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MEETING FUTURE EXHAUST EMISSIONS STANDARDS USING NATURAL GAS AS A VEHICLE FUEL: LESSONS LEARNED FROM THE NATURAL GAS VEHICLE CHALLENGE '92

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ABSTRACT

The Natural Gas Vehicle Challenge '92, organized by Argonne National Laboratory and sponsored by the U.S. Department of Energy, the Energy, Mines, and Resources - Canada, the Society of Automotive Engineers, and many others, 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 strived 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 in achieving good emissions control using natural gas are summarized, and observations concerning necessary components of a successful emissions control strategy are presented.

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 emissions schedules has also increased interest in advanced natural gas vehicle (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 Natural Gas Vehicle 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 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, with twenty teams of college and university engineers accepting the challenge of advancing the state of the art of dedicated NGVs. Teams were chosen on the basis of a written proposal to convert a 1991 General Motors Corporation (GMC) pickup truck to dedicated, optimized, natural gas use. A more complete description of the event and its results will be available in a Special Publication from SAE later this year. The purpose of this paper is to focus on the advances in emission control demonstrated in this year's competition.

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 '75 test cycle. Performance was measured through a combination of acceleration, cold start, and driveability tests, and 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 cost competitiveness of their product, equipment changes need to be limited. Whereas a completely optimized NGV might employ a turbocharger to offset inherent volumetric losses, the costs associated with low-volume mass production are difficult to justify.

Student-built vehicles in the NGV Challenge are not constrained by this production limitation. The event deliberately encourages innovative, advanced approaches to NGV operation. One of the objectives of the event is to see how far NGV technology can be and what advantages NGVs have over production vehicles. The vehicles described herein are perhaps most like manufacturer's developmental vehicles: high-priced alternative fuel thoroughbreds that represent the limits of existing technology. One reason that 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.

RESULTS FROM EMISSIONS TESTING

Vehicles from the competing schools all over North America were shipped to the EPA NFVEL in Ann Arbor, Michigan. Upon arrival at 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 student vehicles emissions performance, the conversion approaches and hardware utilized by the teams for fuel management and exhaust aftertreatment are given in Table I.

For the purposes of this competition, vehicles had to demonstrate that they could meet current federal light-duty truck emission standards in order to gain any points for the emissions event using the FTP '75 urban and highway testing cycle. Teams could earn points by exceeding this minimum if they could demonstrate lower levels of all regulated pollutants simultaneously. The complete scoring schedule is listed in Table II. The maximum amount of points available (250) corresponds to the lowest anticipated future federal emissions standards for NGVs.

The results of the emissions testing are given in Table III on a grams per mile basis (the "Emissions Score" column is based on the schedule in Table II). The fuel used for these emissions tests was commercial grade methane, which explains the near absence of non-methane hydrocarbons (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 III 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. This anomaly of total hydrocarbon (THC) creation in the catalysts for some entries 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 baseline was determined with a medium-duty truck engine, that differs from the light-duty calibrated engine supplied to the schools only in a camshaft designed for more torque at a lower rpm and components for enhanced valve train durability. Its emission control hardware was essentially the same as that for the engine supplied to the schools.

ANALYSIS

Superior emission control requires that both the engine management and the catalyst aftertreatment systems work well individually, as well as together. 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 energy content, which requires 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 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 air/fuel (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 ccs. Even at these increased compression ratios, boosted engines under load did not demonstrate any adverse effects such as detonation or excessive NO_x production.

Sixteen of twenty 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 as well. 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 either advanced spark timing or modified valve timing and overlap. 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, promoting 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, and the fourth ran always lean with high exhaust gas recirculation (EGR), to reduce unburned hydrocarbons (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 carburetted 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 remapped stock ECM. General Motors provided enough information for students to recalibrate spark (as well as fuel, idle air, and transmission torque converter lock-up) controls in the ECM. Eight teams took advantage of this method. With the exception of the University of Maryland, 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. Of schools with poor fuel control, all but Ecole Polytechnique utilized a non-stock ECM. This demonstrates that GM's stock ECM, at a high state of development and with its block learning algorithms, offers many advantages compared to 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.

For optimum performance, both in driveability and catalyst efficiency, the A/F ratio for natural gas should be approximately one percent rich of stoichiometric. Feedback loops must respond quickly and accurately so that the A/F ratio never varies more than half a percent from this point.

The success of a closed-loop system, then, depends on how precisely the system can maintain this A/F ratio. For the eight gaseous fuel-injected systems, feedback information from the exhaust oxygen sensor instructs the A/F computer to vary pulse widths controlling the length of time the injectors are open. Only two of the injected systems were able to do this sufficiently accurately 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. 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. The first approach relies on the mechanical actuation of either a vacuum- or servo-operated valve controlling gas regulator pressure; good results were also obtained in the competition with this method.

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 number varied from one to ten, and various methods were used for thermal management of the exhaust stream leading to the catalysts. All catalysts were close-coupled or underfloor of the pickup in the stock location, and all used at least one combination reduction and oxidation, or three-way catalyst (TWC). 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 III 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 twenty trucks varied, the top three performing trucks (from GMI, Northwestern, and Toronto) utilized moderate volume catalysts produced by Allied Signal with a combined volume per truck of 340 cubic inches. All three used two TWC's in parallel in a dual exhaust system. Toronto had individual, metal substrate pre-catalysts located one-half of the distance from the exhaust port to the main catalysts in addition to catalysts underfloor. The pre-catalysts were welded in each of the eight branches of the tubular exhaust headers. Both 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 these three teams' fuel-control systems allowed catalyst formulations to be chosen to match their A/F strategy. GMI, whose fuel management strategy was biased just rich of stoichiometric, utilized a platinum/rhodium formulation only slightly different from production catalysts. Toronto's pre-catalyst formulation was principally rhodium deposited on a metal substrate, and their main TWC's were palladium/rhodium to match its borderline rich 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 NO_X as efficiently as these three prototype vehicles.

For the other six schools that passed emissions tests, catalyst efficiency also was the key to their success. Catalyst volume on these trucks ranged from 300 to 640 cubic inches. 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, whereas 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 Allied Signal 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 which could have contributed to late catalyst light-off.

Alabama and Maryland, the only two teams using liquefied natural gas (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 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 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 Degusa light-off catalysts, AC Rochester platinum/rhodium/palladium TWC's, air injection, and a heated EGO sensor produced catalyst efficiencies equal to those for the gasoline-engine 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 Camet EHCs in front of a single Allied Signal methane-formulated TWC to achieve good results.

Some of the results for the eleven 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 cubic inches, were slightly lower than the volumes for the trucks that passed. All had exhaust heat retention, either with insulation or, in the case of a one school (Tennessee), with 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, within 1% or 2% of stoichiometric, preferably on the rich side, to be capable of providing an input to the catalyst system that can produce the extremely low levels of emissions required by future standards.

OBSERVATIONS

In 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.

These results may have been affected by the unusually high quality of the fuel used (unlike gasoline, there does not exist an official emissions certification fuel). Originally, plans had been to use natural gas representative of the United States' 90th percentile natural gas composition for the event. At the last minute, commercial grade methane (100% methane) was used, due to availability problems with more conventional fuel. 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 would be used on production NGVs, cost effectiveness must be demonstrated. Turbochargers, tuned exhaust manifolds, multiple pre-catalytic converters, and similar components add substantially to the cost of a NGV that will already have the cost of storage tanks, stainless 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 need to last 100,000 miles. While manufacturers need to demonstrate vehicles that hold their calibrations and maintain emissions levels for this mileage, the competition trucks could install fresh catalysts just days prior to testing. 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. Although the potential for low emissions was demonstrated by the results of this competition, many questions remain unanswered regarding long-term emissions performance.

On the basis of the results of this event, a number of generalizations about the successful attainment of future emission standards for NGVs can be made. First and foremost, precise control of A/F ratios using a closed-loop control strategy is essential. This control must ideally 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. 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 can perform adequately when controlled precisely.

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. Engine calibration remains a near art form, and few schools have the equipment, or engineering students the experience, to approach the efforts 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.

None of these observations can diminish the accomplishments of the students who participated in the NGV Challenge '92. Their efforts help define the performance limits of dedicated NGVs and show their potential for being a significant part of North America's transportation and clean air future. A more complete discussion of the performance, fuel economy, and design aspects of the NGV Challenge '92 vehicles will be published in Fall 1992 in a SAE Special Publication that will also contain the written design papers from the competing teams.

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Table I
Natural Gas Vehicle Challenge '92 Vehicle Attributes

		FUEL CONTROL				CATALYST		
School	C.R.	Fuel Metering	ECM	A/F Computer	Other	Number & Type	Manufacturer	Volume (in^3)
Alabama	12.5:1	Impco mixer	GM Remap	Impco	Programmable electric air pump injection to J-M cats	2 EHC 2 TWC	Camet J-M	2 x 24 2 x 215
Col St. U.	11.9:1	2 x S&S	GM Remap	GM & Sycron Tech	Digitally controlled EGR	2 TWC	Englehard	2 x 147.5
Concordia	13.0:1	Impco 425 w/feedback	Stock	GM & Impco	Heated lambda sensor; Air injection on cold operation	2 light-off 2 TWC	Degussa ACR (Pt/Pd/Rh)	2 x 63 2 x 170
CSUN	14.7:1	8 x BKM	Electromotive	CSUN-developed control	None	2 EHC 2 TWC	EMITEC J-M	2 x 28 2 x 170
Ecole Polytechnique	12.68:1	8 x BKM	GM Remap	Custom Mitsubishi-based controller	No EGR; Multi-layered zirconia EGO sensor	2 TWC	ASACC	2 x 170
GMI	9:1	Impco w/Fuel Pilot	GM Remap	GM & Impco	None	2 TWC	ACR (Pt/Rh)	2 x 170
IIT	9:1	ANGI II mixer	Stock	GM & Superfix	Higher flowing EGR valve	1 TWC	ASACC	1 x 460
Maryland	10.9:1	OHG Carburetor	Fuel Management Systems	FMS	Intake charge intercooled w/LNG vaporization	1 TWC	ASACC	1 x 300
Nebraska	9.8:1	16 x Bosch	Electromotive	DFI System	None	2 TWC	ASACC	2 x 170
Northwestern	13:1	16 x Bosch	GM Remap	GM	Air injection on cold start into manifolds; Externally-fed EGR w/in-line catalyst	2 TWC	ASACC	2 x 170

Table I (Continued)

		FUEL CONTROL				CATALYST		
School	C.R.	Fuel Metering	ECM	A/F Computer	Other	Number & Type	Manufacturer	Volume (in^3)
NYIT	9.8:1	Gaseous Fuel Metering by Clean Fuels	Electromotive	Closed loop	Elec. heated pre-cats	2 EHC 2 TWC	EMITEC J-M	2 x 28 2 x 170
Ohio State	11.1:1	GFI injectors	Stock GM & GFI	GFI	Elec. heated cats initiated by door opening and/or ignition	2 EHC 1 TWC	Camet ASACC	2 x 14 2 x 170
Old Dominion	10.8:1	Electromotive mixer	Electromotive	Closed Loop	None	2 TWC	ACR	2 x 170
Tennessee	9.6:1	Impco 300A mixer	GM Remap and modified MAP sensor	Impco ADP	Air injection; Post-cat EGO input; Higher flow EGR valve	2 EHC 1 TWC	Camet ASACC	2 x 14 1 x 170
Texas-Austin	11.0:1	OHG 450 mixer	None	Autotronics 4046	Heated titania -4 O_2 sensor; 2 x EGR valves	4 TWC	Englehard	2 x 85 2 x 140
Texas Tech	10.92:1	6 x BKM	Electromotive	Electromotive	Externally fed and cooled EGR; Electric air inj. pumps	2 light-off 2 TWC	ASACC ASACC	2 x 63 2 x 200
Toronto	10.6:1	Impco 425	GM Remap	Motorola M68HC11EVB	Air injection	8 pre-cats 2 TWC	unknown ASACC (Pd/Rh)	8 x 2 2 x 170
U of M-Dearborn	11.44:1	Holley Pro Jection	Stock modified to run fuel inj.	Unknown	None	2 light-off 2 TWC	ASACC ASACC	2 x 32 2 x 251
Virginia	12.5:1	GEI CL-2000 mixer	Stock w/Autotronics Recurve Box	Autotronics	Air pump inj. into exh. manifold	2 TWC 2 TWC	ASACC (Pd/Rh) Gasoline	2 x 150 2 x 170
West Virginia	12.5:1	Impco 425A	GM Remap	No computer	None	2 TWC	J-M	2 x 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

Table II

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	10	9.4	8.9	7.8	6.7	5.0
Idle CO (%)	0.50	0.50	0.50	0.50	0.50	0.50	0.50
NOx (g/mi)	1.7	1.7	1.6	1.6	1.4	1.3	1.1
PM (g/mi)	0.13	0.13	0.13	0.13	0.13	0.12	0.12
Your score	0	25	50	75	125	175	250

* ASTM roundoff rules apply.

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

Table III
1992 NGV Challenge
Emissions Results

Team	FTP Weighted Emissions					FTP Engine Out			Idle	Emissions	Control
	THC (g/mi)	NMHC (g/mi)	CO (g/mi)	NOx (g/mi)	CO2 (g/mi)	THC (g/mi)	CO (g/mi)	NOx (g/mi)	CO (percent)	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	NOx
Maryland	1.49	0.02	0.4	1.3	628	2.55	11.9	3.3	<0.1	175	NOx
Nebraska	4.06	0.08	1.4	6.3	482	3.95	12.1	6.4	<0.1	0	NOx
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	NOx
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	NOx
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	NOx
Gasoline Truck	0.36	0.32	3.3	0.7	718	3.18	18.1	2.2	<0.1	--	--

OOR=Out Of Range

END

DATE
FILMED
10/1/92