Conf-9210140--1

ANL/CP--77453

DE93 002997

THE NATURAL GAS VEHICLE CHALLENGE '92: EXHAUST EMISSIONS TESTING AND RESULTS

by

William A. Rimkus
Robert P. Larsen
Michael G. Zammit
James G. Davies
Gregory S. Salmon
Robert I. Bruetsch

Center for Transportation Research
Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois, USA

Received by OSTI

NOV 1 6 1992

For Publication in

SAE Special Publications
"The Natural Gas Vehicle Challenge '92"

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Title Sheet

COVER INFORMATION FOR SAE TECHNICAL PAPERS

In order to ensure that the correct title, author names, and company affiliations appear on the cover and title page of your paper, please provide the information requested below.

PAPER TITLE
(upper and lower case):

The Natural Gas Vehicle Challenge '92:
Exhaust Emission Testing and Results

AUTHORS (upper and lower case)	COMPANY (upper and lower case)
1. William A. Rimkus	1. Argonne National Laboratory
2. Robert P. Larsen	2. Argonne National Laboratory
3. Michael G. Zammit	3. Johnson Matthey
4. James G. Davies	4. General Motors of Canada, Ltd.
5. Gregory S. Salmon	5. General Motors of Canada, Ltd.
6. Robert I. Bruetsch	6. U.S. Environmental Protection Agcy.
7.	7.
8.	8.
9.	9.
10.	10.

The Natural Gas Vehicle Challenge '92: Exhaust Emissions Testing and Results

William A. Rimkus and Robert P. Larsen
Argonne National Laboratory

Michael G. Zammit
Johnson Matthey

James G. Davies and Gregory S. Salmon
General Motors of Canada, Ltd.

Robert I. Bruetsch
U.S. Environmental Protection Agency

ABSTRACT

The Natural Gas Vehicle (NGV) Challenge '92, was organized by Argonne National Laboratory.The main sponsors were the U.S. Department of Energy the Energy, Mines, and Resources - Canada, and the Society of Automotive Engineers. It resulted in 20 varied approaches to the conversion of a gasoline-fueled, spark-ignited, internal combustion engine to dedicated natural gas use. Starting with a GMC Sierra 2500 pickup truck donated by General Motors, teams of college and university student engineers worked to optimize Chevrolet V-8 engines operating on natural gas for improved emissions, fuel economy, performance, and advanced design features. This paper focuses on the results of the emission event, and compares engine mechanical configurations, engine management systems, catalyst configurations and locations, and approaches to fuel control and the relationship of these parameters to engine-out and tailpipe emissions of regulated exhaust constituents. Nine of the student-modified trucks passed the current levels of exhaust emission standards, and some exceeded the strictest future emissions standards envisioned by the U.S. Environmental Protection Agency. Factors contributing to good emissions control using natural gas are summarized, and observations concerning necessary components of a successful emissions control strategy are presented.

1. INTRODUCTION

Natural gas has been designated as an alternative fuel by the Clean Air Act Amendments of 1990 and its use to displace imported oil is an important part of the U.S. National Energy Strategy. Its potential to meet the increasingly stringent future Clean Air Act and California Low Emissions Vehicle schedules has also increased interest in advanced NGV technology. Several U.S. vehicle manufacturers are already producing variations of current models as NGVs, but these initial vehicles are far from optimized.

The NGV Challenge '92 was a student engineering research competition sponsored jointly by the U.S. Department of Energy and its Canadian equivalent, Energy, Mines and Resources - Canada, and the Society of Automotive Engineers (SAE) with the assistance of numerous industry sponsors. It was organized by the Center for Transportation Research at Argonne National Laboratory. The 1992 competition was the second consecutive year this event was held. Twenty teams of college and university engineers accepted the challenge of advancing the state of the art of dedicated NGVs. Teams were chosen on the basis of written proposals to convert a 1991 General Motors Corporation (GMC) pickup truck to dedicated, optimized natural gas use.

The competition was structured to place an equal number of points in four areas: tailpipe emissions, dynamic performance, fuel economy, and vehicle design parameters. Exhaust emissions were measured at the Environmental Protection Agency's (EPA's) National Fuel and Vehicle Emission Laboratory (NFVEL) using both city and highway portions of the Federal Test Procedure 1975 (FTP '75) test cycle. Performance was measured by a combination of acceleration, cold start, and driveability tests. The design aspects were judged by vehicle and gas industry experts. Fuel economy was determined from the FTP testing and measured on both an urban over-the-road driving event and a steady-speed highway event.

Vehicle manufacturers are expending considerable effort to find NGV technology that uses much of the existing vehicle production hardware while attaining significantly improved emissions performance. To maintain the cost-competitiveness of their product, however, equipment changes need to be limited. For example, a completely optimized NGV might employ a turbocharger to offset inherent volumetric losses, but the costs associated with low-volume production would be difficult to justify.

Student-built vehicles in the NGV Challenge are not constrained by this production limitation. The competition encourages innovative, advanced approaches to NGV operation. One of the objectives of the event is to see how far NGV technology can be advanced and what advantages NGVs have over production vehicles. The vehicles described in this paper are perhaps most like manufacturer's advanced developmental vehicles that represent the limits of existing technology. One reason vehicle manufacturers support student engineering competitions is to identify advanced technology that may be applied in future production. The purpose of this paper is to describe the emissions-related technology demonstrated in this event that may be transferable to future production vehicles.

2. RESULTS FROM EMISSIONS TESTING

Vehicles from competing schools from the U.S. and Canada were shipped to the EPA NFVEL in Ann Arbor, Michigan. Upon arrival at the EPA's laboratory, the trucks were inspected for conformance to existing NGV safety regulations for both the United States and Canada. At this time, the vehicle hardware incorporated into the designs was identified and recorded. Because this paper concentrates specifically on the emissions performance of the student vehicles, only the conversion approaches and hardware changes used by the teams for fuel management and exhaust aftertreatment considerations are given in Table 1.

For this competition, vehicles had to demonstrate they could meet current federal light-duty truck emission standards for natural gas as determined by the EPA using the FTP '75 urban and highway testing cycle. Teams could earn competition points by exceeding this minimum if they could demonstrate lower levels of all regulated pollutants simultaneously. The complete emission chart and scoring schedule provided by the EPA is listed in Table 2. The maximum amount of points available (250) corresponds to the transitional low-emission vehicle (TLEV) exhaust standards for non-methane hydrocarbons (NMHC), carbon monoxide (CO), oxides of nitrogen (NO_X), and particulate matter (PM) for MDT3 class vehicles (3/4 - 1 ton trucks over 6000

GVWR). A total hydrocarbon (HC) standard was also included to regulate methane control.

The results of the emissions testing are given in Table 3 on a g/mi basis (the "Emissions Score" column is based on the schedule in Table 2). The fuel used for the emissions tests was commercial-grade methane, which contributes to the near absence of NMHC. Engine-out sampling was drawn before the first catalyst; in the case of dual exhaust systems, both cylinder banks were tapped and joined for a single sampling point. A comparison of tailpipe and engine-out results from Table 3 seems to indicate that the catalytic converters on some trucks actually created hydrocarbons. This anomaly is caused by using a correction factor on the flame ionization detector that was used to calculate NMHCs and is best interpreted as zero catalyst efficiency. In addition, it must be noted that the truck used to determine the gasoline baseline was not identical to the trucks supplied to the students. The gasoline baseline was determined with a medium-duty truck, with an engine that differed from the light-duty calibrated engine supplied to the schools by: a camshaft designed for more torque at a lower rpm, a lower compression ratio, components for enhanced valve train durability, and slightly different control module calibrations. Its emission control hardware was essentially the same as that for the engine supplied to the schools.

A. Hydrocarbon Emissions

Engine-out and tailpipe emission levels are shown in Figures 1 and 2 respectively, with the total FTP HC breakthroughs (1 minus catalyst efficiency) depicted in Figure 3. From Figure 1, FTP engine-out control of HC shows that 10 schools surpassed the level of the gasoline reference vehicle (<3.18 FTP g/mi). Four schools had HC engine-out levels of between 3 and 4 g/mi, while another four schools had between 4 and 7 g/mi. Only two schools recorded out of range values due to identifiable system operating problems. The lowest engine-out value was obtained by Colorado State (1.50 g/mi), which was 50% below the engine-out emission level of the gasoline reference vehicle.

The data suggest that air to fuel (A/F) control at desired ratios was attained by most schools. The relationship between engine fuel management and effective exhaust aftertreatment can be seen in Figure 2. In this figure, the gasoline reference vehicle leads the field with the lowest tailpipe HC emission, barely edging out Toronto for top honors. Five schools failed the HC maximum allowable tailpipe standard of 2.93 g/mi. In addition, the FTP tailpipe HC emissions are separated by cold-transient, cold-stabilized and hot-transient weighted emission values. Bag 1 HC levels of <0.5 FTP g/mi were achieved by the gasoline reference vehicle along with 11 of the schools. Methane control difficulties in Bags 2 and 3 prevented any natural gas vehicle from attaining the aftertreatment performance level of the gasoline system in terms of mass emission levels. For competition vehicles that surpassed the 0.8 FTP g/mi HC level, generally higher cold-stabilized emission values (Bag 2) are seen which indicates that warmed-up catalyst operating temperatures were not optimized for methane oxidation control. Although 15 schools passed the total hydrocarbon (THC) target set for the event, only four universities surpassed the 0.80 g/mi THC standard for the potential to receive the highest point allocation.

Generally, low engine-out HC values will help lower tailpipe emissions, assuming reasonable catalyst system efficiencies are achieved. These efficiencies are shown in Figure 3 as HC breakthrough. Four schools had 100% HC breakthrough corresponding to zero catalyst efficiency.. Again, the gasoline reference vehicle showed its aftertreatment strength with its 11% breakthrough (89% efficient). The best NGV HC efficiency was achieved by Toronto and Texas Tech (80%). The most favorable oxidative catalyst properties and light-off characteristics can be concluded for these systems.

Another way to analyze this data is that, compared with the gasoline reference truck, the best NGV catalyst systems in the competition would have passed twice the level of total HC emissions based on HC breakthrough, assuming equivalent engine-out HC levels. This can be attributed to the increased difficulty in oxidizing methane to CO_2 and H_2O. Figure 4 shows that the majority of the competing schools measured less than 0.1 FTP g/mi NMHC emissions due largely to the testing fuel used (commercial grade methane). The gasoline truck emissions can be seen to have 89% of its tailpipe emissions in non-methane form, whereas the majority of the natural gas systems' THC was measured as methane. In all the NGV systems, improved methane oxidation from the aftertreatment devices would be the major design criterion for improving THC control.

For the relatively fresh (0-4000 mile aged) catalyst systems, 80% catalyst efficiency was the maximum attained due in part to the methane oxidation difficulties. It is unclear whether steady-state catalyst operating temperatures or catalyst light-off properties could have been factors because catalyst temperatures were not measured as part of the competition. A second reasonable explanation for low catalyst efficiencies could be that the rich air to fuel bias selected by many schools using three-way catalysts (TWC) could have limited maximum HC conversion efficiencies. From this year's competition results, catalyst volume and composition concerns did not appear to be major factors for the teams that passed the HC portion of the FTP testing.

Alabama and Maryland. which ran on liquefied natural gas (LNG) systems, had competitive engine-out emission levels with the gasoline and compressed natural gas (CNG) vehicles, but had poorer catalyst operating efficiencies due to either catalyst stoichiometry, operating temperature, light-off deficiencies, or some combination of the three.

B. CO Emissions

Similar to the HC control data above, the CO emission results are shown in Figures 5-7. In Figure 5, engine-out CO levels show seven schools with lower CO emissions than the gasoline reference vehicle (18.1 g/mi), with superior levels achieved by Illinois Institute of Technology (2.0 g/mi). Both LNG-fueled vehicles are also included in this group. Six schools had poor engine-out CO values measuring over 39 g/mi on the FTP cycle. This indicates net rich engine operating conditions and leads to generally unfavorable exhaust aftertreatment for oxidative reactions. Two schools (Old Dominion and Texas Tech), however, were able to control their high engine out CO levels caused by rich operation with air injection (Texas Tech) and direct aftertreatment (Old Dominion).

In Figure 6, the FTP CO tailpipe results show that ten schools surpassed the gasoline reference CO emission level. Twelve schools fell below 5.0 g/mi and achieved CO levels that qualified for the maximum competition points based on the CO standards on the emission chart (Table 2). Both LNG vehicles showed aftertreatment oxidative strengths with tailpipe CO levels falling under 1.0 FTP g/mi. Again, five schools failed the CO portion of the FTP test. The Bag data shows that the majority of the CO emissions occurred in the cold-transient portion of the FTP test and that warmed-up catalyst efficiency was a problem for some schools. Again, mass emission level differences between the cold- and hot-transient portions of the FTP test is indicative of catalyst operating temperature effectiveness.

Carbon monoxide oxidation is mass-transfer limited and is dependent on catalyst volume (space velocity) and operating temperature. Figure 7 shows that the majority of the schools surpassed the catalyst efficiency of the gasoline reference vehicle with 14 schools registering over 90% CO-catalyst efficiency. Some of the remaining systems suggested possible catalyst warm-up control problems, since catalyst light-off is a key factor for CO control. As was observed in last year's competition, CO emission control is not the controlling parameter in designing effective NGV technologies.

C. NO_x Emissions

Good NO_x control from the majority of the schools can be seen from the engine-out emissions in Figure 8. NO_x formation levels ranged from 0.3 to 7.0 g/mi on the FTP test cycle. Eleven schools had NO_x levels close to, or below, that of the gasoline reference truck. Differences in engine compression ratio (combustion temperature) and fuel control stoichiometry play an important part in NO_x formation and control. Fourteen schools passed the NO_x FTP testing requirement, but five schools failed to control other aspect(s) of three-way emission control (HC and/or CO).

The tailpipe values in Figure 9 show that the catalytic reductive properties of seven schools did as well as, or better than, the production gasoline vehicle, and ten schools placed in the lowest NO_x emission category on the emission chart. As this figure shows, six schools failed on the NO_x portion of the FTP testing (>1.7 g/mi). Four of the failures were attributable to excessive engine-out levels (Ecole Polytechnique, Nebraska, Old Dominion, and West Virginia), where acceptable catalyst efficiency would not have overcome the incoming NO_x concentrations. The other two school that failed NO_x testing apparently had appropriate catalyst volume and composition descriptions (Illinois Inst. of Tech and Univ. of Michigan - Dearborn) as seen in Table 1, but probably had net lean operation resulting in poor catalyst reducing behavior.

Figure 10 shows that relatively poor NO_x conversion efficiencies were generally observed. Four schools had excellent NO_x reduction aftertreatment capabilities by maintaining an optimal catalyst environment (ideally rich or near stoichiometric) in the exhaust stream, plus correct catalyst compositions and volumes. NO_x control efficiencies of 50 to 70% were the norm for most of the competing teams. GMI showed the lowest NO_x tailpipe levels while maintaining three-way control with NO_x efficiency of 95% under FTP test conditions. Virginia, on the other hand, passed the NO_x standard with their engine-out emission level and only achieved a 7% NO_x efficiency FTP level. This was primarily due to their strategy of injecting air into the exhaust manifold to ensure catalyst oxidation.

3. ANALYSIS

For low tailpipe emissions, a properly configured catalyst system is as important as engine control systems and hardware. Variables that can affect catalyst performance are composition, operating temperature, volume, and placement in the exhaust system. The second part of this analysis focuses on how teams incorporated catalysts into their emission-control system and how those catalysts differed. Special emphasis will continue to be placed on those systems that achieved good emissions results.

Catalyst systems varied greatly in volume, configuration, and composition among the vehicles prepared by the student engineers. Electrically heated catalysts were employed on five of the trucks; six used smaller catalysts close to the exhaust manifolds, upstream of the main catalysts, for faster light-off when cold. Catalyst numbers varied from one to ten, and various methods were used for thermal management of the exhaust stream leading to the catalysts. Catalyst location(s) ranged from being close-coupled to underfloor in the stock location, and all used TWC strategies with either full-time stoichiometric operation intent or a specific dual bed function design (separate reductive and oxidative catalyst portions). In addition, six schools used programmed air injection into various points in the exhaust for more efficient operation of the oxidation portion of the TWCs.

The combined approaches of engine management and catalyst aftertreatment allowed nine schools to achieve 1991 light-duty truck (LDT) standards. Of the teams that failed to meet this benchmark, six failed on only one regulated constituent, while three failed on two constituents. Table 2 illustrates that most of the failures to meet existing standards were not by a large margin. Only two of the schools had systems so poorly calibrated that they failed three or more constituents.

Although the catalyst volume of the 20 trucks varied, the top three emission performing trucks (GMI, Northwestern, and Toronto) used moderate underfloor catalyst volumes with a combined volume per truck of 340 in.^{3}. All three used two TWCs in parallel in a dual exhaust system. Toronto had eight individual metal substrate pre-catalysts located one-half the distance from the exhaust port to the main catalysts, in addition to the underfloor converters. The pre-catalysts were welded in each of the eight branches of the tubular exhaust headers. Each port catalyst had an approximate volume of 2 in.^{3}. Toronto and GMI insulated their exhaust systems using a thermal wrap to hasten catalyst light-off and retain additional heat to assist oxidation reactions.

The accuracy of the top three teams' fuel-control systems allowed catalyst formulations to be chosen to match their A/F strategy. GMI, whose fuel management strategy was biased rich of stoichiometric, utilized a platinum/rhodium formulation only slightly different from production catalysts. Toronto's light-off catalyst formulation was principally rhodium deposited on a metal substrate, and their main TWCs were palladium/rhodium to match its rich-biased A/F ratio. Although Northwestern's catalyst formulation is proprietary, their fuel management strategy can be seen to be biased slightly lean from their engine-out results. Also, Toronto and Northwestern were two of the six schools that used secondary air injection: Northwestern injected upstream of the catalysts, and Toronto in front of the second oxidizing beds of their main catalysts on cold operation. From the results of the FTP tests, the approaches of these three schools yielded the best overall catalyst efficiencies of the competing trucks. Even the well-developed gasoline catalyst system on the control truck did not convert CO and NOx as efficiently as these three prototype vehicles.

For the top three schools, an interesting observation was that their engine-out emission levels were fairly close for HC/CO/NO_X despite differing conversion approaches. These controls, combined with different aftertreatment technologies, showed the emission-mapping strategies engineered by the three schools. GMI's apparent emphasis on NO_X reduction control came with slight HC and CO sacrifices, whereas Northwestern and Toronto went for stronger oxidation control with smaller NO_X penalties. These vehicles were designed with the best compromises for simultaneous three-way emission control, and all three schools shared the Lowest Emission Award honor.

For the other six schools that passed emissions tests, catalyst efficiency was also the key to their success. Catalyst volume on these trucks ranged from 300 to 640 in.^{3}.

Maryland used a single catalyst, Ohio State three, and the others (Texas Tech, Concordia, Virginia, and Alabama) four each. Electrically heated catalysts (EHC), with different operating strategies, were included on two of the six. Two of the others used smaller light-off catalysts located closer to the exhaust manifold.

Virginia, whose truck actually passed emissions tests on the basis of their engine-out results, used the largest catalyst volume. They employed two palladium/rhodium TWCs supplemented by two standard gasoline-type TWCs for increased THC control. Their A/F ratio was biased lean, and as a result, their catalyst efficiencies were the lowest of all the passing schools. The THC conversion was particularly low (at 30%), possibly due in part to uninsulated, high thermal inertia, cast-iron exhaust manifolds that could have contributed to late catalyst light-off.

Alabama and Maryland, the only two teams using LNG, were similarly hampered by poor THC conversion. Both of these entries were calibrated on the lean side of stoichiometric, but Maryland's was more lean, causing excessive NO_X production despite an innovative charge-air intercooler system, which used the latent heat of the vaporizing LNG to cool the intake charge. Alabama employed both an EHC and air injection upon cold start, and both LNG teams insulated their exhaust systems all the way to the catalyst inlet.

The remaining three teams that passed emissions tests (Concordia, Ohio State, and Texas Tech) used specific hardware to achieve quick catalyst light-off. Concordia and Texas Tech had small "pup"-type converters immediately after the exit to their tubular exhaust manifolds. The supercharged Texas Tech engine had a strongly biased rich A/F ratio. Their combination of heated exhaust gas oxygen (EGO) sensor and air injection in front of the light-off catalysts produced good catalyst efficiencies in the two TWCs, yet the Texas Tech A/F ratio was so far from stoichiometric over the FTP that they could not earn all the available points. Concordia used equipment similar to Texas Tech; a combination of a pair of light-off catalysts, trimetal (Pt/Pd/Rh) TWCs, air injection, and a heated EGO sensor produced catalyst efficiencies equal to those for the gasoline-powered truck for regulated exhaust constituents. The air injection system on Concordia's vehicle was selectively moved via an adjustable distribution system to locations before or after the light-off catalysts, depending on the exhaust temperature. Ohio State used a pair of EHCs in front of a single methane-formulated TWC to achieve good results.

Some of the results for the 11 schools that did not pass the 1991 emissions standard can be explained by the specific problems encountered. Ecole Polytechnique could never achieve satisfactory A/F control. Their vehicle was using a multi port fuel-injected engine, but they received their injectors too late to properly calibrate the system. New York Institute of Technology's turbocharged engine had obvious fuel-control problems, causing their vehicle's A/F ratio to be far too rich. California State-Northridge's truck was handicapped by fuel-control problems from a custom fuel-injection system as well as EHCs that were not functioning.

The remaining eight schools used many of the same techniques as the schools that passed the emissions test. However, their A/F ratios still ended up far enough away from stoichiometric that their catalyst aftertreatment systems could not make up for it. The catalyst volumes, ranging from 170-460 in.^{3}, were slightly lower than the volumes for the trucks that passed. All had exhaust heat retention, either with insulation or, in the case of Tennessee, parallel EHCs. Notably, Tennessee was the only non-passing school that used air injection. The A/F ratio orientations from stoichiometric effected by the remaining eight schools did not seem to matter, as four of these were biased rich, and four were biased lean. These results indicate that for successful emissions control, A/F ratios must be very precisely controlled to be capable of providing an input to the catalyst system that can produce the extremely low levels of emissions that will be required

Superior emission control requires that the engine management and the catalyst aftertreatment systems work together as a system. Engine management systems have to overcome disadvantages specific to dedicated natural gas operation: a slower flame speed than gasoline, which requires a modified spark curve; and a fuel with different physical properties, which requires a revised fuel-control strategy. Mechanical components, too, need to be modified for natural gas use: a fuel system designed for a high-pressure gaseous fuel and engine modifications to take advantage of the higher-octane natural gas.

However, for good emissions results, natural gas-powered engines require many of the same basic operating parameters as a gasoline-fueled engine: accurate spark timing, a strong and consistent spark, good cylinder-to-cylinder distribution of the A/F mixture, precise A/F ratio control, strategies to control NO_X formation, and an efficient exhaust catalyst.

The trucks that were successful in earning points in the emissions scoring had an average compression ratio of 11.5:1. This ratio is slightly higher than the overall average of 11.3:1 and is a full 2.3 points higher than the stock gasoline engine. This increased compression was obtained by reducing combustion chamber volume to a range of 58 to 77 $cm.^3$. Note that the stock truck had a cylinder chamber volume of 75 $cm.^3$.

Sixteen of the 20 teams chose cylinder heads with advantageous characteristics other than a smaller combustion chamber. All of the new cylinder heads had larger port volumes for increased intake flow. Many teams machined or polished the surface in their heads to smooth rough flow transitions. These changes helped improve volumetric efficiency, an especially important consideration given the gaseous form of the fuel.

Other practices to compensate for the lower flame speed of natural gas included modified spark timing or modified combustion chambers (including the piston face and cylinder head volume). Sixteen teams opted to change camshafts. Low levels of valve overlap were employed in most of these camshaft designs to help extend in-cylinder residence time, which promoted more complete combustion. The smaller, closed combustion chamber cylinder head design used in many of the engines also produced a short flame path, which helped to ensure complete combustion from the slower burning fuel. Only four of the teams chose to keep the stock gasoline camshaft. Of these, three utilized an electronic accessory attached to the electronic control module (ECM) that advanced spark timing over stock. The fourth ran always lean with high exhaust gas recirculation (EGR), to reduce unburned HC and control NO_X.

In most cases, the trucks with the best engine-out emissions results had improved their volumetric efficiency by one or more of the following methods: higher lift and longer duration camshaft, larger valves than stock, larger or ported intake passages, and/or tuned intake and exhaust manifolds. Increased volumetric efficiency, besides its other obvious benefits, produces a strong, steady vacuum signal at the throttle plates. This increased vacuum aided the top three overall performing vehicles, whose carbureted systems relied on that accurate vacuum source to meter the majority of fuel demanded by the engine. Tuned intake and exhaust systems also contributed to superior cylinder-to-cylinder mixture distribution. Thirteen of the sixteen teams without turbochargers employed tuned tubular exhaust manifolds.

Spark timing was handled on most of the trucks through a recalibrated stock ECM. General Motors provided information for students to recalibrate spark (as well as fuel, idle air, and transmission torque converter lock-up) tables in the ECM. Eight teams took advantage of this method. All of the teams with relatively good fuel control, as determined by engine-out figures, used the GM ECM in stock or slightly modified form for the purpose of spark control. Additionally, two of the three best-performing schools (Northwestern and GMI) used the GM ECM for fuel control. GM's stock ECM, at a high state of development and with its block learning algorithms, offers many advantages compared with a system requiring custom calibration programming.

Control of the A/F ratio was accomplished primarily through a feedback loop to adjust fuel delivery on the basis of oxygen content of the exhaust. An oxygen sensor similar to that on a production truck was used for this function. Heated oxygen sensors were used in three of the vehicles to hasten the switch from open- to closed-loop operation and to improve their accuracy and reduce their response time. The three teams who chose not to use the feedback loop biased their A/F ratios very lean to keep HC levels low. Unfortunately, the resulting increase in NO_X over the FTP cycle overwhelmed the reduction capacity of their catalysts.

The success of a closed-loop system, then, depends on how precisely the system can maintain the A/F ratio. For the eight gaseous fuel-injected systems, feedback information from the exhaust oxygen sensor instructed the A/F computer to vary pulse widths controlling the length of time the injectors were open. Only two of the injected systems were able to do this accurately enough to keep engine-out emissions at a low level.

The remaining trucks used a traditional carburetor-style gas mixer in a closed-loop system. A combination of intake manifold pressure and exhaust oxygen sensor output is the input to the A/F control computer. Although the carburetor is set up to give near stoichiometric A/F ratios for almost all engine conditions, exact calibration is effected by the A/F computer either by adjusting the outlet pressure of the final stage of regulation before the carburetor or by activating small "trimming" fuel injectors to add just enough extra fuel (usually the last 5% or less) for precise control. The pressure-regulation approach relies on the mechanical actuation of either a vacuum- or servo-operated valve controlling gas regulator pressure. Several of the teams used the standard gasoline-throttle body fuel injectors to trim the A/F mixture with good results; the trimming injectors react much faster than the carburetors can to the transient conditions found in the FTP cycle.

4. OBSERVATIONS/CONCLUSIONS

In the final analysis, it was a substantial achievement that so many competing trucks, built primarily by undergraduate students, could produce such impressive emissions results. Although the ultimate emissions performance potential of the trucks (given their unlimited ability to use exotic components) might have been greater in the hands of experienced industry engineers with state-of-the-art facilities, the results produced by the students were impressive in more than half of the trucks.

The overall results may have been affected by the unusually high methane content of the fuel (an official emissions certification fuel does not exist for natural gas). Originally, plans had been to use natural gas representative of the United States' 90th percentile natural gas composition for the event. Commercial grade methane (100% methane) was used instead, due to availability problems. This fuel did not have the usual number of higher order hydrocarbons, and the calibration systems of the trucks may not have been able to adapt. Catalyst formulation may also have depended upon higher hydrocarbons to obtain better conversion efficiency.

The problem of varying natural gas fuel quality is not unique to the NGV Challenge. Two major obstacles to good performance and emissions from NGVs are fuel variability and the inability of both the engine management and exhaust aftertreatment systems to cope with that variability. One team (Northwestern) developed an approach that could greatly alleviate this problem. They arrived at the event with a prototype natural gas quality sensor that measures the percent of methane in the fuel stream as it enters the engine. This is not unlike sensors being used in variable alcohol/gasoline production vehicles today.

Before any of the features demonstrated in the NGV Challenge '92 can be used on production NGVs, cost effectiveness must be demonstrated. Turbochargers, tuned exhaust manifolds, multiple light-off catalysts, and other components add substantially to the cost of a NGV that will already have the cost of storage tanks, high-pressure lines and fittings, regulators, and other natural gas-specific components amortized into its selling price. Such labor-intensive operations as the special cylinder-head machining seen on some of the competing vehicles is not feasible in a production environment.

An additional complication not addressed in this event is the eventual degradation of emissions-systems components that are required to last up to ten years or 100,000 miles for emission certification. While manufacturers need to demonstrate vehicles that hold their calibrations and maintain emissions levels for this mileage, the competition trucks were tested with relatively fresh catalyst systems. Positioning catalysts at the exits of the exhaust manifold (as most all of the competing trucks did) provides improved emissions performance initially, but may be detrimental to catalyst longevity. Catalyst and system operating temperature issues fell beyond the scope of the competition, but catalyst thermal degradation issues would be an integral part of NGV vehicle design programs.

Although the potential for low emissions was demonstrated by the results of this competition, many questions remain unanswered regarding long-term emissions performance. Natural gas catalytic converter performance and durability from these vehicles impose unique requirements on exhaust aftertreatment systems. Methane conversion, which is very difficult for conventional automotive catalysts, may be required, depending on future regulatory direction. Three-way catalyst operating windows for simultaneous conversion of HC, CO, and NO_X are considerably more narrow with natural gas-engine exhaust. While this study has demonstrated acceptable fresh converter performance, aged performance remains an industry concern. Catalyst issues pertaining to thermal and chemical degradation as they relate to catalyst deterioration based on durability cycle testing is the next step for the development of commercially available natural gas-fueled vehicles.

On the basis of the results of this competition, a number of generalizations about the successful attainment of future emission standards for NGVs can be made. First, precise control of A/F ratios using a closed-loop control strategy is essential. This control must be capable of maintaining the desired A/F ratio at or slightly rich of stoichiometry within one percent. The mechanical aspects of the fuel delivery system are not as important as the ability to respond quickly and accurately to maintain A/F ratios within this narrow window. Several different configurations for fuel introduction showed adequate performance to meet current emission standards when controlled precisely: special high pressure gaseous fuel injectors, carbureted systems using trim injectors or solenoid-controlled pressure regulators, or even fuel injectors originally designed for liquid fuels.

Second, a revised catalyst loading biased towards improved methane oxidation will likely be a necessity for attaining future NGV emissions standards. The loading of this catalyst will be similar to the new generation of catalysts currently being developed for future ever-tightening gasoline emissions standards. The location of the main catalysts will probably remain underfloor, but might be used in conjunction with smaller light-off catalysts mounted closer to the engine. Secondary air injection will likely be employed, especially because this practice is already in production with gasoline-powered vehicles.

Third, the degree of complexity and amount of integration of the engine-control system required to deliver very low emissions, excellent driveability and acceleration performance, good fuel economy, and ten-year reliability is substantial. Thousands of hours of development were necessary to achieve these attributes for existing production-engine controllers. Teams that used a production-based ECM were able to take advantage of this development, and the results showed it. Few schools have the equipment, or engineering students the experience, to approach the engine calibration expertise of a vehicle manufacturer. Nonetheless, this level of sophistication and development will be necessary for NGVs of the future to meet the demands of emissions standards and quality-conscious consumers. If the gasoline-powered control truck was competing in the event, it too would have achieved the 250 point maximum score.

The efforts of the participating schools helped define the performance limits of dedicated NGVs and showed their potential for being a significant part of North America's transportation and clean air future.

5 ACKNOWLEDGMENT

Work supported in part by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, under contract W-31-109-Eng-38.

Table 1
Natural Gas Vehicle Challenge '92 Vehicle Attributes

		FUEL CONTROL				CATALYST		
School	C.R.	ECM (non-fuel control)	A/F Computer	Fuel Metering	Other	Number & Type	Manufacturer	Volume (in^3)
Alabama	12.5:1	GM Remap	Impco	Impco mixer	Programmable electric air pump injection to J-M cats	2 EHC 2 TWC	Camet J-M	2 × 24 2 × 215
Col St. U.	11.9:1	GM Remap	GM & Sycron Tech	2 × S&S	Digitally controlled EGR	2 TWC	Englehard	2 × 147.5
Concordia	13.0:1	Stock	GM & Impco	Impco 425 w/feedback	Heated lambda sensor; air injection on cold operation	2 light-off 2 TWC	Degussa ACR (Pt/Pd/Rh)	2 × 63 2 × 170
CSUN	14.7:1	Electromotive	CSUN-developed control	8 × BKM	None	2 EHC 2 TWC	EMITEC J-M	2 × 28 2 × 170
Ecole Polytechnique	12.7:1	GM Remap	Custom Mitsubishi-based controller	8 × BKM	No EGR; multi-layered zirconia EGO sensor	2 TWC	ASACC	2 × 170
GMI	9.0:1	GM Remap	GM & Impco	Impco w/Fuel Pilot	None	2 TWC	ACR (Pt/Rh)	2 × 170
IIT	9.0:1	Stock	GM & Superfix	ANGI II mixer	Higher flowing EGR valve	1 TWC	ASACC	1 × 460
Maryland	10.9:1	FMS	FMS	OHG Carburetor	Intake charge intercooled w/LNG vaporization	1 TWC	ASACC	1 × 300
Nebraska	9.8:1	Electromotive	DFI System	16 × Bosch	None	2 TWC	ASACC	2 × 170
Northwestern	13.0:1	GM Remap	GM	16 × Bosch	Air injection on cold start into manifolds; externally-fed EGR w/in-line catalyst	2 TWC	ASACC	2 × 170

Table 1 (Continued)

		FUEL CONTROL				CATALYST		
School	C.R.	ECM (non-fuel control)	A/F Computer	Fuel Metering	Other	Number & Type	Manufacturer	Volume (in^3)
NYIT	9.8:1	Electromotive	Closed loop	Gaseous Fuel Metering by Clean Fuels	Elec. heated pre-cats	2 EHC 2 TWC	EMITEC J-M	2 × 28 2 × 170
Ohio State	11.1:1	Stock GM & GFI	GFI	GFI injectors	Elec. heated cats initiated by door opening and/or ignition	2 EHC 1 TWC	Camet ASACC	2 × 14 2 × 170
Old Dominion	10.8:1	Electromotive	Closed Loop	Electromotive mixer	None	2 TWC	ACR	2 × 170
Tennessee	9.6:1	GM Remap and modified MAP sensor	Impco ADP	Impco 300A mixer	Air injection; Post-cat EGO input; Higher flow EGR valve	2 EHC 1 TWC	Camet ASACC	2 × 14 1 × 170
Texas-Austin	11.0:1	None	Autotronics 4046	OHG 450 mixer	Heated EGO sensor; 2 x EGR valves	4 TWC	Englehard	2 × 85 2 × 140
Texas Tech	10.9:1	Electromotive	Electromotive	6 × BKM	Externally fed and cooled EGR; Electric air-injection pumps	2 light-off 2 TWC	ASACC ASACC	2 × 63 2 × 200
Toronto	10.6:1	GM Remap	Motorola M68HC11EVB	Impco 425	Air injection	8 pre-cats 2 TWC	Unknown ASACC (Pd/Rh)	8 × 2 2 × 170
U of M-Dearborn	11.4:1	Stock modified to run fuel inj.	Unknown	Holley Pro Jection	None	2 light-off 2 TWC	ASACC ASACC	2 × 32 2 × 251
Virginia	12.5:1	Stock w/Autotronics Recurve Box	Autotronics	GEI CL-2000 mixer	Air pump inj. into exh. manifold	2 TWC 2 TWC	ASACC (Pd/Rh) Gasoline	2 × 150 2 × 170
West Virginia	12.5:1	GM Remap	No computer	Impco 425A	None	2 TWC	J-M	2 × 170

Abbreviations:						
	J-M	Johnson-Matthey	EHC	Electrically heated catalyst	CR	Compression ratio
	ASACC	Allied Signal Automotive Catalyst Co.	TWC	Three-way catalyst	FMS	Fuel Management Systems
	ACR	AC Rochester	ECM	Engine control module	S&S	Stewart & Stevenson
			EGO	Exhaust gas oxygen		

Table 2

1992 SAE Natural Gas Vehicle Challenge Emissions Chart*

Pollutant	Any Pollutant Greater Than	Controlling Pollutant Equal to or Less than					
THC (g/mi)	2.93	2.93	2.69	2.46	1.98	1.51	0.80
NMHC (g/mi)	0.67	0.67	0.64	0.61	0.55	0.48	0.39
CO (g/mi)	10.00	10.00	9.40	8.90	7.80	6.70	5.00
Idle CO (%)	0.50	0.50	0.50	0.50	0.50	0.50	0.50
NOx (g/mi)	1.70	1.70	1.60	1.60	1.40	1.30	1.10
PM (g/mi)	0.13	0.13	0.13	0.13	0.13	0.12	0.12
Your score	0.00	25.00	50.00	75.00	125.00	175.00	250.00

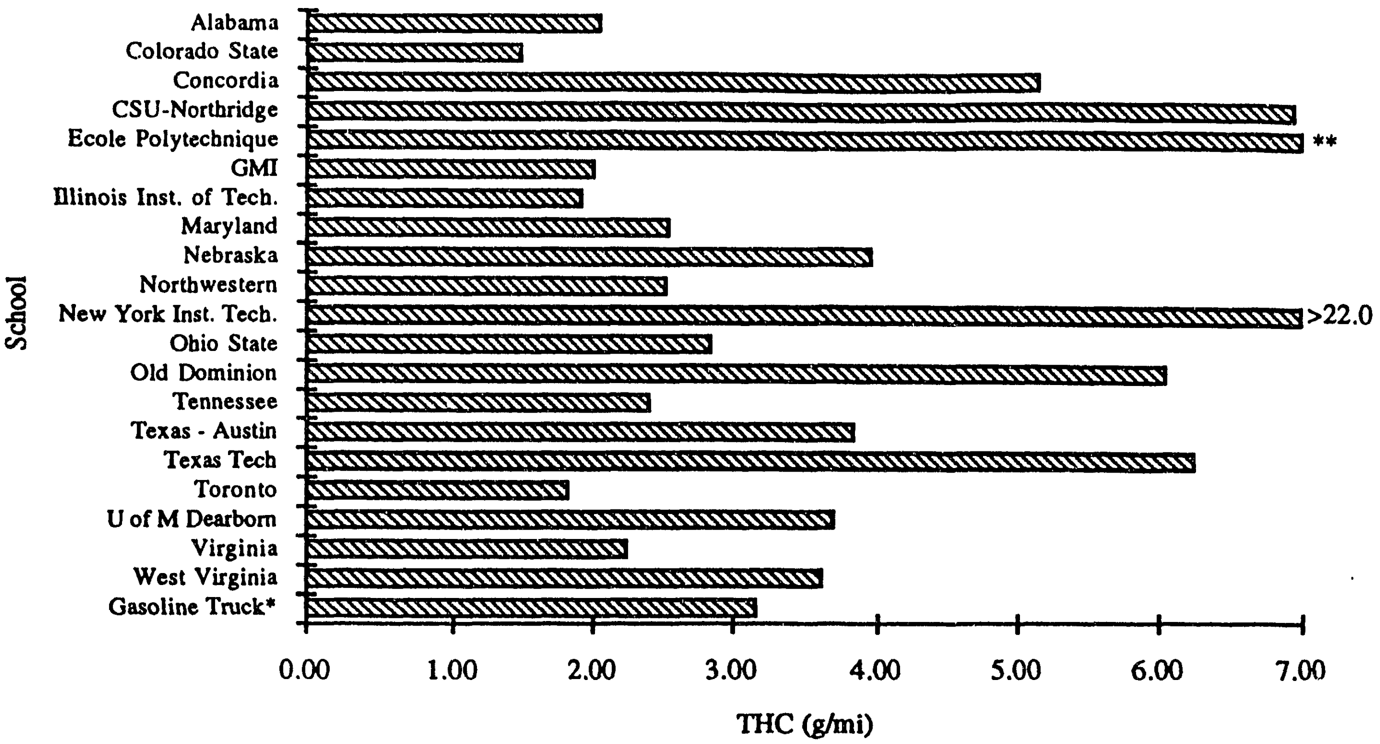
* ASTM roundoff rules apply.

LEGEND:
THC = total hydrocarbons
NMHC = non-methane hydrocarbons
CO = carbon monoxide
NO_x = oxides of nitrogen
PM = particulate matter

Table 3
1992 NGV Challenge
Emissions Results

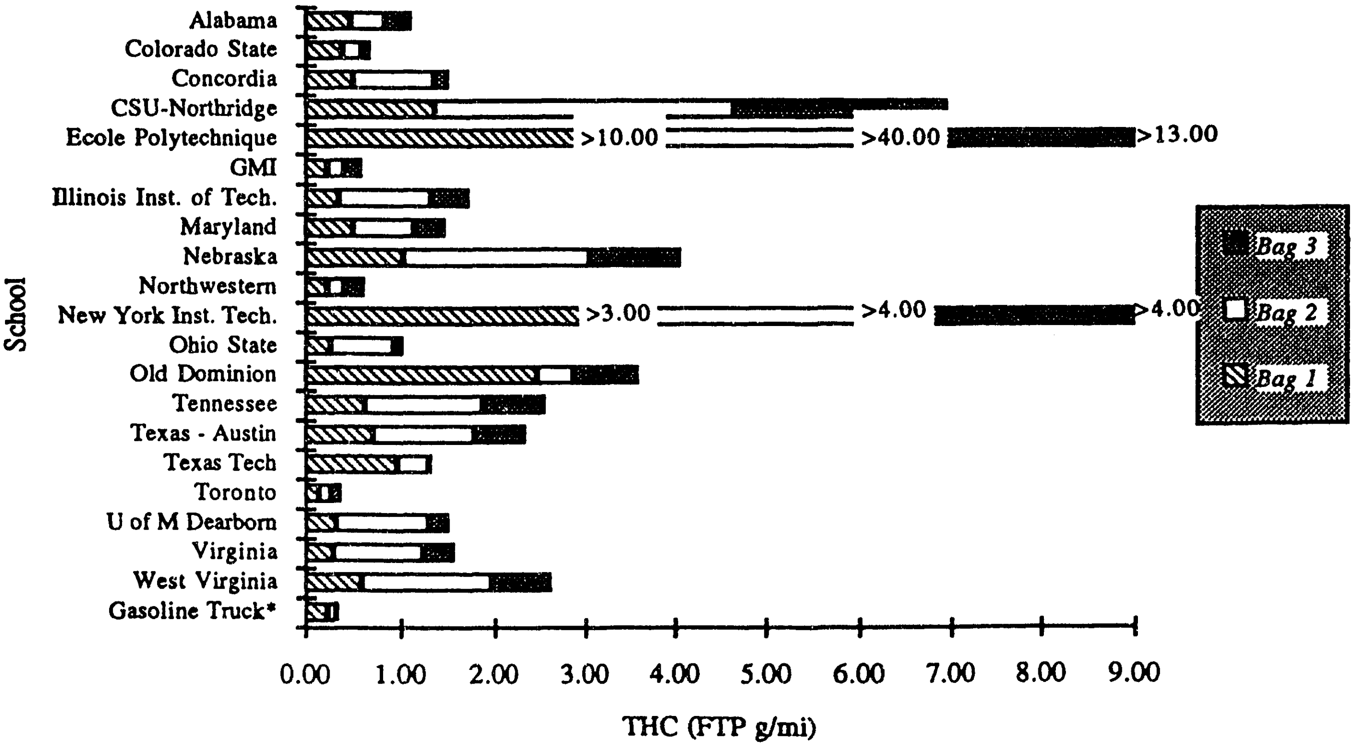
Team	FTP Weighted Emissions					FTP Engine Out			Idle	Emissions	Control
	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO^2 (g/mi)	THC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO (%)	Score	Pollutant
Alabama	1.11	0.01	0.8	1.1	632	2.06	15.2	1.8	<0.1	175	THC
Colorado State	0.69	0.01	9.1	0.3	682	1.50	20.8	0.7	1.8	0	ICO
Concordia	1.51	0.04	3.2	1.1	510	5.16	26.0	2.3	<0.1	175	THC
CSU-Northridge	6.99	<0.01	46.8	0.2	537	6.94	105.7	2.4	0.3	0	CO
Ecole Polytechnique	OOR	OOR	42.6	3.0	503	OOR	98.6	7.0	0.6	0	CO
GMI	0.59	0.01	2.0	0.1	523	2.02	22.1	1.9	<0.1	250	
Illinois Inst. of Tech.	1.75	0.07	0.1	3.4	459	1.92	2.0	3.5	<0.1	0	NO_x
Maryland	1.49	0.02	0.4	1.3	628	2.55	11.9	3.3	<0.1	175	NO_x
Nebraska	4.06	0.08	1.4	6.3	482	3.95	12.1	6.4	<0.1	0	NO_x
Northwestern	0.65	0.01	0.2	0.7	491	2.53	18.3	2.2	<0.1	250	
New York Inst. Tech.	12.45	3.27	54.6	<0.1	657	22.10	140.9	0.3	–	0	CO
Ohio State	1.03	0.01	4.9	0.2	531	2.85	27.4	2.0	<0.1	175	THC
Old Dominion	3.61	0.41	5.7	2.6	542	6.04	67.4	4.9	<0.1	0	NO_x
Tennessee	2.57	0.06	17.0	1.3	490	2.43	31.4	2.4	<0.1	0	CO
Texas - Austin	2.37	0.05	14.5	1.4	590	3.84	39.2	4.2	<0.1	0	CO
Texas Tech	1.31	<0.01	5.2	1.1	750	6.25	64.5	2.5	<0.1	175	CO
Toronto	0.39	0.01	0.9	0.7	585	1.83	23.8	2.3	<0.1	250	
U of M Dearborn	1.52	0.02	0.3	2.1	480	3.71	12.4	3.2	<0.1	0	NO_x
Virginia	1.58	0.04	0.2	1.3	561	2.26	7.6	1.4	<0.1	125	THC
West Virginia	2.66	0.09	0.2	6.7	474	3.63	8.4	7.1	<0.1	0	NO_x
Gasoline Truck	0.36	0.32	3.3	0.7	718	3.18	18.1	2.2	<0.1	--	--

OOR = Out of Range



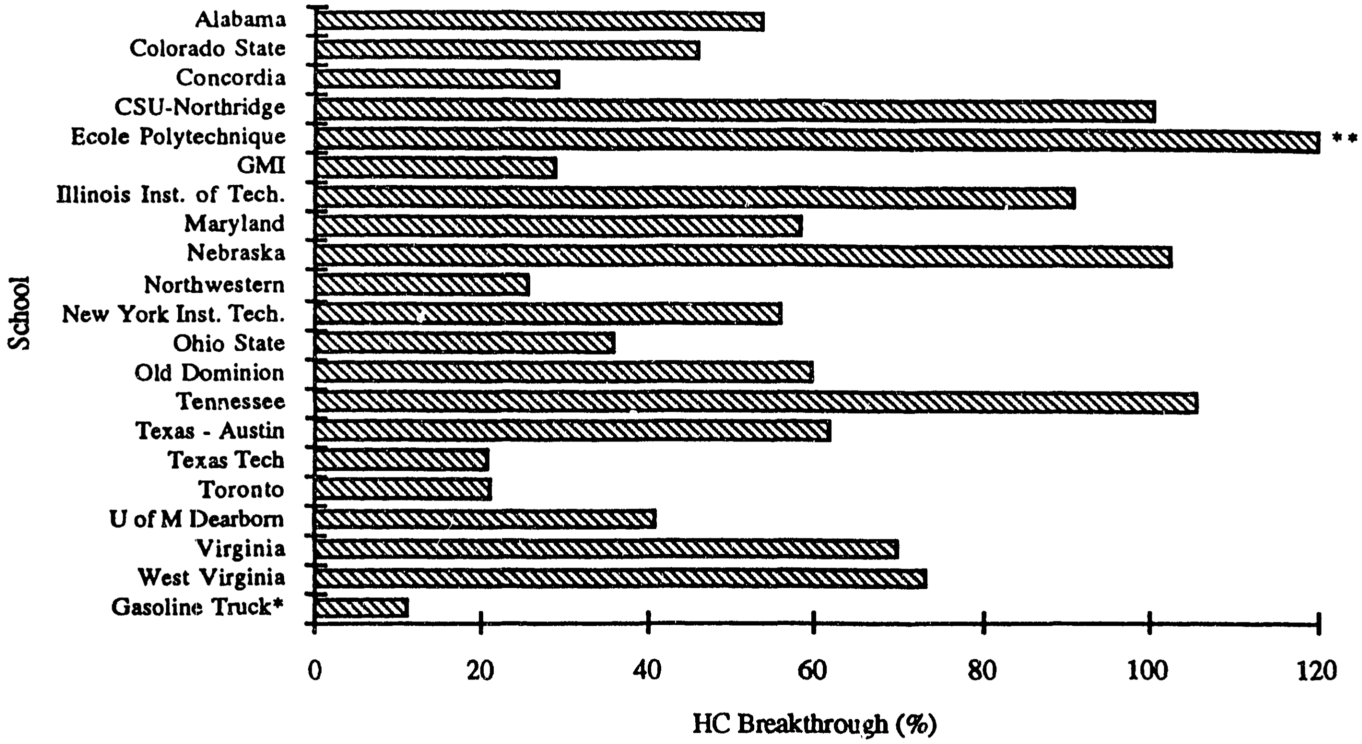
* Gasoline Truck included for comparison ** Out of Range

Figure 1. Total Hydrocarbon (THC) Engine Out Emissions



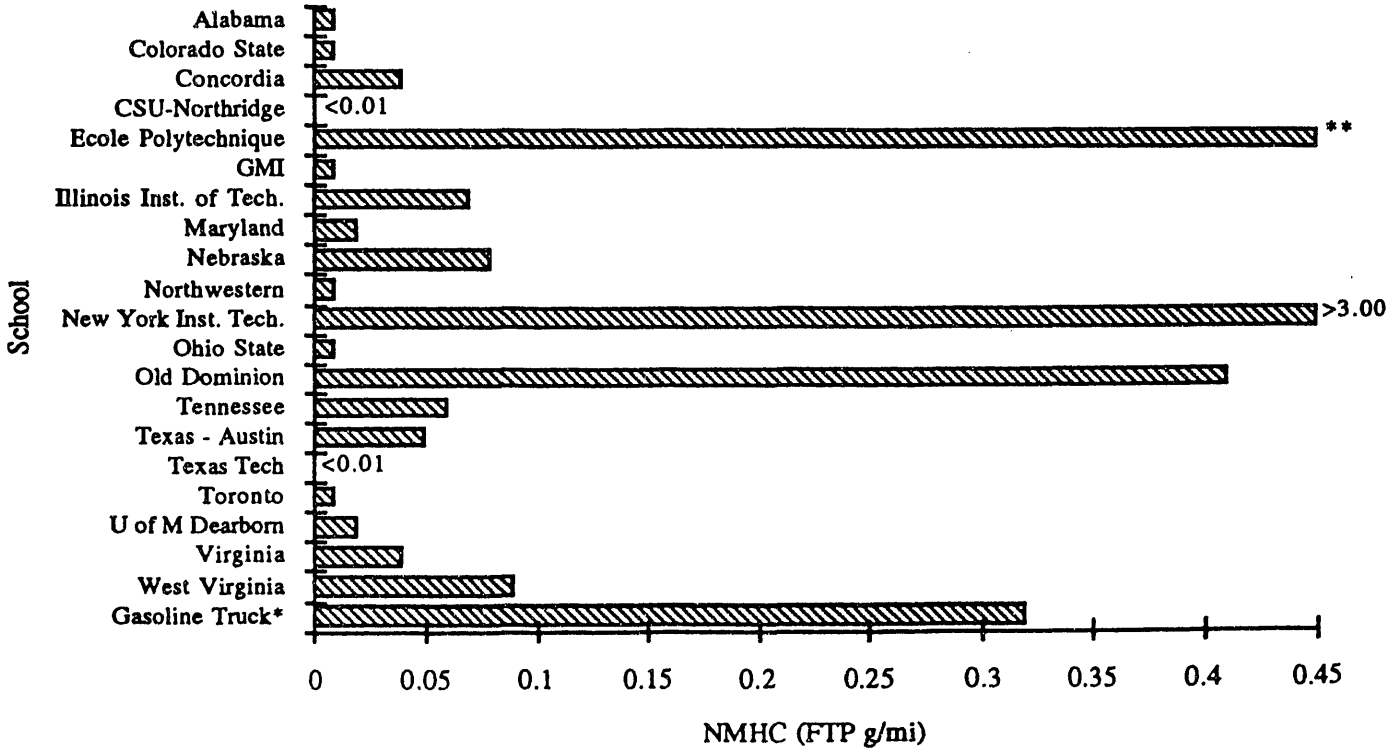
* Gasoline Truck included for comparison

Figure 2. Weighted Total Hydrocarbon (THC) Tailpipe Emissions



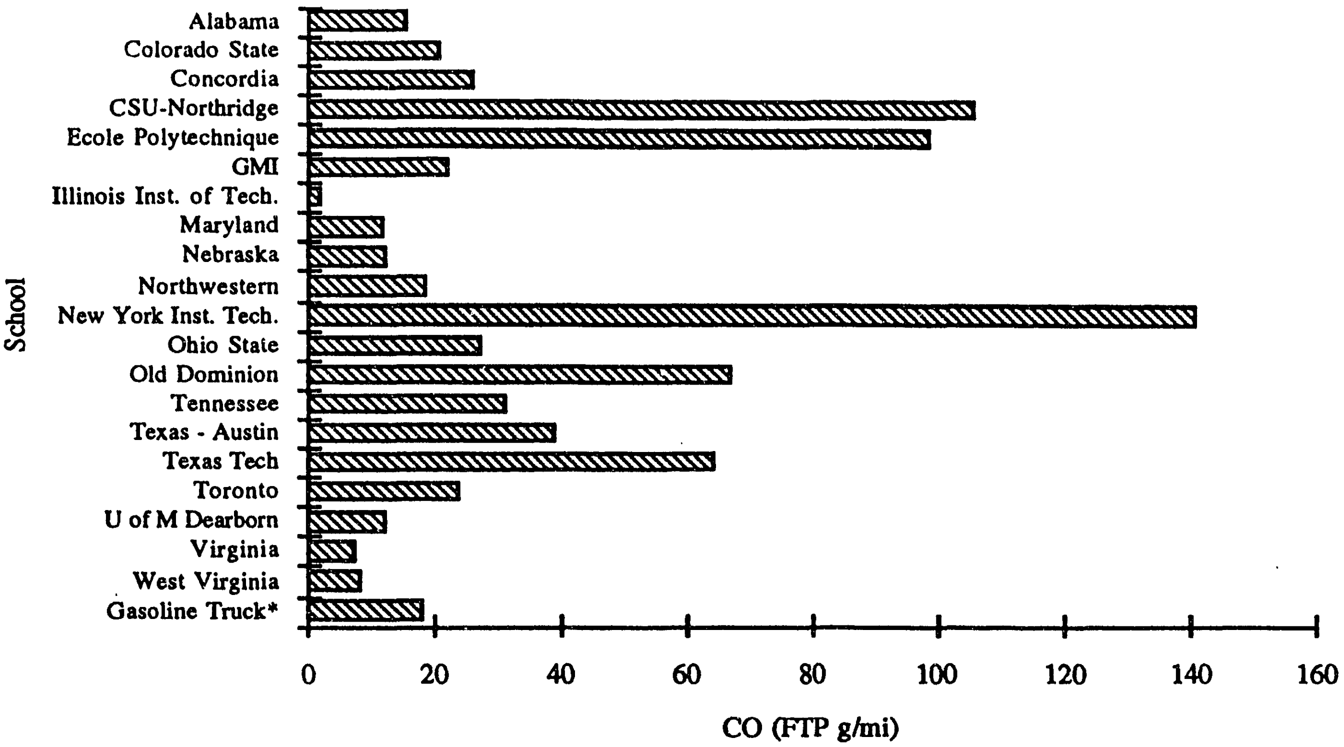
* Gasoline Truck included for comparison ** Out Of Range

Figure 3. Hydrocarbon (HC) Catalyst Efficiency



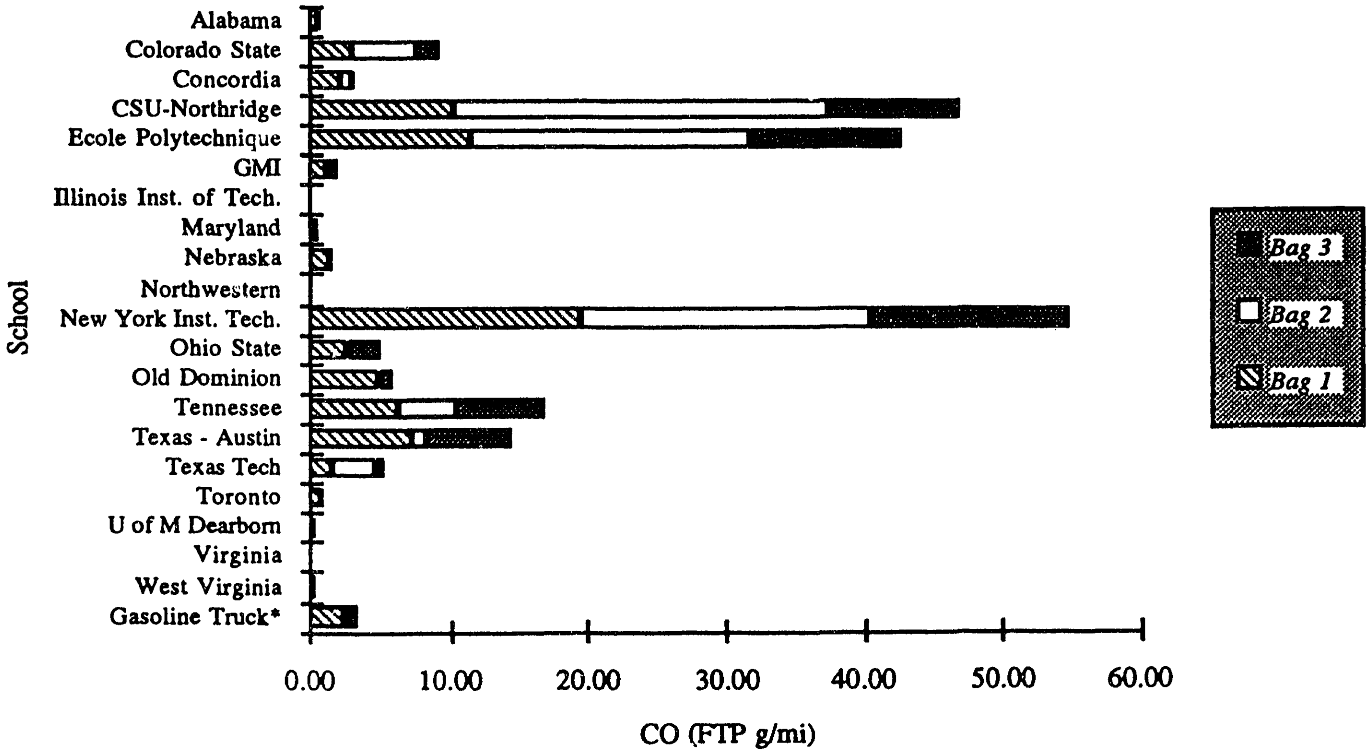
* Gasoline Truck included for comparison ** Out Of Range

Figure 4. Weighted Non-Methane Hydrocarbon (NMHC) Tailpipe Emissions



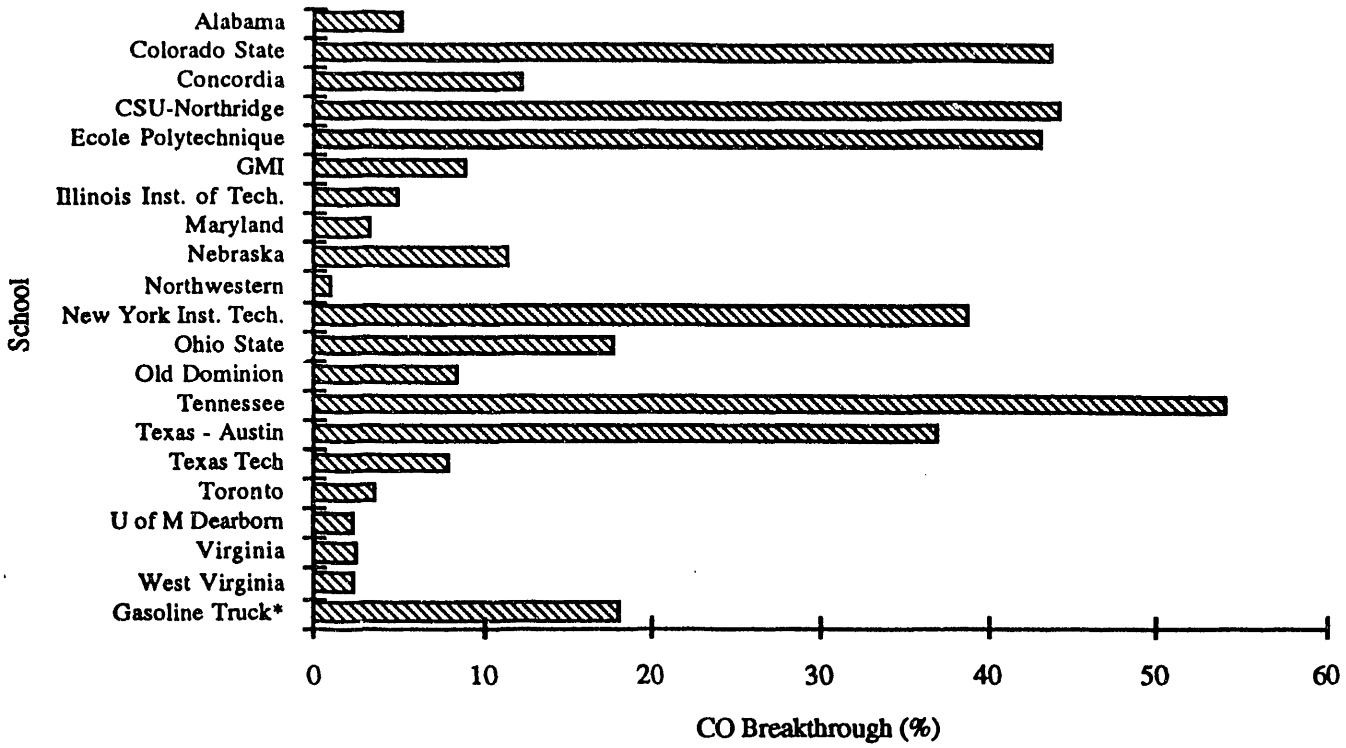
* Gasoline Truck included for comparison

Figure 5. Carbon Monoxide (CO) Engine-Out Emissions



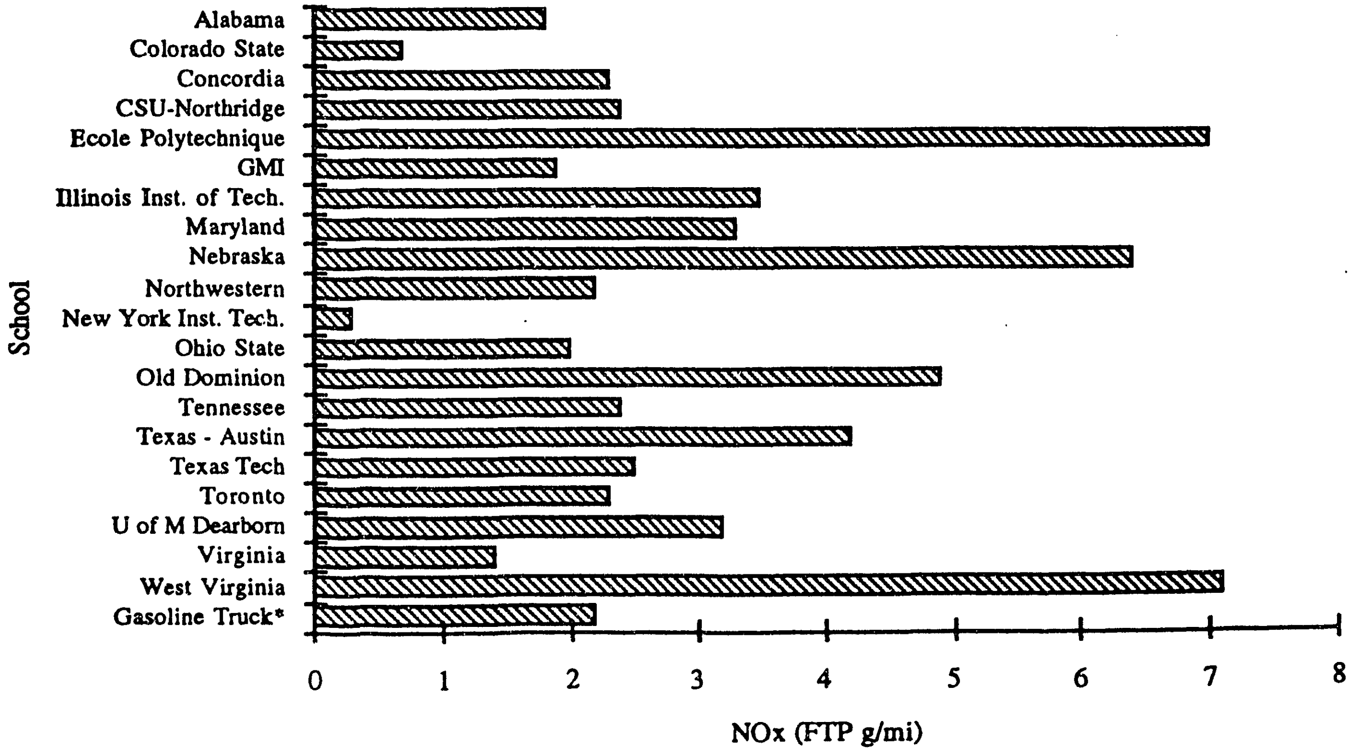
* Gasoline Truck included for comparison

Figure 6. Weighted Carbon Monoxide (CO) Tailpipe Emissions



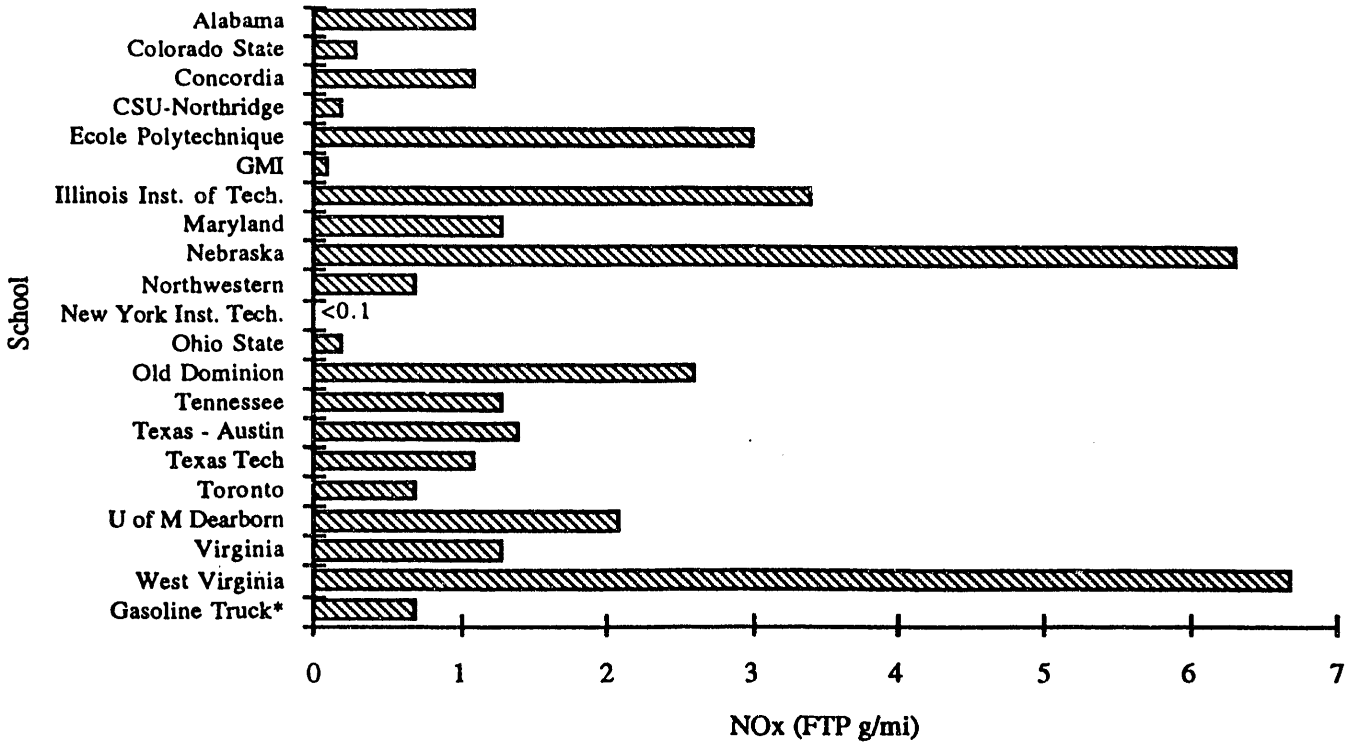
* Gasoline Truck included for comparison

Figure 7. Carbon Monoxide (CO) Catalyst Efficiency



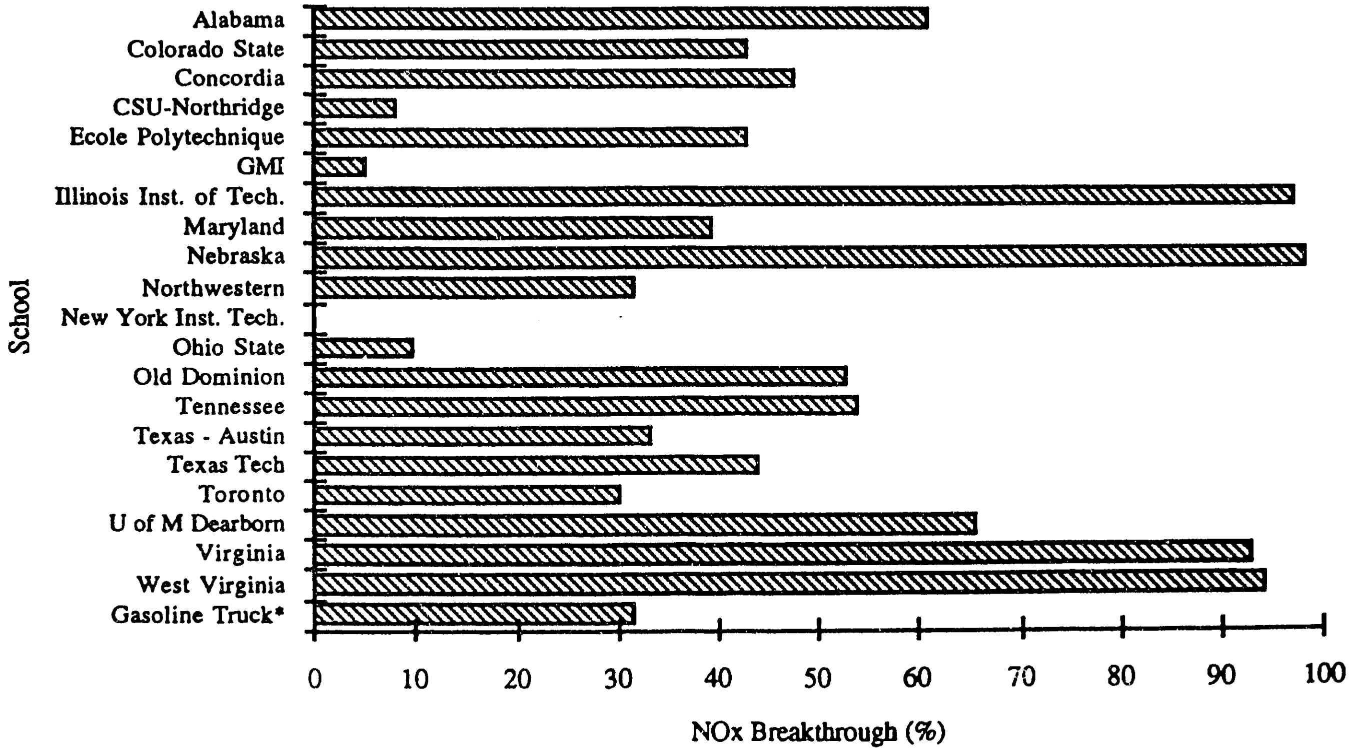
* Gasoline Truck included for comparison

Figure 8. Oxides of Nitrogen (NO_X) Engine-Out Emissions



* Gasoline Truck included for comparison

Figure 9. Weighted Oxides of Nitrogen (NO_X) Tailpipe Emissions



* Gasoline Truck included for comparison

Figure 10. Oxides of Nitrogen (NO_X) Catalyst Efficiency

END

DATE FILMED

1 / 13 / 93