. Weighted average FTP CO emissions were also reduced, to 6.3 grams per mile, with the no-heat/3-minutes air addition catalyst operating scheme. This level of CO emissions is well below the recently proposed 20°F standard of 10.0 grams per mile.[16] In each test in which air addition was called for, this operation was conducted in the same manner. A technician opened the manually controlled diverter valve to the one-third open position immediately after Bag 1 cold start. The valve was held in this position and air was admitted over the catalyst for 3 minutes of the cycle. At the end of this 3-minute period, the valve was manually closed and pump air was diverted to the atmosphere during the remainder of the test.
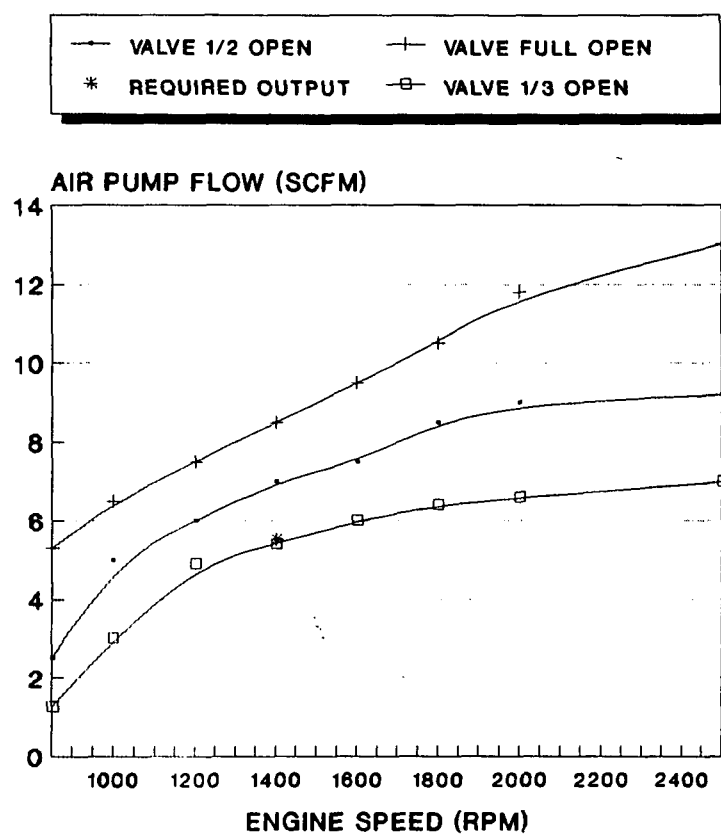
FIGURE 2
CAMET CATALYST EVALUATION
AIR PUMP CALIBRATION

	VALVE 1/2 OPEN		VALVE FULL OPEN
*	REQUIRED OUTPUT		VALVE 1/3 OPEN

AIR PUMP FLOW (SCFM)

ENGINE SPEED (RPM)

FIGURE 3
CO, AVERAGE FTP
20 DEG. F AMBIENT CONDITIONS

■ CO, GRAMS/MILE

CATALYST HEAT/AIR ADDITION SCHEME

Scheme	Value
NO HEAT, NO AIR	12
10/50*, NO AIR	12.5
NO HEAT, 3 MINS AIR	6.3
10/80, 3 MINS AIR	3.9
10/170, 3 MINS AIR	4.6

0 2 4 6 8 10 12 14

CO, GRAMS/MILE
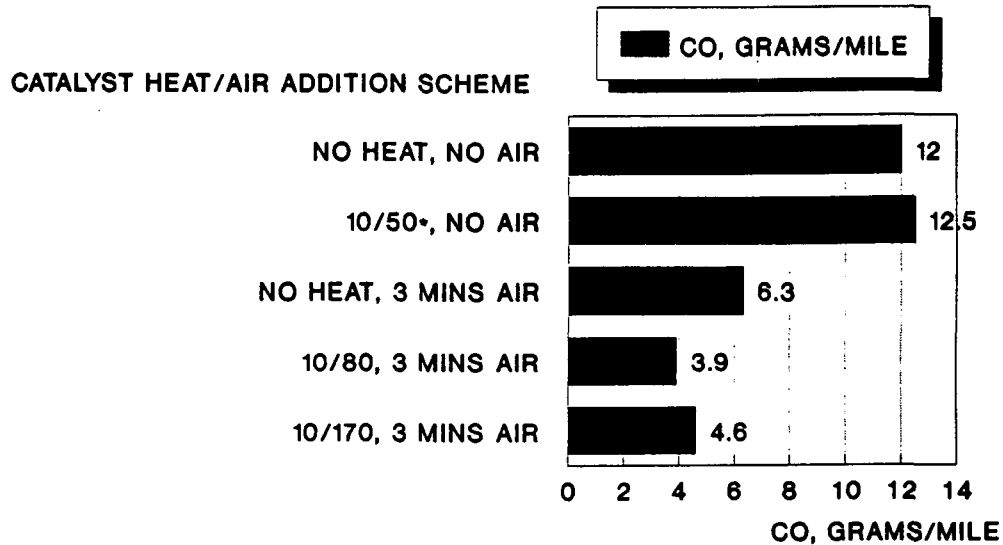
*DENOTES HEAT 10 SECONDS PRIOR TO,
50 SECONDS FOLLOWING COLD START

FIGURE 4
CO, BAG 1 OF FTP
20 DEG. F AMBIENT CONDITIONS

■ CO, GRAMS

CATALYST HEAT/AIR ADDITION SCHEME

Scheme	Value
NO HEAT, NO AIR	201.1
10/50*, NO AIR	210.8
NO HEAT, 3 MINS AIR	105.3
10/80, 3 MINS AIR	63.5
10/170, 3 MINS AIR	73.1

0 50 100 150 200 250

CO, GRAMS
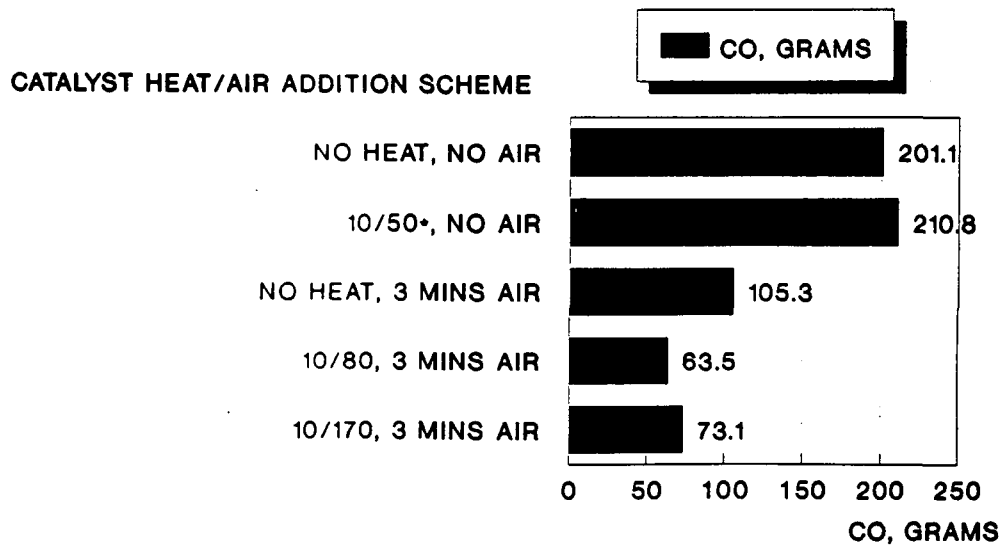
*DENOTES HEAT 10 SECONDS PRIOR TO,
50 SECONDS FOLLOWING COLD START

Resistively heating the catalyst was next attempted with the simultaneous addition of air from the air pump. Resistive heating was applied at 10 seconds prior to cold start and continued for 80 seconds following cold start. Air was admitted in front of the catalyst immediately following cold start; air addition continued for 3 minutes.

The combination of resistive heating and air addition provided a substantial improvement in CO emissions over the use of air addition alone. Bag 1 CO emissions were reduced to 63.5 grams, an almost 70 percent decrease in emissions from no-heat/no-air levels. This was also an almost 40 percent improvement over emission levels from the configuration which employed the addition of air for 3 minutes and no resistive heating.

The improvement in Bag 1 emissions translates into a substantial improvement in weighted FTP CO emissions. Average FTP CO emissions for this heated-catalyst/air-addition configuration were 3.9 grams per mile, close to the current light-duty car standard. The importance of Bag 1 emissions to weighted FTP emissions is again evident because this 3.9 grams per mile represents a 70 percent improvement from no-heat/no-air configuration levels, the same improvement realized in Bag 1 emissions.

Extending the period of catalyst resistive heating while leaving other variables unchanged did not appear to improve CO emission levels. The period of catalyst heating was increased to 3 minutes, approximately the time period relating to the production of significant quantities of CO mentioned previously. CO emissions were slightly higher in Bag 1 than those experienced with heating for 90 seconds only. Only two tests were conducted with the heating period extended to a full 3 minutes, however. The data from this limited amount of testing did not indicate that an improvement in CO emission levels would occur by merely extending the period of resistive heating beyond 90 seconds.

We are unable to account for the increase in CO emissions that occurred when the heating period was extended to 3 minutes. It was expected that emissions would have remained at the same level or decreased when the heating period was extended. This phenomena could be related to the part of the driving cycle covered by the additional resistive heating; a sharp decelleration and short idle period are included in this extended period of heating. This would not have been an expected result, however. The resistive heating/air addition schemes have not yet been optimized for this lower ambient temperature application; more work must be done to determine the cause of this phenomena.

HC emission levels over the FTP in grams per mile for the catalyst configurations tested are presented in Figure 5. Figure 6 contains average Bag 1 HC emission levels in grams.

The application of 1 minute of resistive heating without air addition had no effect on Bag 1 HC emissions at 20°F ambient conditions. Average HC emissions were 8.95 grams over Bag 1 with resistive heating only; this compares to 8.70 grams when no resistive heating or air addition was utilized. Similar to our experience with CO emissions, however, the use of additional air without resistive catalyst heating substantially reduced HC emissions from no-heat/no-additional air configuration levels. Bag 1 HC emissions were reduced to 4.56 grams by the addition of air during the first 3 minutes; this represents a 50 percent increase in efficiency from the no-heat/no-air configuration. FTP HC emissions were reduced to 0.30 grams per mile, a decrease of 44 percent from the 0.54 grams per mile experienced with the no-heat/no-air addition configuration.

The combination of resistive heating and air addition lowered HC emissions below levels obtained through the addition of air in front of the catalyst alone. Bag 1 HC was reduced to 2.88 grams with the 10/80 heating scheme; this represents reductions in emissions of 67 and 37 percent respectively from levels obtained with the no-heat/no-air and the no-heat/3-minutes air addition configurations. Average total HC emissions over the FTP were reduced to 0.20 grams per mile with this configuration; this is below the 0.25 grams per mile non-methane hydrocarbon standard referred to in the President's proposed Clean Air Act Amendments legislation.[16]

Extending the period of resistive heating from 1.5 to 3 minutes with air addition did not improve Bag 1 HC efficiency. Bag 1 HC emissions were 3.00 grams, approximately the same level as the emissions from the configuration utilizing 1.5 minutes of resistive heating. Average FTP HC emissions for the 3-minute resistive heating configuration were 0.21 grams per mile, essentially unchanged from the 0.20 grams per mile measured withheating for 1.5 minutes. Again, only two tests were conducted with the heating period extended to a full 3 minutes. The data from this limited amount of testing did not indicate that an improvement in HC emission levels would occur by merely extending the period of resistive heating beyond 90 seconds.

FIGURE 5
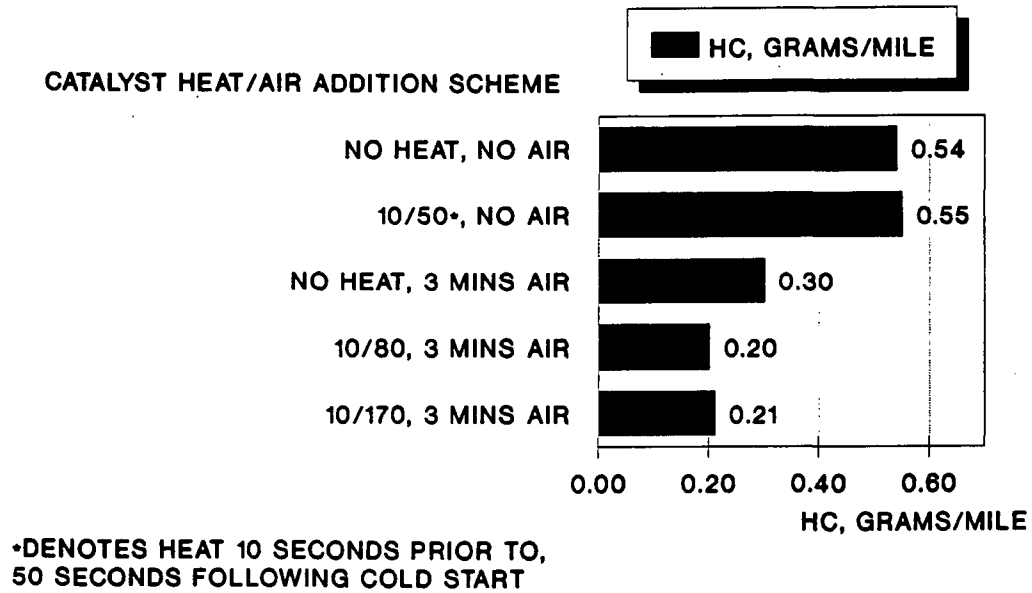## HC, AVERAGE FTP
20 DEG. F AMBIENT CONDITIONS

■ HC, GRAMS/MILE

CATALYST HEAT/AIR ADDITION SCHEME

Scheme	HC, GRAMS/MILE
NO HEAT, NO AIR	0.54
10/50•, NO AIR	0.55
NO HEAT, 3 MINS AIR	0.30
10/80, 3 MINS AIR	0.20
10/170, 3 MINS AIR	0.21

0.00 0.20 0.40 0.60

HC, GRAMS/MILE

•DENOTES HEAT 10 SECONDS PRIOR TO,
50 SECONDS FOLLOWING COLD START

FIGURE 6
HC, BAG 1 OF FTP
20 DEG. F AMBIENT CONDITIONS

■ HC, GRAMS

CATALYST HEAT/AIR ADDITION SCHEME

Scheme	HC, GRAMS
NO HEAT, NO AIR	8.70
10/50•, NO AIR	8.95
NO HEAT, 3 MINS AIR	4.56
10/80, 3 MINS AIR	2.88
10/170, 3 MINS AIR	3.00

0.00 3.00 6.00 9.00 12.00

HC, GRAMS

•DENOTES HEAT 10 SECONDS PRIOR TO,
50 SECONDS FOLLOWING COLD START
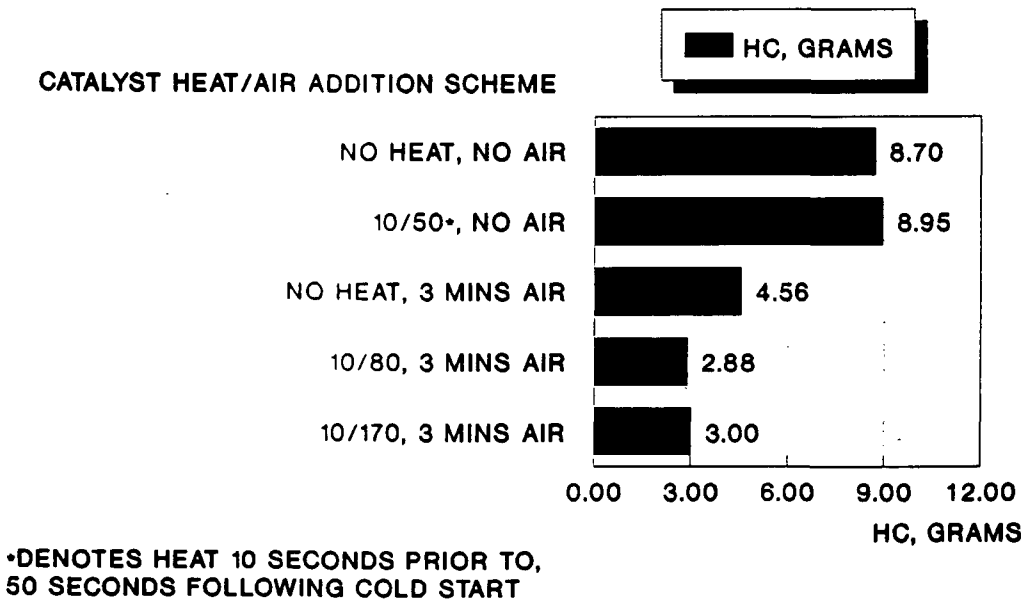
The reduction of NOx emissions at 20°F ambient conditions was not a goal of this project. We had noticed an increase in Bag 1 NOx at 20°F in our previous work when resistive heating and the addition of air was employed.[13] We therefore monitored NOx emissions during this testing to determine the effects of resistive heating and air addition on NOx levels. NOx emissions over the FTP in grams per mile for the tested catalyst configurations are presented in Figure 7. Figure 8 contains average Bag 1 NOx emission levels in grams.

The addition of air caused an increase in Bag 1 NOx emissions to approximately 2.8 grams; NOx emissions over the FTP rose to almost 0.9 grams per mile as a result. NOx emissions approaching 0.7 grams per mile over the FTP were measured in the absence of additional air. Catalyst resistive heating, in the absence of air added by the air pump, did not appear to substantially increase NOx emissions. Figures 7 and 8 may suggest that the additional air from the pump during Bag 1 may account for a substantial increase in NOx irrespective of the catalyst resistive heating scheme.
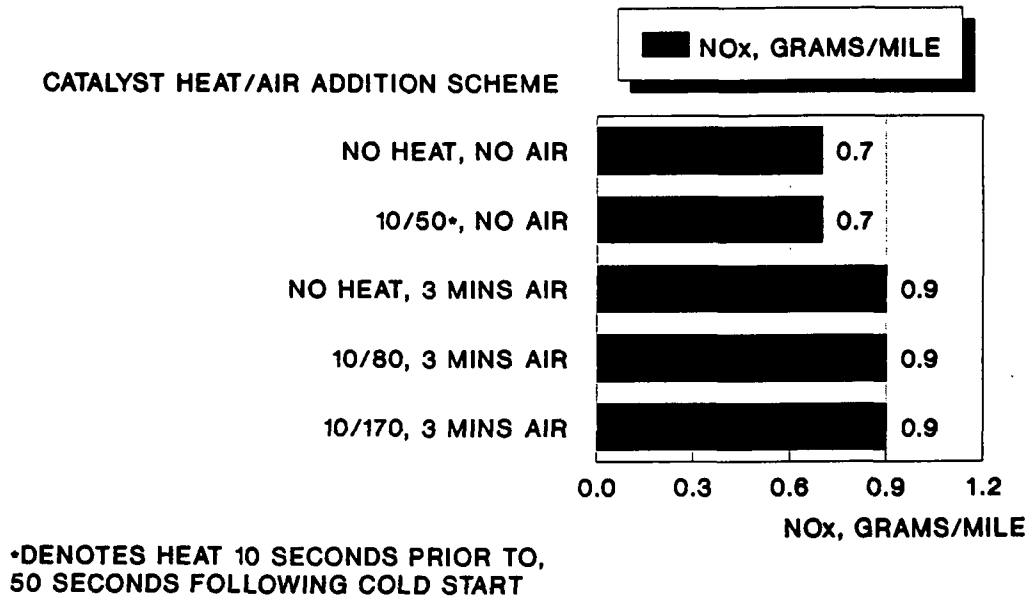
Another phenomena relating to NOx emissions that was noted during this project was an apparent increase in NOx over time from tests with the same catalyst configuration. Individual FTP test results from this work are given in Appendix B; Bag 1 emissions in grams from these tests are presented in Appendix C.

The first 4 tests listed in Table B-1 refer to catalyst testing without resistive heating/air addition. The first 2 tests were conducted at the start of the program. The third test was conducted at the midpoint of the program, and the fourth was the last test of the program.
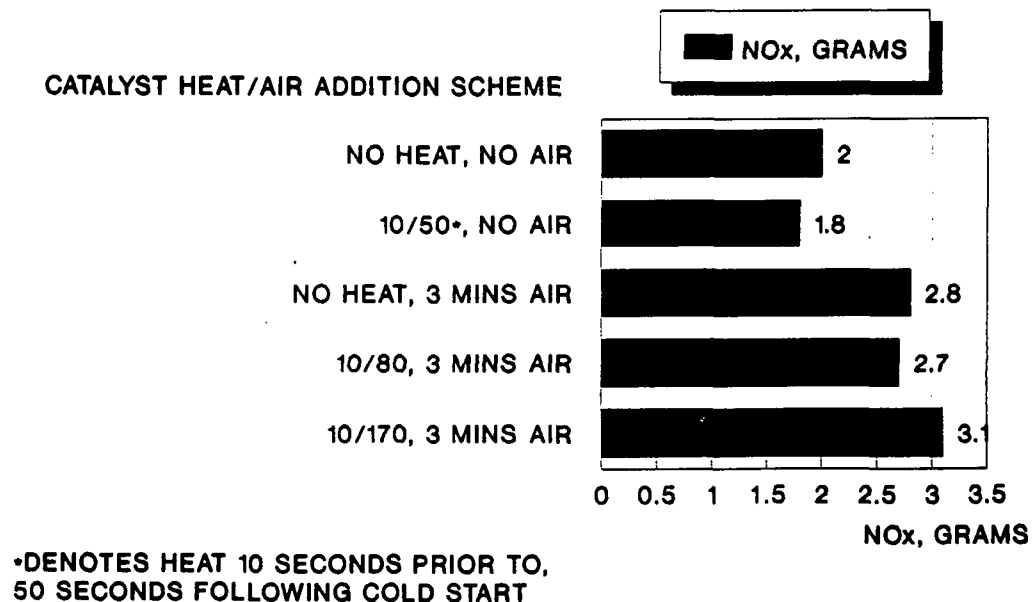
NOx levels during the first two tests were approximately 0.57 grams per mile over the FTP. NOx rose to 0.83 grams per mile during the third test conducted at the midpoint of the program. HC and CO emissions did not change substantially however, between the third and the two initial tests. NOx rose to 0.98 grams per mile on the final no heat/no air test conducted at the end of the program. HC emissions measured on this fourth test were approximately at the same level as HC emissions over the first 3 no heat/no air tests; CO was lower on this final test than previously measured levels with the same catalyst configuration.

Only a limited number of tests were conducted with the no heat/no air catalyst configuration; it may be difficult to draw conclusions from this limited amount of testing. Increasing NOx emissions may be occurring, however, because of some effect related to the noble metal catalyst itself, rather than the resistive heating. If this is the case, it would be difficult to ascertain precisely the effects on NOx formation from catalyst resistive heating/air addition.

FIGURE 7
NOx, AVERAGE FTP
20 DEG. F AMBIENT CONDITIONS

CATALYST HEAT/AIR ADDITION SCHEME

| | NOx, GRAMS/MILE |

Scheme	NOx
NO HEAT, NO AIR	0.7
10/50*, NO AIR	0.7
NO HEAT, 3 MINS AIR	0.9
10/80, 3 MINS AIR	0.9
10/170, 3 MINS AIR	0.9

0.0   0.3   0.6   0.9   1.2

NOx, GRAMS/MILE

*DENOTES HEAT 10 SECONDS PRIOR TO,
50 SECONDS FOLLOWING COLD START

FIGURE 8
NOx, BAG 1 OF FTP
20 DEG. F AMBIENT CONDITIONS

CATALYST HEAT/AIR ADDITION SCHEME

| | NOx, GRAMS |

Scheme	NOx
NO HEAT, NO AIR	2
10/50*, NO AIR	1.8
NO HEAT, 3 MINS AIR	2.8
10/80, 3 MINS AIR	2.7
10/170, 3 MINS AIR	3.1

0   0.5   1   1.5   2   2.5   3   3.5

NOx, GRAMS

*DENOTES HEAT 10 SECONDS PRIOR TO,
50 SECONDS FOLLOWING COLD START

The goal of this project at its inception was primarily the oxidation of CO and secondarily HC at lower ambients; consideration was not given to the conversion of NOx or the prevention of NOx formation. The exact noble metal loading of the catalytic material on the substrate is available from the manufacturer, Camet, Inc. Different choices for the catalytic mixture might have been possible had NOx control been used as a criteria for evaluation. The location of the catalyst in the exhaust stream and its configuration in a single underfloor can may also have substantially influenced NOx emissions.

VII. Highlights From Testing

1.   CO emissions over the FTP with the catalyst in the no resistive heating/no additional air configuration were 12.0 grams per mile. These emissions were not reduced by resistively heating the catalyst in the absence of additional air from the air pump.

The use of the air pump over the first 3 minutes of Bag 1 without resistively heating the catalyst reduced CO emissions over the FTP by almost 50 percent, to 6.3 grams per mile. Heating the catalyst for 1-1/2 minutes together with 3 minutes of air addition during Bag 1 reduced CO to 3.9 grams per mile over the FTP, an increase in efficiency of 68 percent over no resistive heat/no air configuration levels.

2.   HC emissions in Bag 1 were not reduced by catalyst resistive heating in the absence of additional air from the air pump. The 10/80 resistive heating/3-minutes air addition scheme reduced HC emissions in Bag 1 to 2.88 grams; this was a 67 percent reduction in emissions from no heat/no air configuration levels. HC emissions over the FTP were reduced to 0.20 grams per mile with this resistive heating/air-addition scheme.

3.   NOx emissions over Bag 1 of the FTP were measured at 2.0 grams with the no resistive heating/no additional air catalyst configuration. Bag 1 NOx increased to 2.8 grams with the addition of air for 3 minutes. Resistively heating the catalyst in the absence of additional air did not cause a substantial rise in NOx emissions, however.

It is unclear whether resistively heating the catalyst with the addition of excess air caused the rise in NOx emissions from no heat/no air configuration levels. During the last test of the no resistive heating/no air addition configuration, the final test in this program, NOx emissions over the FTP were measured at 0.98 grams per mile. This is a substantial increase from levels measured earlier in the program with this configuration. The control of NOx emissions should be considered a criteria for evaluation in future efforts with this technology at lower ambient temperatures.

VIII. Future Effort

We are currently evaluating this resistively heated substrate with two different catalysts (palladium-only, and a base-metal configuration) for use as light-duty methanol vehicle catalysts. This work is being conducted at 72°F ambient conditions and will be the subject of a future EPA technical report.

Future efforts may utilize catalysts better suited to take advantage of the substrate's resistive heating characteristic. For example, an optimized system for low temperature CO control may require an oxidation catalyst rather than a three-way catalyst. The position of the converter in the exhaust stream is another factor which may be addressed in a future effort. We placed the resistively-heated catalyst in the same underfloor location as the stock converter in order to compare test results [12, 13]. The underfloor location used may not be the most desirable location in the exhaust stream for the converter if the design is tailored to a specific application, such as low temperature CO control.

The use of a two-catalyst system for specific applications may also be evaluated. A resistively heated substrate catalyzed specifically for formaldehyde control might be used with a second catalyst for optimal control of a variety of emissions from a methanol-fueled vehicle. A thermostatically controlled bypass valve might also be incorporated into this system.

The air addition strategy used in this work was simplified to facilitate project completion in a minimum amount of time. The optimum air strategy for low temperature CO oxidation was therefore probably not determined here. Future work may involve refinement of the air addition strategy for lower temperature CO control.

IX. Acknowledgements

X. References

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APPENDIX A

TEST VEHICLE SPECIFICATIONS

Vehicle Type	1987 Volkswagen Golf
Fuel	Indolene clear

Engine:

Displacement	1.78 liter
Bore	8.10 cm
Stroke	8.64 cm
Compression ratio	9.0 to 1
Maximum output SAE net	85 hp at 5250 rpm
Fuel System	Continuous injection system (fuel injection) with Lambda feedback control, electric fuel pump

Transmission:

Type	Hydradynamic torque converter and planetary gearing with three forward and one reverse gears
Torque converter stall torque ratio	2.50
Torque converter stall speed	2400-2600 rpm

Gear ratios:

1	2.71
2	1.50
3	1.00
Axle	3.41
Curb weight	2340 lbs
Equivalent test weight	2500 lbs

APPENDIX B

INDIVIDUAL FTP RESULTS

Table B-1

Camet Catalyst - 20°F Ambient Conditions
Individual FTP Results

Test Number/Type	HC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)
892792/no heat, no air	0.53	11.88	353.	0.57
892810/no heat, no air	0.58	13.07	387.	0.56
893132/no heat, no air	0.51	12.73	361.	0.83
894564/no heat, no air	0.55	10.12	370.	0.98
892854/heat 10/50 Bag 1, 5/20 Bag 3 no air	0.55	11.53	360.	0.65
893128/heat 10/50 Bag 1, 5/20 Bag 3 no air	0.55	13.44	367.	0.73
892853/no heat, 3 minutes air Bag 1	0.27	5.92	362.	0.77
893133/no heat, 3 minutes air Bag 1	0.33	6.45	376.	0.90
893850/no heat, 3 minutes air Bag 1	0.29	6.56	386.	0.95
892811/heat 10/80 Bag 1, 3 minutes air Bag 1	0.20	3.51	371.	0.61
892812/heat 10/80 Bag 1, 3 minutes air Bag 1	0.21	3.98	376.	0.64
893129/heat 10/80 Bag 1, 3 minutes air Bag 1	0.21	3.96	360.	0.66
893130/heat 10/80 Bag 1, 3 minutes air Bag 1	0.20	4.12	360.	0.84
893848/no heat 10/80 Bag 1, 3 minutes air Bag 1	0.15	4.00	379.	0.96
893849/heat 10/80 Bag 1, 3 minutes air Bag 1	0.22	3.94	383.	1.09
893851/heat 10/80 Bag 1, 3 minutes air Bag 1	0.22	4.01	381.	0.95

Table B-1 (cont'd)

Camet Catalyst - 20°F Ambient Conditions
Individual FTP Results

Test Number/Type	HC (g/mi)	CO (g/mi)	CO2 (g/mi)	NOx (g/mi)
893852/heat 10/80 Bag 1, 3 minutes air Bag 1	0.20	3.49	370.	1.05
893847/heat 10/80 Bag 1, 3 minutes air Bag 1	0.16	3.71	397.	1.10
894261/heat 10/170 Bag 1, 3 minutes air Bag 1	0.22	3.98	381.	0.89
894169/heat 10/170 Bag 1, 3 minutes air Bag 1	0.21	5.15	369.	0.91

APPENDIX C

BAG 1/BAG 3 EMISSION LEVELS
OVER THE FTP CYCLE

Table C-1

Camet Catalyst – 20°F Ambient Conditions
Bag 1/Bag 3 Emission Levels Over The FTP Cycle

Test Number/Type	HC gms/gms	CO gms/gms	CO2 gms/gms	NOx gms/gms
892792/no heat, no air	8.39/0.22	199.74/1.09	1366/1186	1.07/1.70
892810/no heat, no air	9.46/0.22	222.62/1.22	1534/1223	1.55/1.63
893132/no heat, no air	8.30/0.20	215.05/1.22	1376/1183	2.26/2.56
894564/no heat, no air	8.66/0.30	166.80/2.03	1416/1204	3.19/2.79
892854/heat 10/50 Bag 1, 5/20 Bag 3 no air	8.96/0.20	194.14/0.82	1379/1169	1.65/1.92
893128/heat 10/50 Bag 1, 5/20 Bag 3 no air	8.94/0.18	227.40/1.08	1398/1197	1.87/1.93
892853/no heat, 3 minutes air Bag 1	4.14/0.23	100.00/1.01	1496/1158	1.71/2.34
893133/no heat, 3 minutes air Bag 1	5.14/0.25	107.83/1.50	1536/1227	2.99/2.57
893850/no heat, 3 minutes air Bag 1	4.39/0.23	108.01/1.90	1606/1269	3.57/2.89
892811/heat 10/80 Bag 1, 3 minutes air Bag 1	2.92/0.22	58.76/1.21	1589/1175	1.77/1.75
892812/heat 10/80 Bag 1, 3 minutes air Bag 1	3.08/0.20	67.24/0.92	1617/1182	1.83/1.74
893129/heat 10/80 Bag 1, 3 minutes air Bag 1	3.27/0.19	66.61/1.11	1576/1200	2.05/1.80
893130/heat 10/80 Bag 1, 3 minutes air Bag 1	2.92/0.22	69.98/0.90	1501/1176	2.28/2.16

Table C-1 (cont'd)

Camet Catalyst - 20°F Ambient Conditions
Bag 1/Bag 3 Emission Levels Over The FTP Cycle

Test Number/Type	HC gms/gms	CO gms/gms	CO2 gms/gms	NOx gms/gms
893848/heat 10/80 Bag 1, 3 minutes air Bag 1	2.13/0.19	65.42/1.34	1557/1218	2.64/2.92
893849/heat 10/80 Bag 1, 3 minutes air Bag 1	2.98/0.18	63.03/1.63	1522/1257	3.50/2.96
893851/heat 10/80 Bag 1, 3 minutes air Bag 1	3.26/0.19	64.23/1.48	1595/1196	3.52/2.70
893852/heat 10/80 Bag 1, 3 minutes air Bag 1	2.94/0.22	56.64/2.25	1602/1248	3.46/3.04
893847/heat 10/80 Bag 1, 3 minutes air Bag 1	2.40/0.17	59.49/1.21	1668/1209	3.58/2.49
894261/heat 10/170 Bag 1, 3 minutes air Bag 1	3.23/0.24	63.97/1.71	1587/1204	3.43/2.77
894169/heat 10/170 Bag 1, 3 minutes air Bag 1	2.77/0.24	82.21/1.80	1513/1183	2.69/2.33