Conf-920233--3

The 1991 Natural Gas Vehicle Challenge

Developing Dedicated Natural Gas Vehicle Technology

ANL/CP--75223

DE92 007371

1. Robert Larsen
2. James Davies
3. Mike Zammit
4. William Rimkus
5. Philip Patterson

1. Argonne National Laboratory
2. General Motors of Canada Limited
3. A.C. Rochester
4. Argonne National Laboratory
5. U.S. Department of Energy

ABSTRACT

An engineering research and design competition to develop and demonstrate dedicated natural gas-powered light-duty trucks, the Natural Gas Vehicle (NGV) Challenge, was held June 6 -11, 1991, in Oklahoma. Sponsored by the U.S. Department of Energy (DOE), Energy, Mines, and Resources - Canada (EMR), the Society of Automotive Engineers (SAE), and General Motors Corporation (GM), the competition consisted of rigorous vehicle testing of exhaust emissions, fuel economy, performance parameters, and vehicle design. Using Sierra 2500 pickup trucks donated by GM, 24 teams of college and university engineers from the U.S. and Canada participated in the event. A gasoline-powered control vehicle was included in the performance testing as a reference vehicle. This paper discusses the results of the event, summarizes the technologies employed, and makes observations on the state of natural gas vehicle technology.

BACKGROUND OF THE EVENT

DEVELOPMENT OF THE EVENT'S CONCEPT - DOE has joined with EMR, SAE, and GM to organize several successful engineering research and design competitions focusing on developing dedicated methanol-powered vehicle technology. In 1989, the Methanol Marathon set the pattern for production-vehicle-based over-the-road competitions. The Marathon was followed in 1990 by the Methanol Challenge, an event that tested the students' creativity and engineering abilities even further. The success of these events encouraged DOE to consider using the proven format of the methanol events to accelerate the development of the technology for dedicated natural gas-powered vehicles. Still in a relatively unsophisticated form, NGV technology was selected by DOE and EMR as an appropriate focus for efforts to accelerate development and demonstrate viable alternatives to the use of imported petroleum. Engineering research and design competitions have proven themselves as cost-efficient ways of accomplishing this goal.

Persons at the GMC Truck Division of GM indicated interest in pursuing NGV technology in parallel with their own efforts to develop a production natural gas-powered version of their full-sized Sierra pickup; they agreed to donate the vehicles. The state of Oklahoma showed considerable interest in hosting the event to highlight their abundant supplies of natural gas and encourage the development of NGVs. The state also became a major sponsor. With a keen interest and considerable experience in alternative-fueled vehicles, GM of Canada agreed to supply technical assistance to the selected teams. A steering committee for the event, consisting of representatives from the major sponsors, was formed by the Center for Transportation Research at DOE's Argonne National Laboratory (ANL). ANL, with SAE and the Sarkey Energy Center at the University of Oklahoma, administered the event.

SELECTION OF STUDENT TEAMS - In the Spring of 1990, after developing the content of the event and its rules, a Request for Proposals (RFP) was sent to all accredited engineering programs in the U.S. and Canada asking the schools to detail their approach to building a dedicated NGV. The RFP emphasized safety, vehicle performance, a 250-mile minimum range, high fuel economy and low emissions, and innovative design in the conversion of pickup trucks to natural gas operation. The events in the competition and the points associated with them are shown in Table 1; the entire RFP is included in Appendix A.

Thirty-six U.S. and Canadian schools responded to the RFP. The proposals were judged by a team of experts from the automotive and natural gas industries and government agencies and laboratories according to the following criteria:

Innovative design for improving fuel economy	25%
Innovative design for emission control	25%
Innovative design for improving power density	15%
Feasibility of design in time allowed	15%
Fuel storage and vehicle utility	10%
Facilities and resources available	10%

Cost-effectiveness was weighed with innovation and feasibility. The evaluators chose a balance between simple, straightforward and more complex, innovative approaches. To be considered, each team needed written commitments from their school and their local gas utility for support and backing.

Table 1 NGV Challenge Event Summary

Event		Points
Emissions (FTP Test)		250
Design		225
Written Design Report	75	
Vehicle Design Inspection	75	
Oral Design Presentation	75	
Fuel Economy		250
Endurance Event	125	
Road Rally	50	
FTP Fuel Economy	75	
Performance		275
-20°F Cold Start	50	
Acceleration with 1000-lb Load	50	
Weight Pull	50	
Cold Start & Driveability	50	
Hot Start & Driveability	25	
Rally Performance	50	
TOTAL		**1,000**

The following schools — 20 U.S. and four Canadian — were chosen as competitors by the judges:

University of Alabama
University of British Columbia
Colorado State University
Concordia University, Montreal
California State University, Northridge
Florida Institute of Technology
GMI Engineering and Management Institute
Illinois Institute of Technology
University of Maryland
University of Michigan, Dearborn
University of Nebraska
New York Institute of Technology
Northwestern University
Ohio State University
Old Dominion University
University of Oklahoma
Ecole Polytechnique, Montreal

University of Tennessee
University of Texas, Austin
Texas Tech University
University of Toronto
University of Virginia
Washington University, St. Louis
West Virginia University

GMC Truck Division donated an identically equiped 1991 Sierra 2500 pickup truck, as shown in Figure 1, to each school in the competition. The trucks were shipped to local GMC dealers, where ceremonies were held to present the trucks to the student teams. The teams were also provided with competition rules and seed money to partially defray the costs of the conversions ($5,000 was sent to each U.S. school and $10,000 to each Canadian school by their respective governments).

An electronic bulletin board was made available at ANL for ease of communication between schools and the event organizers. GM of Canada provided technical support to advise the student teams on technical matters and answer questions. Questions that involved rule interpretations were referred to the NGV Steering Committee. The bulletin board made information quickly and universally available. A copy of the rules is provided in Appendix B.

Figure 1 Twenty-four teams of engineering students converted GMC Sierras to dedicated natural gas operation. This is the entry from the University of Alabama, which operated on liquefied natural gas.

CONVERSION OF VEHICLES TO NATURAL GAS OPERATION

STATE OF NGV TECHNOLOGY - To appreciate the technical innovation of the competition, some history on the current state of NGV technology is in order.

Natural gas has been used as a vehicle fuel longer than gasoline; the first engine ran on natural gas. Due to the cumbersome storage technology at the time, gasoline with its higher energy density prevailed. Since then, gasoline technology has been evolving at a tremendous pace, while natural gas technology has been slow in advancing.

Natural gas-powered vehicles have developed as a result of their environment. Virtually all the natural gas-powered vehicles on the road today are dual-fuel vehicles that have not been optimized for operation on natural gas.

Due to the limited access to high-pressure natural gas for refueling and the traditional low vehicle range, vehicle owners prefer to have the option of operating on gasoline. Unfortunately, the optimized systems for gasoline and natural gas are mutually exclusive: one can optimize for either natural gas or gasoline, but not both. Dual-fuel vehicles are further penalized with respect to range. They must carry two smaller fuel systems, and the engine's fuel economy is not maximized.

Most NGVs are conversions of vehicles that ran on gasoline. In the past, it was believed that there was an endless supply of cheap gasoline, and the words "environmentally friendly" were not yet part of our culture. Thus, there was little demand for natural gas-powered vehicles. The low potential sales volumes acted as a barrier for original equipment manufacturers (OEMs), because they could not take advantage of economies of scale. The high development and validation costs would not likely ever be recovered.

Two other factors have contributed to the lagging of NGV technology. First, the traditional approach to ensuring the safety and integrity of natural gas-powered vehicles was through design standards in the form of rigid codes for vehicle conversions. These codes do not readily address new technological developments due to

Robert Larsen

the lack of a safety history of the technology proposed. Second, there have been no performance standards for these vehicles, such as crash-worthiness performance or emission standards. As gasoline vehicles were evolving to meet increasingly stringent requirements, NGVs remained unchanged. This relatively low level of NGV technology has been embraced by installers due to its simplicity.

Fuel Control - Typical conversion equipment fuel control can be categorized into two groups: mechanical open-loop and mechanical closed-loop. Mechanical open-loop systems, consisting of three-stage regulators with carburetion mixers, are analogous to pre-emission-standards gasoline carburetors. This hardware is very sensitive to installation. Mechanical closed-loop systems are designed to operate the engine at a stoichiometric air-fuel ratio (i.e., the right amount of fuel for the amount of air ingested by the engine). These systems incorporate an oxygen sensor in the exhaust to determine whether the mixture is rich or lean of stoichiometry. Once the air-fuel ratio is determined, corrections are made. These devices generally work by adjusting the pressure in the final stage of the system pressure regulator. These systems are analogous to closed-loop gasoline carburetors. Since it is a mechanical system, the response is slow, and the corrections to fueling are not very precise.

Spark Control - Electronics are popular in the after-market for advancing spark-ignition curves for engines with traditional distributor systems. New distributorless ignition systems are difficult to modify in the after-market. As a result, some after-market manufacturers have designed complete distributorless ignition systems of their own.

Natural gas combustion characteristics are quite different from those of gasoline. For example, "engine knock" rarely occurs with natural gas but is quite frequent with gasoline. The computer on the vehicle detects knocking and activates a "service engine soon" light for the operator. Electronic modules are usually necessary on NGV conversions to "fix" the OEM's electronic diagnostics.

Performance - Performance of the traditional conversion systems is very sensitive to the equipment chosen and the fashion in which it is installed. As a result, the emissions and driveability performance of these vehicles over time cannot be guaranteed with a high level of confidence. These characteristics make this technology unacceptable to regulatory agencies and OEMs.

In anticipation of stricter emission standards and higher customer expectations, a number of organizations have been developing a new generation of electronically controlled natural gas conversion equipment. Some of these systems, or variations of them, found their way onto many of the NGV Challenge vehicles.

VEHICLE CONVERSION CHARACTERISTICS - A brief overview of the conversion characteristics of the teams participating in the event is presented below. General Motors provided technical support for the NGV Challenge teams. Included was the release of sufficient information to recalibrate the engine control module to support the NGV conversions. The teams were capable of recalibrating electronic spark timing, fuel control, idle air control, and transmission torque-converter lock-up speeds and of disabling specific engine diagnostic tests.

The discussion regarding conversion characteristics in the NGV Challenge will address the following:

- Fuel control
- Spark control
- Emissions control
- Engine modifications
- Fuel storage

Fuel Control - By far the most popular strategy for fuel control was the stoichiometric closed-loop system with a three-way catalyst. The schools that placed at the top of the competition used this approach. The remainder of the vehicles used open-loop systems (i.e., systems that did not incorporate a feedback and correction system). A couple of schools used the "lean burn" strategy. These "lean burn" teams typically had to use other systems to regain power that is typically lost when operating lean of the stoichiometric air-fuel ratio. Hardware used ranged from the traditional mechanical systems to electronically controlled, solenoid-operated systems. The solenoid-operated systems were either (1) remote mounted assemblies (e.g., on an inner fender) that metered and then introduced the gas at steady-state conditions into a mixer or manifold or (2), in a system analogous to port fuel injection, solenoids located in intake manifolds. The latter systems were typically noisy due to the large number of injectors and to the simultaneous activation of the solenoids. The remote-mounted solenoid systems undeniably provided superior emissions results.

One team used the stock gasoline throttle body injectors to introduce low-pressure gas to trim or fine-tune the fuel delivery. This was supplementary fuel to the primary fuel system.

Spark Control - Ignition systems included the stock High Energy Ignition (HEI), modified HEI, and complete after-market systems. The modified systems utilized multiple spark-discharge systems to upgrade the performance of the stock system. It was not demonstrated that modified systems provided performance advantages over the stock system. An after-market distributorless ignition system that included its own control computer was used by several teams. Some teams chose to use spark recurve modules to modify the ignition advance for natural gas, rather than recalibrate the stock computer.

It was noted that some of the schools determined from their engine dynamometer testing that there was no advantage to advance timing further than stock for high-compression configurations.

Emission Control - Few teams recognized the emission benefits of using a heated oxygen sensor. These sensors allowed the fuel systems to determine the air-fuel ratio and make fueling corrections sooner. These sensors were popular with the same teams that had remote-solenoid fuel control. It can be said that this strategy was a contributor to the better emissions performance of these vehicles.

Due to time limitations, most schools did not pursue exhaust-gas recirculation modifications, but one school designed an elaborate gas-to-air heat exchanger to cool their exhaust gas dramatically before it was reintroduced for combustion. The emission benefits of this system could not be demonstrated at the competition.

The most interesting aspects of emission control were the creative strategies applied to the use of catalytic converters. There were strategies exploring catalyst volume, formulation, and minimization of light-off time. Several converter manufacturers provided natural gas catalysts designed specifically for the very nonreactive methane in the natural gas. Due to their proprietary nature, details of formulations could not be released. Total catalyst volume was increased by many schools, to as many as six three-way catalytic converters.

In order to reduce warm-up time of the converters, several schools located close-coupled converters or "pup" converters as close to the exhaust manifolds as possible. Many schools wrapped the exhaust manifolds with insulation to retain as much heat in the exhaust as possible. One school incorporated a heated catalytic converter that started warming up as soon as the driver's door was opened. Unfortunately, this feature was not working at the time of the competition, and its benefits could not be demonstrated. As the compression ratio of an engine is increased, peak combustion temperatures increase, and exhaust temperatures decrease. This is due to the increased work done on the piston by the gas. Therefore, any efforts to retain heat in the exhaust, or electrically heating emission components, are directly beneficial.

Engine Modifications - Engine modifications were done to address three areas:

- Combustion
- Fictional losses
- Volumetric efficiency

Given the very high octane rating for natural gas, many of the schools recognized that increasing their engine's compression ratio would increase the engine's thermal efficiency. The compression ratios for the normally aspirated engines ranged from 9:1 to 14.4:1.

Robert Larsen

The turbocharged or supercharged engines had ratios that ranged from 7.4:1 to 12.5:1. Increases were obtained by installing different heads, domed pistons, and crankshafts. Some teams changed the block in order to build a "square" engine (one in which the cylinder bore diameter equaled the stroke of the piston), a configuration that many people believe to be optimal. Longer rods were used by some teams to improve the engine's torque characteristics. To minimize frictional losses in the engine, many teams employed such components as roller followers and roller rocker arms to replace the stock ones.

To address the inherent power loss due to the induction of a gas, many teams increased the engine's volumetric efficiency with tuned intake and exhaust manifolds, turbochargers, superchargers, and intercoolers. Nine engines were boosted, of which five were intercooled. The boost ranged from 5 to 10 psi.

Fuel Storage - Three schools stored fuel in the liquid phase, as LNG, and the remainder of the vehicles stored it as a compressed gas. The compressed gas cylinders included steel cylinders, fiberglass-wrapped steel cylinders, wrapped aluminum cylinders, and all composite cylinders. An example CNG tank installation is shown in Figure 2. Creativity was difficult with respect to fuel storage, in that the schools were limited to a small library of cylinder manufacturers and their specific tank sizes. The universities were not in a position to design, test, or validate the safety of new cylinders.

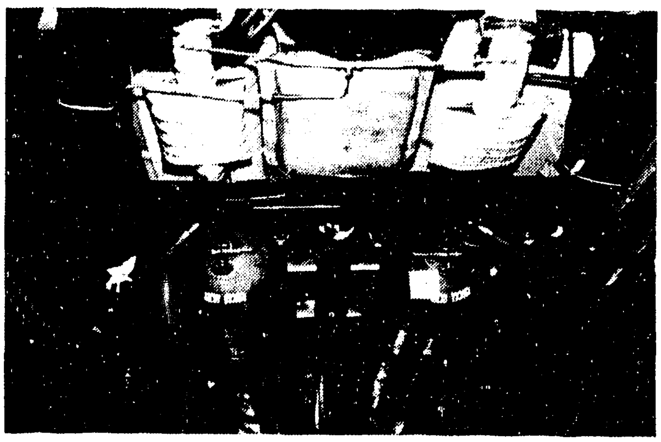

Figure 2 Efficient packaging of fuel tanks was required to meet the minimum 250-mile range. Note the insulated and shielded catalytic converters.

One notable design feature was incorporated by a school that used LNG. This school used an extra tank to catch the small amount of methane vented from the main fuel storage tanks. This tank was also the first tank purged when the vehicle was started.

SUMMARY OF TEAMS' DESIGN APPROACHES

The following is a summary, by team, of each truck's powertrain configuration at the event. Highlighted are the engine modifications and methods of exhaust after-treatment. Table 2 gives a concise listing of many of the components used in the conversion to dedicated natural gas operation.

CALIFORNIA STATE UNIVERSITY - The California State University conversion featured a unique variable 4-6-8 valving system, which was originally used on 1981 Cadillac V8 engines. This system allows operation on 4, 6, or 8 cylinders, resulting in improved fuel economy, mostly at cruising speeds. It was fitted to smaller-combustion-chamber (64cc) cylinder heads, which increased the compression ratio to 11:1 with the stock flat-top pistons. Gas delivery was accomplished using an ORTECH GFI system to control seven (7) fuel-metering valves. The air/fuel ratio was kept stoichiometric in a closed-loop fashion using a heated oxygen sensor feedback. A dual exhaust system was installed that incorporated two (2) specially designed three-way catalytic converters, one on each side. An EGR system was also used to control NO_x emissions.

COLORADO STATE UNIVERSITY - The Colorado State University engine, shown in Figure 3, started with a 305-cid block, which was bored to 3.796 inch. Using a 3.875-inch stroke, the engine had a displacement of 351 cid. The 267-cid heads, ported and milled, were fitted to this block. With custom-forged aluminum, flat-top pistons, and 6.000-inch connecting rods, a compression ratio of 14.4:1 was achieved. The camshaft selected had low overlap, produced by an increased lobe separation, and high lift requiring the use of roller lifters and rockers. This engine was equipped with a tuned port injection (TPI) system with an enlarged throttle

Table 2 Vehicle Hardware Concepts

School	Engine Size	C.R.	Pistons	Head	Valve Sizes	Cam	Rollers
Stock	350	9.1					No
Tennessee	334	9.6	Forged Al	Corvette Al 57cc	1.94, 1.50	EIVC, Low Ov	Yes
Colorado	351	14.4	Flat, forged Al	Milled 267, 45cc	1.78, 1.42	Comp, Low Ov	Yes
Concordia	350	Stock	Stock	Stock	Stock	Stock	No
Ecole Poly	364	12.7	Dome-shaped	Corvette Al	1.94, 1.50	Speed Pro	Yes
Cal State	350	11.1	Stock	64 cc	1.94, 1.60	Stock	No
Texas Tech	335	11.8	305 Stock	88 Corvette, 53cc	1.94, 1.50	Adv IVO	Yes
West Virginia	350	12.6	Dome-shaped	Dart-II, 64cc	2.02, 1.60	Comp	Yes
Northwestern	350	13.0	Domed forged Al	Covette Al, 56cc	1.94, 1.50	Isky NG	No
Illinois	350	Stock	Stock	Stock	Stock	Stock	No
Ohio	355	12.4	Domed Al	Dart-II, 64cc	2.02, 1.60	Crane	Yes
Virginia	350	Stock	Stock	Stock	Stock	Stock	No
Texas-Austin	350	11.0	Forged Al	Dart-II	2.02, 1.60	Crower, 0 over	Yes
Washington	305	12.5	Forged, domed	Corvette Al	1.94, 1.50	Stock	No
Toronto	383	10.8	Cast Al	Corvette Al 58cc	1.94, 1.50	Comp	No
Alabama	350	12.5	Forged	Dart-II, 64cc	2.05, 1.60	Stock	No
Michigan	350	Stock	Stock	Stock	1.94, 1.50	Stock	No
Br. Columbia	309	10.5	Forged, flat	Wedge, 58cc	1.94, 1.50	Isken, 0 over	No
Florida	350	Stock	Stock	Stock	Stock	Stock	No
Old Dominion	268	7.4	268 stock	Stock, Ch mod	1.85, 1.48	Custom, Low Ov	Yes
New York	305	9.8	Custom		Stock	Custom	Yes
Oklahoma	350	12.7	Domed	Stoc, Ch mod	Stock	Edelbrock	No
GMI	334	10.3	Forged, flat	GM #492	2.05, 1.60	Comp, Custom	Yes
Maryland	357	10.5		'70 350 stock	1.94, 1.50	Custom LEVO	No
Nebraska	355	9.8	Forged	68cc, polished	1.94, 1.50	Crane #109511	Yes

Table 2 (Cont'd)

School	Boost	Ignition	Control	Regulator	Fuel Metering	Throttle Body	Intake Manifold
Stock	None	HEI	GMCM		TBI	TBI	Stock GMC
Tennessee	Garr, 5.5	Stock	Stock	Meco/Impco	Impco mixer, UT	Stock	Corvette Al
Colorado	None	Stock + MSD	Stock + Ortech	Ortech	Ortech, Multi	TPI	Stock
Concordia	None	Stock	Remap GMCM	Impco/Imco	Impco95/Stock 5	Stock	Stock
Ecole Poly	None	Stock	Remap GMCM	Meco/Impco	Impco mixer	Stock	Stock
Cal State	None	Stock	Remap GMCM	Ortech	GFI	Stock	B&M, FIM
Texas Tech	B&M Super	DIS	Electro	MECO	6 BKM Servo, UT	Stock	Stock
West Virginia	None	Stock	Stock	Impco/Impco	Impco mixer	Stock	Stock
Northwestern	None	Stock	Remap GMCM	Meco/Impco	Impco mixer	Stock	Stock
Illinois	None	Stock	Remap GMCM	ANGI	Angi mixer	Stock	TPI
Ohio	None	Stock + MSD	Stock + Auto	Meco/Garr	Custom mixer	TPI	Stock
Virginia	None	Stock	Remap GMCM	Landi Renzo	Custom mixer	Stock	Edelbrock
Texas-Austin	None	Stock + MSD	Mallory	Meco/Impco	Impco mixer	Holley	Stock
Washington	2 Garr interc	Stock + MSD	Remap GMCM	Meco/Garr	Custom mixer	Custom	Dual plenum
Toronto	None	Stock	Remap GMCM	Yugotech	Yugo95/stock 5	Holley TBI	Edelbrock Perf.
Alabama	None	DIS	Electro	Impco II Sears	Impco II Electro	Stock	Stock
Michigan	None	Stock	Stock	Impco/Impco	Impco mixer	Stock	Stock
Br. Columbia	Twin Garr T2	Complete MSD	Auto	2 H Nzig, II	6 BKM Servo	Stock	Stock
Florida	None	Stock + MSD	Stock + Auto	Angi-D, (2)	ANGI Mixer	Stock	TPI
Old Dominion	Turbo	DIS	Electro	MECO	GCI, UT	GM 2.8 V6	Corvette
New York	Garr interc	DIS, MSD	Electro	2 1st + 2 2nd	Multi	TPI	Edelbrock
Oklahoma	None	Stock			Multi, BKM	After-market	Corvette
GMI	Garr interc	DIS	Electro	Impco/Impco	Electro UT	TPI	B&M, FIM
Maryland	Garr interc	DIS	Electro		8 injectors UT	GM V6 2.8	TPI
Nebraska	2 Garr interc	DIS	Electro	Modern	8 BKM Serve	Custom	

Table 2 (Cont'd)

School	A/F Control	Computer	Accessory	Catalyst	Exhaust	Driveline
Stock						3.73
Tennessee	Closed	Auto		2 AS 3-way	Headers, Single	GV Over, 4.10
Colorado	Closed	Ortech/Stock		Englehard 3-way	Headers, Insul	
Concordia	Closed	Stock		M 150 ACR	Headers, Dual	
Ecole Poly	Closed	Stock	Superfix	Stock	headers, bed ex	
Cal State	Closed	Ortech/Stock		2 3-way	Dual	
Texas Tech	Closed	Electro		AS, 2-L, 2-S.	Dual	3.42/4.10, AT
West Virginia				PFP 3-way	Stock	
Northwestern	Open	Stock		2 monolith	Dual	GV Over 0.78
Illinois	Open	Stock	Superfix-1	Elec Heated	Stock, Insul	
Ohio	Closed	GM + Garr	Superfix-1	Stock + 2 Camet	Headers	
Virginia	Open	Stock	Superfix	2 Plat-Rhodium	Dual, WTM	
Texas-Austin	Closed	Auto		Englehard 3-way	Headers, Dual	
Washington	Open	Stock		L: No Catalyst	Dual	
Toronto	Closed	Own Design		2 Corvette	Headers, Dual	
Alabama	Closed	Electro		Johnson-Matthey	Single, Rerouted	
Michigan	Open	Stock		Stock + 2 Custom	Headers, Insul	
Br. Columbia	Closed	Own Design		Englehard 3-way	Insul	
Florida	Open	Stock	Superfix	Stock	Stock	American Over
Old Dominion	Closed	Electro		2 Walker 3-way		
New York	Closed	Electro		NG 3-way	Super Trapp	3.23
Oklahoma	Open	Haltech	Superfix	Johson-Matthey	Headers Insul	
GMI	Closed	Electro TEC		AS Custom, ACR		
Maryland	Closed	Electro TEC		2-way & 3-way		
Nebraska	Open	Own Design		2 NAPA #15124	Headers, Dual	

Table 2 (Cont'd)

Key to Abbreviations Used in the Table of Vehicle Hardware Concepts

Engine size	expressed in cubic inches.		
C.R.	Compression Ratio		
Head			
Ch mod	Chamber modified		
Valve Sizes	expressed in inches		
Cam			
Adv IVO	Advanced Intake Valve Opening	LEVO	Late Exhaust Valve Opening
Comp	Competition Cams	Low over	Low overlap
EIVC	Early Intake Valve Closing	0 over	No overlap
Isken	Iskenderian Cams		
Boost			
Garr	Garrett		
Inter	Intercooled		
Super	Supercharged		
Ignition			
DIS	Distributorless Ignition System		
HEI	High Energy Ignition (stock GM)		
MSD	Multiple-Spark Discharge		
Control			
Auto	Autotronic	GMCM	General Motors Control Module
Electro	Electromotive	Remap	Remapped
Regulator			
ll	Parallel	H	Heated
Garr	Garretson		

Table 2 (Cont'd)

Fuel Metering			
Multi	Multiport	Servo	Servojet
Electro	Electromotive	TBI	Throttle-Body Injection
GCI	Gaseous Continuous Injection	UT	Upstream Turbo
GFI	Gaseous Fuel Injection	Yugo	Yugotech
Throttle Body			
TBI	Throttle-Body Injection		
TPI	Tuned Port Injection		
GM	General Motors		
Intake Manifold			
FIM	Forced Induction Manifold		
Perf	Performer		
A/F Control	Air/Fuel Ratio Control		
Computer			
Auto	Autotronic		
Electro	Electromotive		
Garr	Garretson		
Catalyst			
ACT	AC Rochester	NG	Special Natural Gas
AS	Allied Signal	PFP	Products for Performance Inc.
Elec	Electric	Plat	Platinum
L	Lean Burn		
S	Rich/Stoichiometric Burn		
Exhaust			
Bed ex	Bed exhaust		
Insul	Insulation		
WTM	Walker Turbo Muffler		
Driveline			
AT	Auxiliary Transmission		
GV			
Over	Overdrive		

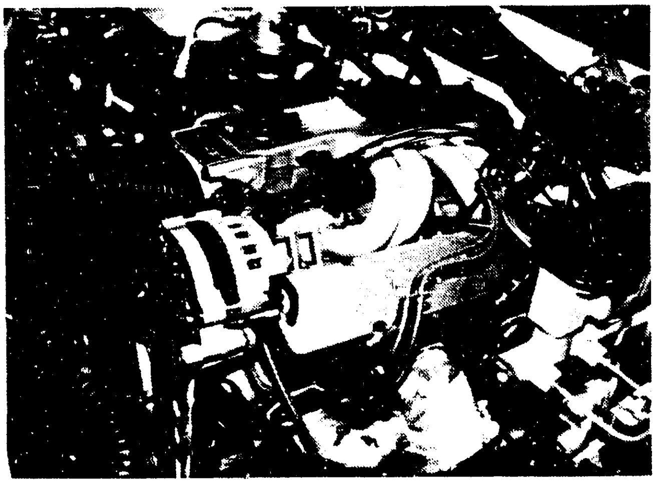

Figure 3 The engine of the Colorado State University entry, winner of the Best Conversion Award.

bore and custom tube runners. The fuel rail of the port fuel-injection system was modified to accept natural gas brass flow nozzles. Air/fuel ratio was maintained slightly rich by the ORTECH GFI system, which uses a speed/density strategy. Spark duration was extended using an MSD unit, while stock timing was retained. Exhaust gases were routed through short headers, each connecting to a three-way catalytic converter designed to optimize oxidation of unburned methane. Production of NO_x was also controlled by a vacuum-operated EGR valve.

CONCORDIA UNIVERSITY - The Concordia University conversion was kept relatively simple, with the aim of building a well-tuned, reliable truck. The engine itself was the stock 350 cid. The main gas delivery system was a standard Impco conversion kit, composed of a pressure regulator and carburetor/mixer assembly. This system supplied 90-95% of the gas, while the stock throttle body injection was used to keep the air/fuel ratio at stoichiometry by providing the remaining 5-10% with GM's closed-loop system. The GM ECM was recalibrated (advanced) for improved spark timing with natural gas. Low restriction headers routed the exhaust gases to six three-way (three on each side) catalytic converters. An air injection system was also installed, which injected air either to the manifold or just before the last converter, depending on the engine coolant temperature. Finally, the rear suspension was modified to facilitate the installation of the tanks.

ECOLE POLYTECHNIQUE DE MONTREAL - The Ecole Polytechnique de Montreal's truck could be easily identified by its distinctive chromed exhaust pipe mounted in the truck's bed, just behind the cabin. In front of the cabin, the engine was a 364-cid engine with a 12.7:1 compression ratio. This was accomplished by using a 3.570-inch stroke crankshaft, installing new dome-shaped pistons, and rounding off the combustion chamber edges. Corvette aluminum cylinder heads were fitted, coupled to tuned-port intake manifolds. The area of the intake manifold's air ducts was reduced to increase flow velocity without decreasing maximum air flow. Furthermore, a Speed Pro camshaft with roller rocker arms was chosen to make the most of the modifications cited above.

An Impco natural gas mixer was used in a closed-loop control mode for low engine speeds. Below 1500 rpm, which would correspond to a cruising speed of approximately 50 mph, a stepper motor adjusted the idle screw, which had a direct effect on the mixture's richness. A Mitsubishi microcontroller was set to adjust air/fuel ratio to 19.8:1 at cruising speed and to stoichiometry when engine speed was below 1500 rpm. The catalytic converter and EGR valve were stock, but the EGR was controlled by the Mitsubishi microcontroller.

FLORIDA INSTITUTE OF TECHNOLOGY - The modifications to Florida's entry were minor. All engine components remained stock, with the exception of the fuel delivery system. For this purpose, an ANGI D-regulator feedback system was used. Catalysts remained stock as well. The only other change was the installation of a 0.7:1 overdrive system.

GMI ENGINEEERING AND MANAGEMENT INSTITUTE - GMI replaced the engine block in its truck with a 305-cid model that had a long-stroke 400-cid crankshaft. Total displacement was then 334 cid. With forged pistons, bow tie connecting rods, and GM 492 heads, the compression ratio for the motor was 10.2:1. The cylinder heads were ported for better flow and then ceramic-coated in the port and combustion chamber areas. The piston tops and the valve faces and backs were similarly coated. A single Garrett turbocharger with intercooler was used. Fuel was introduced downstream of the turbocharger through three 1/16-inch-orifice solenoids; upstream of the turbocharger, an Electromotive system supplemented the fuel delivery in high load situations. Dual custom-designed catalysts with rhodium-doped substrate replaced the original.

ILLINOIS INSTITUTE OF TECHNOLOGY - Illinois Institute of Technology made no changes to the engine internally. An Angi fuel-metering system with a two-barrel venturi mixer was installed above the existing throttle body. This system used open-loop control. Spark timing was uniformly advanced by 6° of crank angle. An electronic "Superfix I" box was also used to avoid error codes due to lean operation. The conversion also included an electrically heated catalytic converter.

NEW YORK INSTITUTE OF TECHNOLOGY - New York used a 305-cid engine with 9.8:1 compression ratio. Its pistons and roller camshaft were custom-made. The engine was turbocharged with a Garrett unit and intercooled. The boosted mixture was distributed through a Corvette TPI intake manifold. Engine management was accomplished with an Electromotive control unit in closed-loop format. For exhaust catalysts, a special three-way catalyst for natural gas was used. The rear axle gear ratio was also changed, to a value of 3.23.

NORTHWESTERN UNIVERSITY - Northwestern University achieved a 13:1 compression ratio through replacement of the cylinder heads and pistons in the original engine. Pistons were forged aluminum from BRC with shallow 6-cc domes, while the heads were replaced with Chevrolet Corvette production aluminum heads. Camshaft and lifters were replaced with an Isky cam/lifter arrangement specifically designed for natural gas operation. This design utilized increased valve lift and shortened valve opening/closing rates. Fuel metering was performed by an Impco mixer with an open-loop control system using engine vacuum. Emissions control systems included two (2) catalytic converters designed for natural gas and a modified EGR. The new EGR provided higher flow rates and greater exhaust gas cooling.

OHIO STATE UNIVERSITY - Ohio State University's engine modifications were made to increase compression ratio and improve air intake. Original pistons were replaced with domed aluminum pistons by Keith Black. Dart-II cylinder heads with 65-cc combustion chambers were fitted, resulting in a 12.4:1 compression ratio. The new heads required a change of rocker arms, which were replaced with roller rocker arms. A Crane cam with a steeper ramp and higher lobes replaced the original cam. A 1989 Z-28 tuned port intake (TPI) manifold was used. Fuel metering was performed by a Garretson carburetion system with closed-loop control. A microprocessor controlled the speed of a fan, which activated a diaphragm, changing the amount of fuel entering the mixer. The mixer, which was custom-built, was placed in front of the existing throttle plate. Two (2) Camet electrically heated catalytic converters were mounted to the exhaust headers, while the original catalyst was retained. However, the heating capabilities of the Camet converters were inoperative at the competition.

OLD DOMINION UNIVERSITY - Old Dominion used a 268-cid engine, blueprinted. The rotating assembly had been lightened, and care was taken to balance compression from cylinder to cylinder. A 7.4:1 compression ratio was attained with stock pistons. The pistons were used because their high top compression ring reduced the amount of stagnant mixture trapped above the rings. A custom camshaft with low duration was used, as were 1.6:1-ratio roller rocker arms. The cylinder heads were the stock ones for the motor; however, they were reshaped in the combustion chamber and port areas for improved flow and combustion characteristics. A GM TPI plenum and intake manifold from a 5.0-liter engine was used to distribute the air-fuel mixture. The manifold also played a part in a regenerative heat cycle, where exhaust gases circulated through EGR passages to heat the incoming mixture. Additional heat was added downstream of the GM V6 throttle body, where a modified turbocharger mildly compressed the intake stream and a low efficiency heat exchanger imparted enthalpy to the flow. The modified turbocharger's main role was to homogenize the incoming air and fuel. Fuel was metered through a two-stage pressure regulator into a gaseous continuous-injection system, teamed with pulse-width-modulated

Robert Larsen

solenoids. The stock exhaust manifolds routed spent gases to the homogenizer first, and then to two Walker three-way catalysts.

TEXAS TECH UNIVERSITY - Texas Tech University's conversion involved extensive engine modifications. A 305-cid block combined with a 3.75-nch stroke crankshaft from a 400-cid engine yielded a displacement of 335 cid. The use of 53-cc combustion chamber heads allowed a 11.75:1 compression ratio with the stock 305-cid flat-top pistons and 5.565-inch connecting rods. The camshaft was also modified to allow longer burn time during the power stroke. Roller rocker arms and hydraulic roller lifters were used to reduce friction. The intake system incorporated a supercharger that also acted as a fuel mixer. Gas was injected through six (6) BKM/servojet injectors, which were driven by an Electromotive pulse-width-modulated computer. A special injector manifold mounted the injectors above the supercharger and below the throttle body. Emissions control strategy included a liquid-cooled EGR system, light-off and main catalytic converters, and an electric air-njection pump.

UNIVERSITY OF ALABAMA - Alabama was one of the three LNG schools in the competition. Their approach included a compression increase obtained by a cylinder head and piston swap. Forged pistons and 64-cc combustion chamber heads replaced the originals. The resultant compression ratio was 12.5:1. The cylinder heads utilized larger intake valves than stock. The fuel system used consisted of an Impco natural gas carburetor supplemented by an Electromotive ECFI system. The system was designed so that the carburetor would supply a slightly lean mixture and the Electromotive unit would adjust the mixture downstream of the carburetor, subject to engine requirements. The stock catalytic converters were replaced with three heat-shielded converters, designed specifically for natural gas operation, in a cascade configuration.

UNIVERSITY OF BRITISH COLUMBIA - UBC's turbocharged engine, shown in Figure 4, was based on a 30-mil over-bored block that displaced 309 cid. Flat-topped, forged pistons and GMC "K"-type connecting rods were used. With 58-cc heads, the compression ratio was 10.5:1. The camshaft used had 0.450 lift, 240 degrees duration, and no overlap. Ignition of the fuel-air mixture was aided with an MSD unit. Two Garrett T2 turbochargers, plumbed to the engine's oil system, had integral waste gates that limited boost to a maximum of 8 psi. An EGR system was designed but not used in competition, due to observed, unacceptable increases in HC emissions. Fuel was delivered by 6 BKM Servojet injectors with throttle body injection. Closed-loop control of the injection used an air mass-flow sensor in the intake stream and a GM lambda sensor in the exhaust. The stock catalyst was replaced by a three-way model by Englehard.

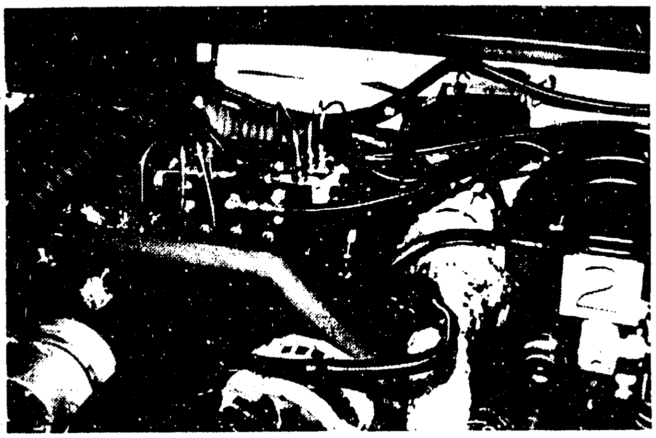

Figure 4 Custom natural gas fuel-injection system on the twin-turbocharged engine from the University of British Columbia.

UNIVERSITY OF MARYLAND - Maryland used an over-bored 350 block to achieve a 357-cid motor. With 1970 vintage cylinder heads, the measured compression ratio was 10.5:1. Their engine used a Garrett turbocharger with an intercooler. Engine management was through an Electromotive system.

UNIVERSITY OF MICHIGAN, DEARBORN - Michigan's entry was modestly modified. The powertrain remained stock, with the exception of Impco regulators and mixer for fuel delivery and insulated tubular exhaust headers leading to the stock catalyst, plus two additional custom catalysts.

Robert Larsen

UNIVERSITY OF NEBRASKA - Nebraska's engine was over-bored to displace 355 cubic inches. They used forged pistons and cylinder heads with polished 68-cc combustion chambers to arrive at a 9.8:1 compression ratio. A Crane roller cam and lifters were used also. Induction was through dual, intercooled, Garrett T03 turbochargers and a TPI intake manifold. Eight BKM Servojet injectors metered fuel that was regulated by a Modern Engineering regulator. The exhaust strategy was to insulate a custom tubular header system back to, and including, the twin NAPA catalysts.

UNIVERSITY OF OKLAHOMA - The LNG-fueled engine in Oklahoma's truck had a displacement of 350 cid. Compression was raised to 12.5:1 by installing domed pistons. The pistons were coated with a ceramic thermal barrier (as were the exhaust headers). An Edelbrock manifold was modified for port injection operation; the injectors used were eight BKM Servojets. A Ford throttle body was mated to the manifold. The camshaft was also an Edelbrock item. Engine management worked through an open-loop system and was controlled by a Haltech ECU. The stock catalyst was replaced by a Johnson-Matthey three-way natural gas catalyst.

UNIVERSITY OF TENNESSEE - The University of Tennessee team built their engine around a 305-cid block with a 400-cid crankshaft, yielding a displacement of 334 cid. Six-inch connecting rods were selected along with custom-forged aluminum pistons. The use of aluminum heads featuring 57-cc fast-burn combustion chambers resulted in a compression ratio of 9.6:1. A custom-ground cam coupled to roller lifters and roller rocker arms provided quick opening and low overlap of the valves. Custom headers routed the exhaust through a single Garrett turbocharger, which was set to produce 5.5 psi of boost. The engine itself made 320 foot-pounds of torque @ 2,000 rpm on the dynamometer.

Fuel metering was accomplished by an Impco 300 mixer controlled by an Autotronic closed-loop feedback system. A heated oxygen sensor provided input to maintain a stoichiometric air/fuel ratio. The converted engine's spark timing was then calibrated for optimal operation with natural gas. Emission control devices included two three-way catalysts in series, air injection, and Exhaust Gas Recirculation (EGR). The final drive ratio was changed from 3.73:1 to 4.10:1, and an auxiliary overdrive unit was installed.

UNIVERSITY OF TEXAS, AUSTIN - The engine that came with the 1991 Sierra was retained with minor changes. The pistons were replaced with forged aluminum pieces, which raised the compression to 11.0:1. The cylinder heads used were the cast iron Dart-II heads, chosen for their small combustion chambers. The rotating assembly was dynamically balanced. A roller camshaft with zero overlap and roller rocker arms were employed. The intake system used consisted of a dual-plane intake manifold matched with a Holley throttle body. An Impco mixer was used. Control of air/fuel ratio was accomplished in closed-loop mode with an Autotronics unit. A dual exhaust system with headers carried the burnt gases through a proprietary Englehard three-way catalyst.

UNIVERSITY OF TORONTO - The engine used by Toronto was over-bored 30 mil and fitted with a long-stroke crankshaft to produce 383 cid. Flat-top cast pistons, with Corvette cylinder heads, produced a 10.8:1 compression ratio. A dual plenum intake manifold with a Holley throttle body topped off the engine. Fuel was supplied by a tandem system comprising a Yugo-Tech gaseous induction system and regulator, which supplied the majority of the fuel required, and a Holley TBI, fed by a second regulator. Compensation of air/uel ratios was closed-loop, with a control system of their own design. Exhaust was through tubular headers connected with a balance pipe. Twin Corvette catalysts were employed, as was an air injection system to enhance catalyst efficiency.

UNIVERSITY OF VIRGINIA - Virginia essentially kept its powertrain stock and concentrated mainly on the fuel system. Fuel regulation was through a three-stage Landi Renzo regulator and a custom-made mixer. The truck ran dual exhausts with platinum-rhodium catalysts. The Virginia team used a Super-Fix to keep the stock ECM functioning properly, and

Robert Larsen

the truck retained dual fuel capabilities with an easily removable gas can in the bed.

WASHINGTON UNIVERSITY, ST. LOUIS - Washington University's truck was based on a strengthened 305-cid, 4-bolt block. The team utilized a forged crankshaft with six-inch connecting rods and slightly domed, forged pistons. With milled Corvette closed-chamber aluminum heads, the compression ratio was 12.5:1. The team's strategy to meet all the challenges of the event was to run the engine in the lean region of air/fuel mixtures. To get acceptable performance, turbocharging was selected. Twin Garrett T2 turbochargers with Buick Grand National intercoolers were used. These fed a custom mixer mounted on the stock manifold. Ignition was aided by an MSD unit. The team felt that catalysts were not necessary to meet emission standards, so they were deleted. The engine was intended to be a low-rpm, torque-producing motor, so the team changed the final drive ratio to 3.42:1 and modified the transmission to limit downshifts during part throttle operation. Their engine control computer was a reprogrammed GM ECM.

WEST VIRGINIA UNIVERSITY - West Virginia University's engine size was kept stock (350 cid). The compression ratio was raised to 12.6:1 with the use of domed, forged pistons and high-performance, 64-cc combustion chamber heads. A camshaft with a larger exhaust lift and duration was selected, along with roller rockers and lifters. The camshaft also had a smaller lobe separation than stock. An Impco carburetion system, including a pressure regulator and a gas mixer, was selected. The engine was tuned to be rich for better cold starting, leaning out to a stoichiometric level after engine warm-up. The ignition system was kept stock, with an initial spark advance of 18°.

THE COMPETITION

EARLY EVENTS - Because of the length of time required to perform full exhaust-emissions and cold-start testing, the rules required that competing vehicles be shipped to a certified testing facility three weeks in advance of the competition. All trucks were to arrive at the National Institute for Petroleum and Energy Research (NIPER) in Bartlesville, Oklahoma, by 5 p.m. Friday, May 17, 1991, for emissions and cold-start testing. Late-comers incurred 25 penalty points per working day.

In spite of several non-injury accidents en route and some eleventh-hour crises, 22 of the 24 competitors completed the testing at NIPER. The testing consisted of the city and highway cycles of Federal Test Procedure (FTP) emissions testing and cold-start testing in an enclosed chamber at -5°F. The emissions testing included separate modal data collection for hydrocarbon speciation and over the cold and hot transient phases, as described below.

EXHAUST EMISSIONS TESTING AND RESULTS

The vehicles were to achieve federal tailpipe emissions standards for 1991 light-duty trucks or incur penalty points. A team could earn up to 250 points by further reducing exhaust emission levels, as determined by the results of standard Federal Testing Procedure (FTP) emissions tests. Points were awarded using brackets corresponding to emission levels of all regulated pollutants. The brackets had values for each pollutant corresponding to the difficulty of controlling emissions of the pollutants simultaneously. The brackets and their point values have been adjusted for natural gas engine operation and established by the U.S. Environmental Protection Agency (EPA) Motor vehicle Emissions Laboratory. A listing of the brackets and their corresponding point values may be found in Table 3. Changes to the production exhaust emission control system were allowed, but appropriate heat shielding for the catalytic converter and other relevant exhaust system components was required for safety. Individual team scores were determined listed in Table 3. A team was not eligible to win the Best Fuel Economy Award or the Best Conversion Award if its entry failed the federal tailpipe emissions standards for 1991 light-duty trucks.

All testing at NIPER included measurements of regulated emissions, aldehydes, and

Table 3 1991 SAE Natural Gas Vehicle Challenge Emissions Chart

Pollutant	Any Pollutant Greater Than	Controlling Pollutant Equal to or Larger than	Contolling Pollutant Equal to or Larger than	Controlling Pollutant Equal to or Larger than	Controlling Pollutant Equal to or Larger than	Contolling Pollutant Equal to or Larger than	Contolling Pollutant Equal to or Larger than
HC (g/mi)	1.50	1.25	1.00	0.75	0.50	0.41	0.41
NMHC (g/mi)	—	0.50	0.39	0.25	0.13	0.08	0.04
CO (g/mi)	10.0	9.0	9.0	9.0	9.0	3.4	3.4
Idle CO (%)	0.50	0.50	0.50	0.50	0.50	0.50	0.50
City FTP NO_x (g/mi)	1.7	1.5	1.0	1.0	1.0	0.7	0.7
Highway NO_x (g/mi)	—	2.0	1.3	1.3	1.3	0.9	0.9
Total Particulates	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Your Score	-100	25	50	75	125	175	250

NOTE: Late arrival penalty at emissions/cold-start test facility = 25 points per working day after 5:00 p.m. May 17, 1991.

Legend: HC = Hydrocarbons
NMHC = Nonmethane hydrocarbons
CO = Carbon Monoxide
NO_x = Oxides of nitrogen

All emissions tests will be performed in advance of the actual competition. Teams will be notified via the computer bulletin board as to when their vehicle will be tested and may observe the test at their own expense.

hydrocarbon speciation. In addition, there were two types of modal measurements:

1. Regulated emissions at 10-second intervals over the first 100 seconds of both the cold and hot transient phases of the Urban Duty Driving Schedule (UDDS).

2. Hydrocarbon speciation of the first 80 seconds (cumulative) of both the cold and hot transient phases of the UDDS.

Engine-out emission data collected from the FTP tests were desired to enable catalyst efficiency measurements for HC, CO, and NO_x. Engine-out exhaust sample ports were a late addition to the rules, and fewer than a quarter of the competition vehicles were so equipped. Exhaust sample ports will be required for 1992, and details of their installation will be published and supplied to next year's participants.

Table 4 summarizes the FTP results obtained at NIPER. The listed order corresponds to the FTP testing order at NIPER. Only four schools passed the federal tailpipe emission standards for 1991 light-duty trucks. California State University - Northridge was the overall winner in the emissions category, followed by Colorado State in second place. Northwestern and the University of Tennessee tied for third place. The remaining 18 vehicles tested failed to simultaneously pass the regulated emission standards for HC, CO, and NO_x. Table 5 summarizes the competition emission test points awarded to each school and indicates FTP compliance for HC, CO, and NO_x with a pass/fail rating. At first, the results look discouraging, considering the majority of the schools failed the FTP test and started the competition with a negative score. However, a close inspection of the emission test results reveals that 10 schools passed the HC standard, 17 passed the CO standard, and 10 passed the NO_x standard. Eight schools that failed the FTP test failed on one constituent (HC fail = 2 schools; CO fail = 2; NO_x fail = 4). Nine schools failed two FTP constituents (HC and CO fail = 2;

Table 4 Natural Gas Vehicle Challenge Final Results - Emissions Testing

School	HC corrected for response to CH_4 — FTP Emissions HC gpm*	NMHC gpm	CO gpm	NOx gpm	H'way NOx gpm	Idle Emissions (ΣCX=9.8%) HC (ppm C)	CO (%)
British Columbia	10.00	1.06	1.6	3.63	3.15	1830	0.41
Colorado State	0.63	0.06	2.5	1.33	1.14	30	0.01
West Virginia	3.10	0.46	0.1	5.17	5.36	3740	0.00
Old Dominion	1.50	0.17	1.2	2.17	2.38	770	0.00
Ohio State	2.42	0.25	4.6	2.07	3.24	2420	2.15
Fla. Inst. Tech.	1.45	0.22	26.6	0.72	0.54	370	0.00
Tennessee	1.50	0.13	0.8	0.68	0.66	1190	0.00
Virginia	1.83	0.20	10.7	3.91	2.09	13540	0.00
Ill. Inst. Tech.	1.43	0.16	0.4	2.28	2.12	1390	0.00
Concordia	1.09	0.10	1.1	1.98	1.77	1160	0.00
Texas	3.16	0.47	0.5	4.62	5.43	2670	0.00
Northwestern	1.05	0.22	0.1	1.77	1.67	2240	0.00
Toronto	5.76	0.74	0.7	2.09	1.94	6260	0.00
Michigan	2.33	0.36	8.2	0.86	0.98	6510	0.40
Texas Tech.	1.02	0.20	0.6	2.03	1.14	640	2.51
Cal. State	0.37	0.09	4.9	0.28	0.03	80	0.02
Maryland	14.54	5.09	149.3	0.40	2.33	470	1.22
Alabama	1.43	0.49	19.7	0.20	0.06	170	0.03
Washington	4.20	1.09	2.8	3.80	3.68	1000	0.20
New York Inst. Tech.	2.60	0.38	4.3	1.01	1.06	1970	0.03
Ecole Polytechnique	4.01	0.56	0.1	2.30	2.76	5930	0.00
Oklahoma	11.09	2.89	84.3	0.13	0.09	8870	1.84

*gpm = grams per mile.

Table 5 FTP Emissions Test

School	Points	1991 LDT Truck Emissions (Pass/Fail)		
		HC	CO	NO_x
Alabama	-100	P	F	P
Brit. Columbia	-100	F	P	F
Colorado St.	50	P	P	P
Concordia	-100	P	P	F
CSUN	175	P	P	P
Ecole Poly.	-100	F	P	F
FIT	-100	P	F	P
GMI*	-100	-	-	-
IIT	-100	P	P	F
Maryland	-100	F	F	P
Michigan	-100	F	P	P
Nebraska*	-100	-	-	-
Northwestern	25	P	P	P
NYIT	-100	F	P	P
Ohio St.	-100	F	P	F
Oklahoma	-100	F	F	P
Old Dominion	-100	P	P	F
Tennessee	25	P	P	P
Texas	-100	F	P	F
Texas Tech.	-100	P	P	F
Toronto	-100	F	P	F
Virginia	-100	F	F	F
Washington	-100	F	P	F
West Virginia	-100	F	P	F
Gasoline Sierra*	75	P	P	P

*Vehicles not FTP-tested at NIPER.

HC and NO_x fail = 7), and one school failed all these FTP test constituents. Two vehicles were not tested at NIPER due to mechanical failures.

The four participants that passed the FTP emission tests ran on CNG using three-way catalytic converters (TWCs). The catalyst systems found on these vehicles were supplied by three different automotive catalyst companies. Two converters were found on each of these vehicles, and total system catalyst volumes were in the 200-400-in.^{3} range. Details on the TWC composition of these catalysts are proprietary in nature and cannot be determined. The engine management systems seen on these vehicles were stock TBI with closed-loop A/F control (Tennessee, Cal State), TPI with closed-loop A/F control (Colorado State), and stock TBI with an open-loop system (Northwestern). Exhaust heat management consisted of thermally wrapped tubing and catalyst locations underfloor, in close proximity to the gasoline production location.

Three competition vehicles were converted to run on liquefied natural gas (LNG). All had good NO_x control but had after-treatment oxidation weaknesses. TWCs were employed, and each school utilized a different engine management control (stock, after-market, other GM). Open-loop A/F control was used on one LNG truck.

With respect to exhaust-gas after-treatment, the remaining 15 CNG competition conversions yielded catalyst volumes ranging from 0 to 900 in.^{3} (the one vehicle without a catalyst did pass the CO standard). Warm-up and electrically heated catalysts were also seen. Five vehicles had the stock gasoline catalyst, and two schools added upstream converters to help the stock underfloor converter (1 electric heat; 1 warm-up). Combined oxidative and TWC systems were also seen.

In general, the emission performance showed overall weaknesses in simultaneous emission control strategies. Six schools failed to pass HC, CO, or both HC and CO standards. Four schools had trouble reducing exhaust NO_x concentrations to meet the current LDT standard, and eight schools had three-way control problems.

Meeting the federal tailpipe standards for 1991 light-duty trucks proved to be more difficult than anticipated. Considering that the catalysts were generally supplied by industry and were relatively fresh (the majority of the odometers registered under 3,000 miles), the cause for the poor emission results can be attributed either to failure to optimize engine management systems for emissions or to catalyst operating temperatures being below desired levels. Catalyst operating temperatures were not recorded, so this hypothesis remains untested. Individual vehicle catalyst efficiency measurements cannot be determined from the data collected at NIPER.

It is recognized that the emissions area is one of the most difficult for student teams to address. The cost for private FTP tests or steady-state emission testing equipment was beyond most schools' conversion budgets. The unavailability of commercial catalytic converters designed for natural gas operation also left teams reliant upon unproven and donated technology.

One explanation for the poorer than expected emission results is the CNG fuel that was used in testing. Teams were assured that the content of the test fuel would be 95% methane by volume. The analysis of the fuel at the beginning (5/21) and again at the end of the emission testing (6/4) is shown in Table 6. The volume percent methane was nearer to 90%, and this could have adversely affected the calibration settings for the emission tests. Table 7 summarizes the LNG fuel analysis at NIPER. The three LNG competition vehicles were emission-tested with the on-board fuel that they contained upon delivery.

The two types of modal data measurements collected at the tailpipe during FTP testing were the cumulative mass emissions (HC, CO, NO_x) collected at 10-second intervals over 100 seconds and the hydrocarbon speciation over the first 80 seconds of the cold and hot transient phases. The intent of the mass emission collection was to compare the fuel management (combustion) and catalyst efficiencies of the various systems. Since exhaust gas and catalyst temperatures were not collected, catalyst operating temperatures and light-off characteristics cannot be determined. Wide ranges of emission levels were observed for all

Table 6 NGVC CNG Fuel Analyses at NIPER

	Analysis, by Date	
Component	5/21 (vol %)	6/4 (vol %)
Methane	89.5	89.6
Ethane	5.2	5.2
Propane	1.5	1.5
Butanes	0.4	0.4
Pentanes	0.1	0.1
Nitrogen		
Carbon Dioxide	0.3	0.2
Helium		
Oxygen		
Unknowns	3.0	3.0
Total	100.0	100.0
H/C	3.805	3.809
O/C	0.006	0.004
X/C	0.028	0.028
Gross Btu/SCF[a]	1055	1056
Net Btu/SCF	952	953
gC/100,000 Btu	1611	1609

[a]SCF = standard cubic foot (feet).

three regulated components. Figure 5 shows the unweighted cumulative HC collected for the first 100 seconds of the cold and hot transient phases. Ten teams passed the FTP HC standard and are indicated by asterisks. Generally, the schools with the lower-value cold transient of HC emissions (in grams) passed the FTP HC constituent. The difference in the cold and hot transient values is indicative of warmed-up catalyst activity. Lower cold-start HC emittance is also indicative of either good cold-start fuel control (for either stoichiometric or

Table 7 NGVC LNG Analyses at NIPER

Component	Ala. (vol%)	Md. (vol %)	Okla. (vol %)
Methane	98.4	83.3	98.7
Ethane	1.5	16.3	0.8
Propane	0.1	0.3	0.1
Butanes	0.0	0.0	0.4
Pentanes	0.0	0.0	0.0
Total	100.0	100.0	100.0
H/C	3.968	3.708	3.957
Gross Btu/SCF	1025	1144	1029
Net Btu/SCF	923	1034	927
gC/100,000 Btu	1581	1625	1583

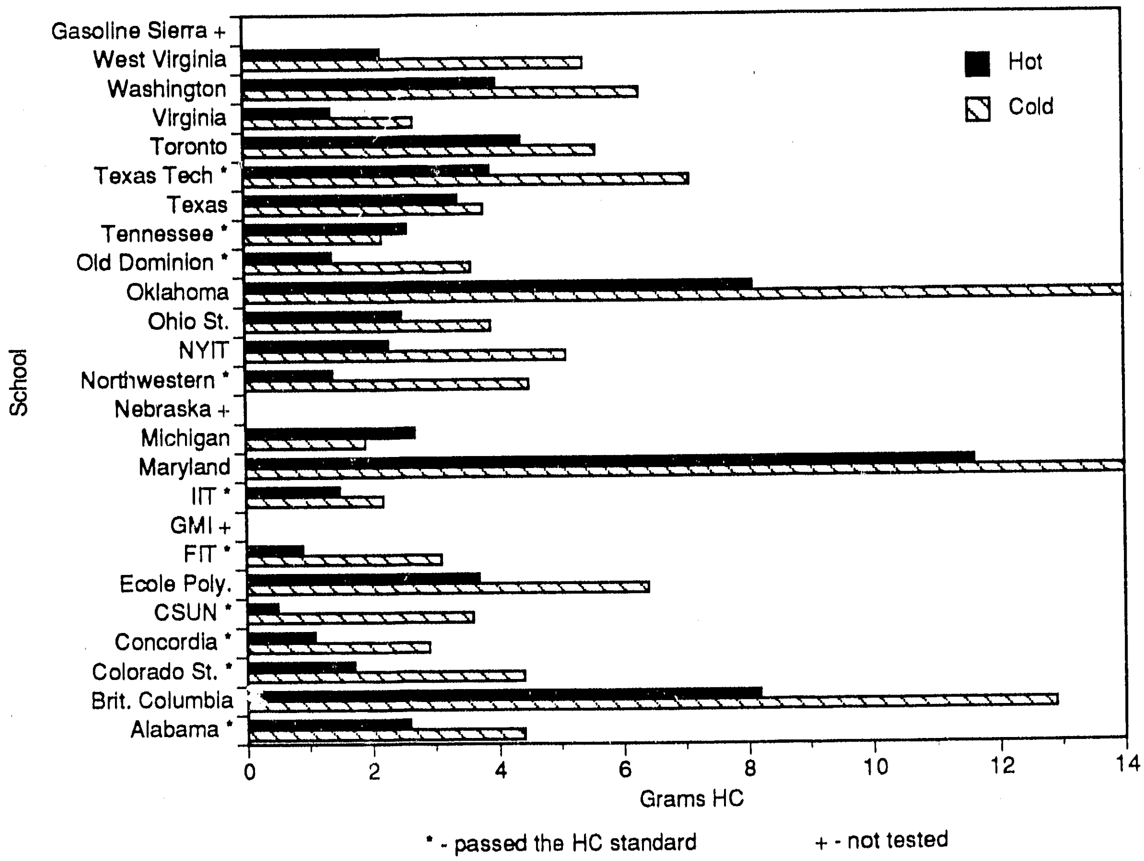

Figure 5. Cumulative HC collected during the first 100 seconds of the hot and cold FTP transient phases.

lean-burn strategies) or good catalyst light-off characteristics. The vehicles that failed the FTP HC test had poorer cold-start HC emittance (poor fuel management or long light-off times) and higher hot transient cumulative HC values (poor catalyst performance due to formulation or operating temperature). Two of the three LNG vehicles had high cold transient HC emissions (teams 9, 15) that were catalytically controlled to some degree in the hot transient test. There were a few HC-failing participants whose 100-second emission levels in the transient phases were similar to or lower in magnitude than those of some of the schools that passed the FTP HC testing. Here, poor catalyst performance (efficiency) would be a possible cause.

Figure 6 similarly depicts the FTP unweighted CO emissions during the first 100 seconds of the transient phases. Only five schools failed to meet the CO standards. All three LNG vehicles (teams 1, 9, 15) failed CO, where poor catalyst efficiency is indicated by the hot transient CO results. Very good CO control was obtained by many schools, and the 10.0-g/mi limit was easily achieved. Only four schools that passed the CO standard, set at 10.0-g/mi, did not pass the 3.4 g/mi target. Cold transient CO levels showed a wide range of values, and good catalytic control was demonstrated by most passing teams with very low (zero in many cases) hot transient CO values.

Figure 7 graphs the transient NO_x results for the first 100 seconds. Ten teams met or surpassed required FTP values. A wide range of cumulative values was observed. Good NO_x conversions are seen when comparing cold to hot transient emission levels. Lower cold transient cumulative NO_x emission levels were indicative of teams that were able to pass the NO_x requirements. Again, meeting or surpassing the NO_x requirement was achieved either with good engine management control or with exhaust after-treatment. The schools that

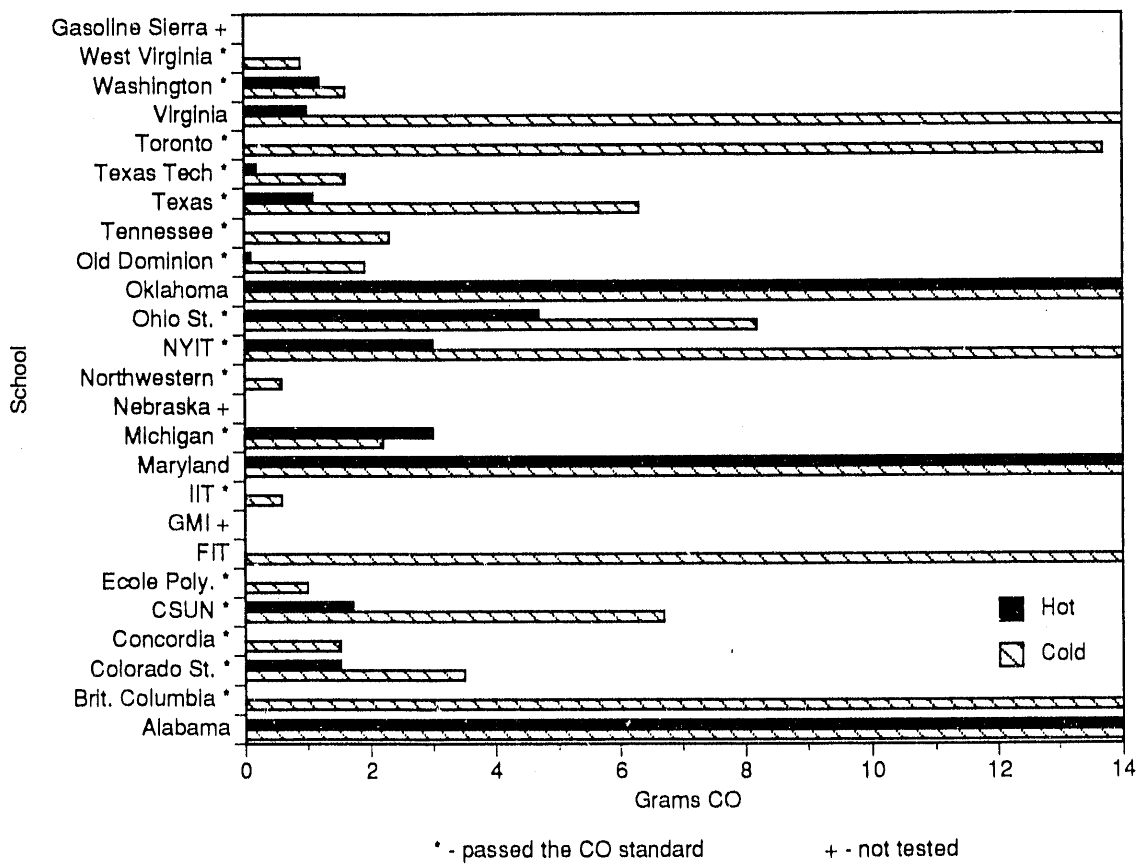

Figure 6. Cumulative CO collected during the first 100 seconds of the hot and cold FTP transient phases.

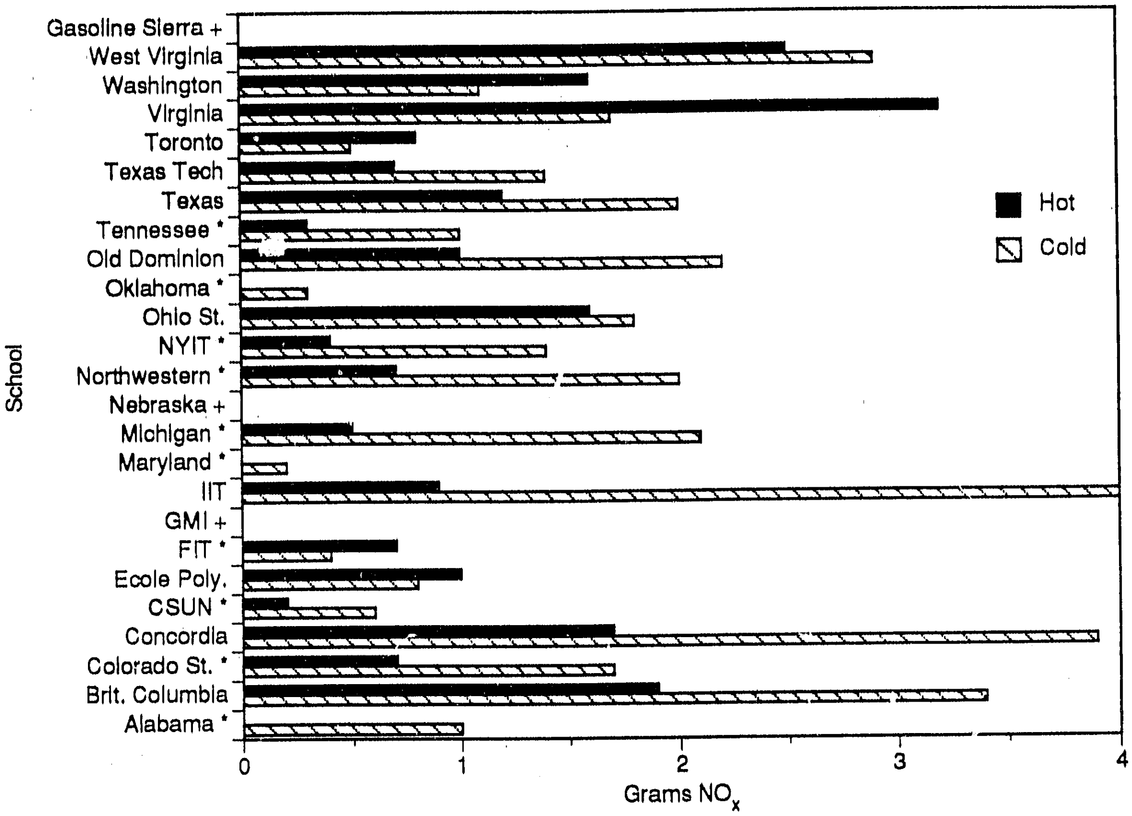

Figure 7. Cumulative NO_x collected during the first 100 seconds of the hot and cold FTP transient phases.

did not pass NO_x requirements but had cold transient emissions of approximately 2 g displayed poor hot transient conversions and hints of poor catalyst reduction properties.

Finally, the second type of modal data collected was the hydrocarbon speciation of the first 80 seconds (cumulative) of both the cold and hot transient phases of the UDDS. The speciation analysis was done by gas chromatography. Approximately 200 hydrocarbon species are quantifiable in this type of analysis. For CNG vehicles, the major HC constituents in the transient phases were methane, ethane, and propane, the same major constituents present in the fuel composition (Table 6). For the 19 CNG vehicles, methane weight percents ranged from 78 to 85% for the cold transient and from 81 to 96% for the hot transient. Ethane weight percents ranged from 4 to 10% for both transient phases. Propane fractions ranged from 1 to 4 wt %. Other significant exhaust constituents (~1 wt %) were ethylene and butane. The HC exhaust speciation for the LNG vehicles had lower cold and hot transient methane emissions (45-63 wt % and 54-83 wt %, respectively) and higher ethane fractions (14-34 wt %) in the transient phases.

COLD-START EVENT - Cold-start testing was performed in a refrigerated semi-trailer capable of containing two of the Sierras. The trucks were a tight fit, requiring NIPER personnel to climb over them and squeeze through the doors to perform the test. Originally, testing was to be done at -20°F, but the typically hot weather of late May in Oklahoma made testing at that temperature impossible. The lowest temperature that the refrigerated trailer could consistently maintain was -5°F, so it was decided to perform the testing at that temperature.

After an overnight soak at -5°F, 14 of the 22 teams tested started within the prescribed cranking time of five seconds. Six vehicles started in less than five seconds, idled in neutral, and ran for five minutes held in gear against the brake without driver intervention. This performance was defined as superior and received the full 50 points available for this event, plus a three-point bonus for every second less than five when a start occurred.

Five additional vehicles started, idled, and ran for five minutes in gear but took more than five seconds of cranking time. Three more teams started in the allotted time and ran for 30 seconds but would not run for five minutes in gear without driver intervention. In fact, 21 of the 22 competitors tested eventually started and ran for 30 seconds, but seven of them exhausted all the available points for the event before demonstrating their ability to start at cold temperatures. Overall, scores for this event ranged from zero (a total of 10 competitors, including two that were not tested) to 59 points for the best starting truck, that of the University of Michigan - Dearborn. The scores for this event are depicted graphically in Figure 8.

OPENING DAY - On June 6, 1991, two members from each student team were present to convoy their vehicle from the NIPER facility in Bartlesville to the State Capitol in Oklahoma City, where opening ceremonies were to be held. The competing vehicles were lined up in front of the NIPER facilities and displayed for the public and media before a brief ceremony. Along the way, the teams participated in a media event while refueling at a Texaco natural gas refueling facility in a service station in Tulsa. A similar refueling and media stop occurred at a Phillips Petroleum natural gas refueling facility at a service station located in a rest area along the interstate highway at Stroud, between Tulsa and Oklahoma City.

At the state capitol, James Townsend, Interim Director of the Oklahoma Department of Pollution Control, representing the state and its Governor, greeted the teams. Jerry Allsup, Director of DOE's Office of Alternative Fuels, and Tom Smyth, Manager of Vehicle Technologies, Alternative Energy Division, Energy, Mines, and

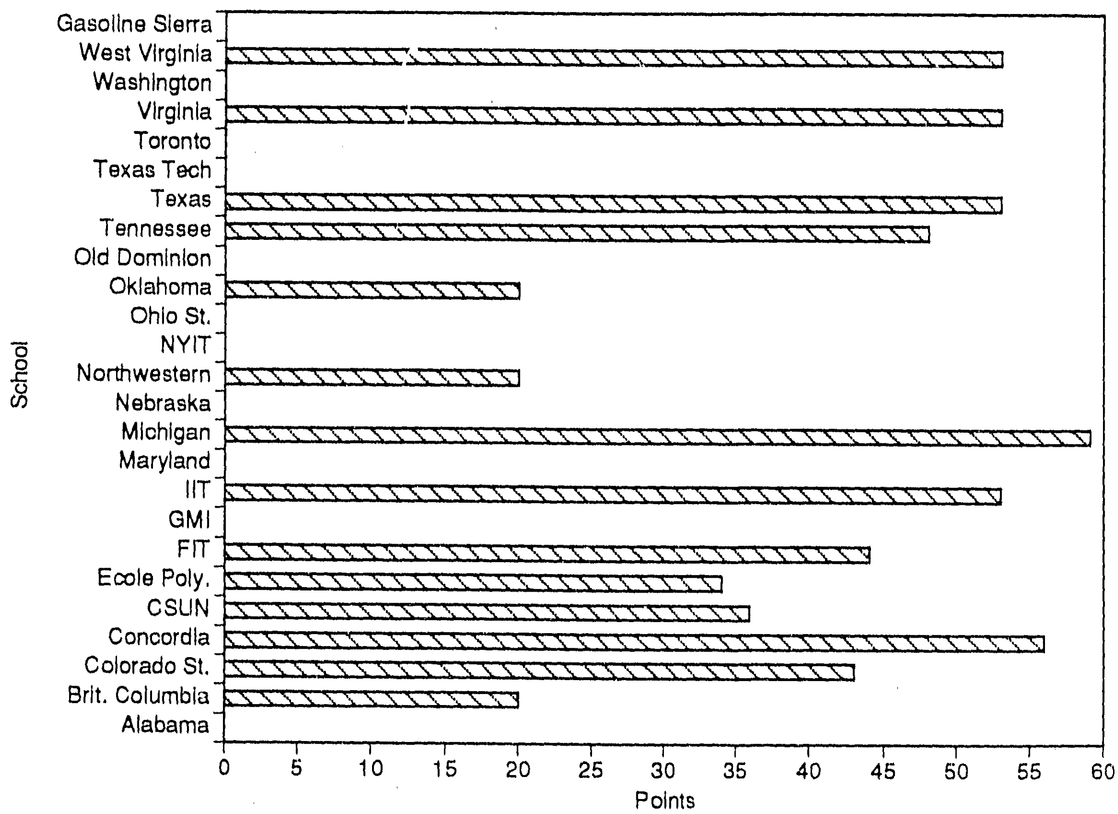

Figure 8. -5°F Cold Start Performance Event

Resources - Canada, both made welcoming remarks and praised the students' achievements in developing alternatives to imported petroleum. John Christie, Manager of Powertrain Design, GM of Canada, congratulated the students on their efforts and observed that the skills they developed in this event would be valuable throughout their careers. The Honorable Carl Rufelds, Canadian Consul General, spoke of the potential of natural gas as a vehicle fuel and as an area of cooperation between the U.S. and Canada. The event was widely reported in the local print media and appeared on television that evening.

After the ceremonies, the teams drove to the Energy Center on the University of Oklahoma Campus in Norman, where the rest of the team members were being registered. Once at the Energy Center, teams, faculty advisors, and judges were treated to a reception courtesy of the American Gas Association. Dr. Lemont Eltinge, President of SAE, spoke to the teams about the importance of refining their professional skills and developing a network of colleague contacts to help them in their careers. He encouraged them to take advantage of events such as this to keep their skills sharp and keep abreast of new developments in the fast-changing engineering profession.

STATIC EVENTS - All teams submitted a design report, describing their conversion and operation approaches, in advance of the actual competition. Topics addressed included how they controlled their trucks' exhaust emissions and how they overcame other technical challenges, including cold and hot starting and driveability, fuel economy, and performance. This event was included to provide a record of the teams' activities, as well as to emphasize the importance of communicating and documenting the engineering decisions made in the process of vehicle design and development. The papers were weighted according to the following criteria:

NGV Conversion	35 points
Emissions Control System	20 points
Performance Design Characteristics	20 points

The results of the design report event are shown in Figure 9. The University of British Columbia scored 47 out of 50 possible points, with Colorado State finishing a close second with 46.6 points and the University of Nebraska third with 43.5 points. A copy of the design paper scoresheet is included in Appendix C. The same judges that donated their time to review the design papers also served on the panel that judged the design inspection event held on Day Two of the competition. During the design inspection, the vehicles themselves were judged according to innovation, craftsmanship, and feasibility of design in terms of readiness for production and cost. Texas Tech University won this event, with the University of Maryland and Colorado State finishing a close second and third, respectively. The results of this event are shown in Figure 10. A copy of the design inspection scoresheet also appears in Appendix C. The judges listed in Table 8, without whose efforts these events could not have been held, are thanked heartily by the organizers.

Also on Day Two, teams gave 10-minute oral presentations of their designs to a panel of 16 judges. This event was included in the competition to stress the importance of verbal communication of technical information as a professional engineer. A five-minute question and answer session followed each presentation. Points were awarded according to content, format, and delivery. Concordia University took the top spot in this event, with the Universities of Tennessee and Toronto in second and third place. Complete results of this event are found in Figure 11. The oral presentation scoresheet appears in Appendix C. The individuals listed in Table 9 donated their time to serve as oral presentation judges; the organizers wish to thank them for contributing to an important part of the event.

PERFORMANCE EVENTS - The hot driveability event was conducted when the vehicles were completely warm on Day Two, after the design inspection event. The trucks were driven over identical courses on the University of Oklahoma campus and scored with a modified version of the driveability test used to

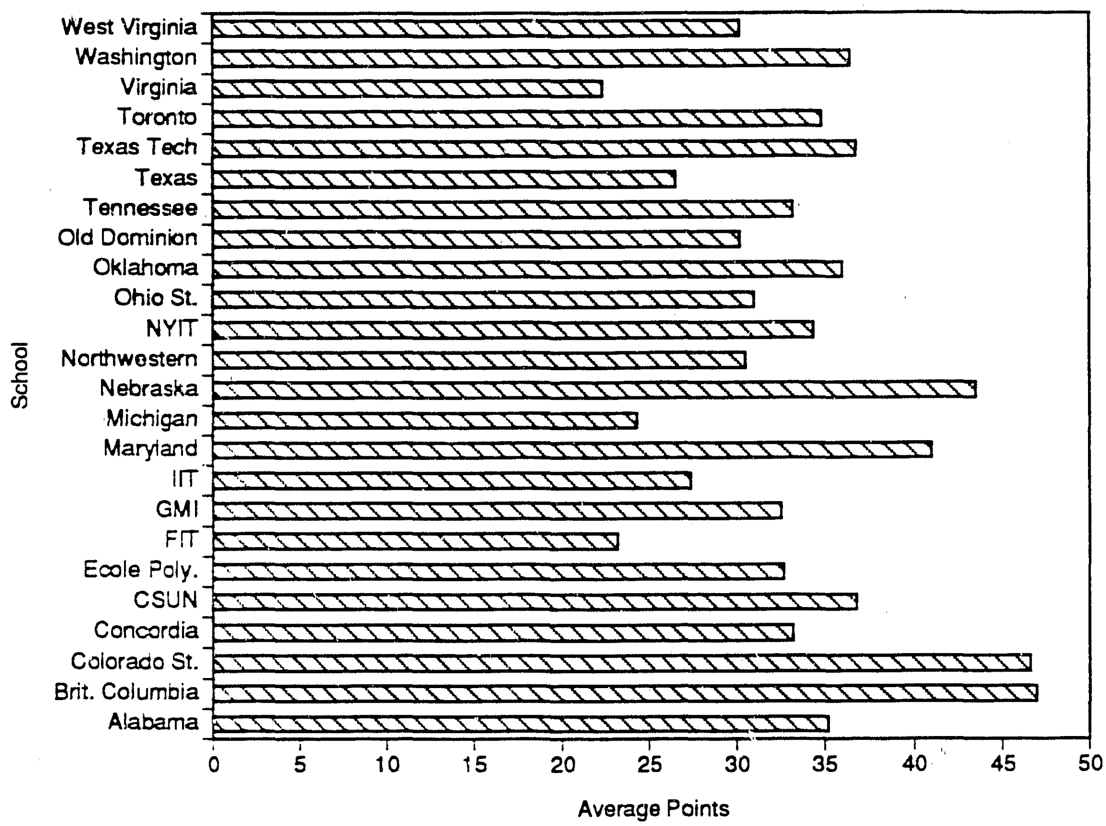

Figure 9. Results of the Design Report Event

qualify production vehicles. A trained GM evaluator drove each of the trucks to ensure comparability of the scores. In general, the performance of the trucks was quite good, with four of the teams achieving perfect scores: the University of Alabama, Concordia University, Illinois Institute of Technology, and Ohio State University. Most of the top-performing teams used a near-stock conversion system with a mechanical gas mixer. The Alabama team used LNG; the other top finishers were fueled by CNG.

The cold driveability event was conducted at 5:30 a.m. on Day Three of the competition. The trucks were at an ambient temperature of about 45°F after they sat overnight in a locked parking lot on campus. The same trained GM evaluator performed both the hot and cold driveability events to assure uniformity in judging. Several vehicles scored highly in this event. The University of Michigan-Dearborn truck performed as well as the control vehicle, with 99 out of 100 possible points, and slightly better than the trucks from Concordia and Illinois, which both earned 98 points. The results of both the hot and cold driveability events are found in Figure 12.

An unused taxi-way at the University of Oklahoma Airport was the site of several performance events on Day Three. First came the acceleration event. The trucks competed on an eighth-mile course from a standing start with 1000-pound loads in their beds. With photo cells and digital timers, officials timed two runs per truck by each of two drivers. The fastest time of each of the driver's runs were averaged for the scores in this event. Seven trucks out-performed the gasoline-powered control vehicle. The Texas Tech University truck was clearly the fastest of the trucks, helped by the engine strategy of using a supercharger. The Universities of Tennessee and Texas placed second and third in the acceleration event. Figure 13 shows the results from this event and how the trucks' performance related to that of the control truck. During the acceleration event, the team from the University of Nebraska arrived at

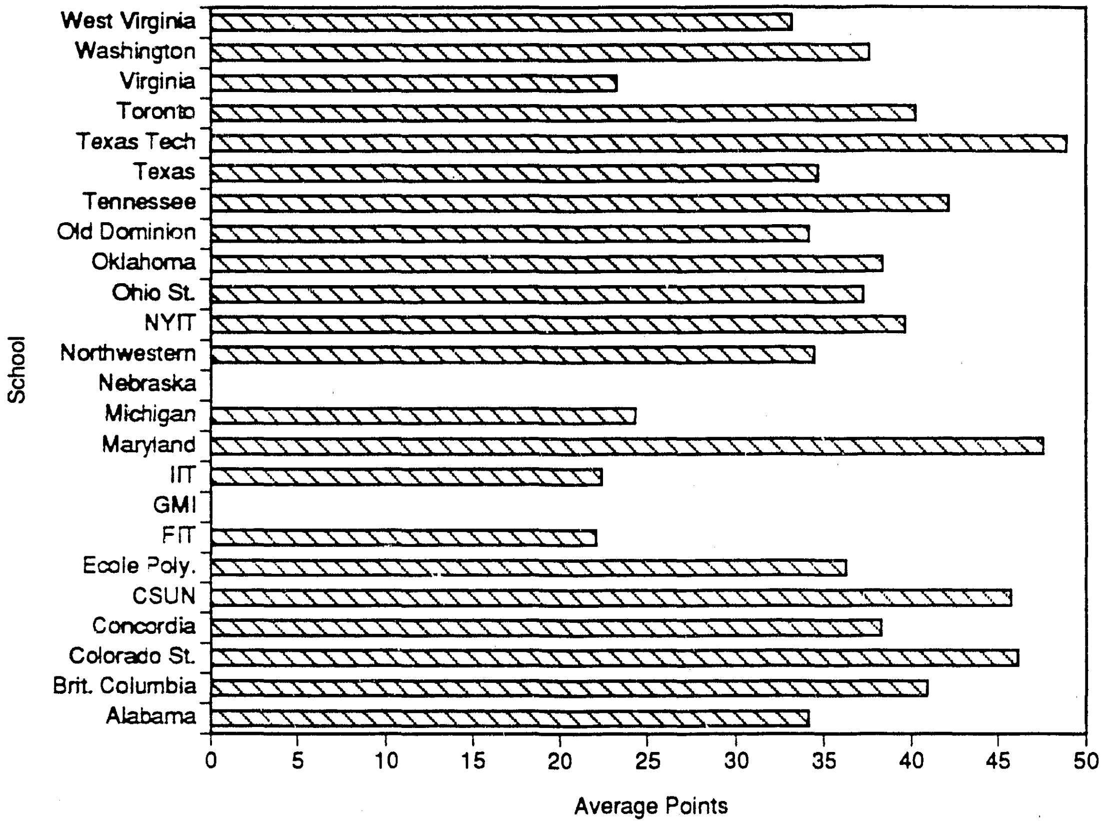

Figure 10. Results of the Vehicle Design Inspection Event

Table 8 Paper and Design Judges

Dr. Viswananth Javasraman, Consolidated Natural Gas
Roy Duncan, Hamilton Street Railway Co.
Keith Davidson, Gas Research Institute
Terry Ostapiuk, General Motors of Canada Ltd.
Dr. Roberta Nichols, Ford Motor Company
Christopher S. Weaver, Engine, Fuel & Emissions Eng.
Andy Beregsvasey, Office of Energy, Mines, and Resources - Canada
Douglas Horne, Atlantic Gas & Light Co.
Rob Bruetsch, Environmental Protection Agency
D.R. Gates, Chevrolet-Pontiac-Canada Group

---

the competition. The team had had an engine failure the previous week and had worked around the clock to repair their truck and participate in the competition.

Later, a special run of the fastest-accelerating trucks was held without the weight in the beds after the official timing was complete. This ad hoc event was quickly organized and schools. This rivalry resulted in lots of excitement and tire smoke; however, the Texas Tech team was again the clear winner, with an obvious power advantage over the rest of the field.

The exhaust noise event, performed in conjunction with the acceleration trial, was run according to the standard SAE test procedure J986b and modified for existing conditions. Only Texas-Austin's truck exceeded the federally mandated 80-decibel limit, incurring 10 penalty points.

Robert Larsen

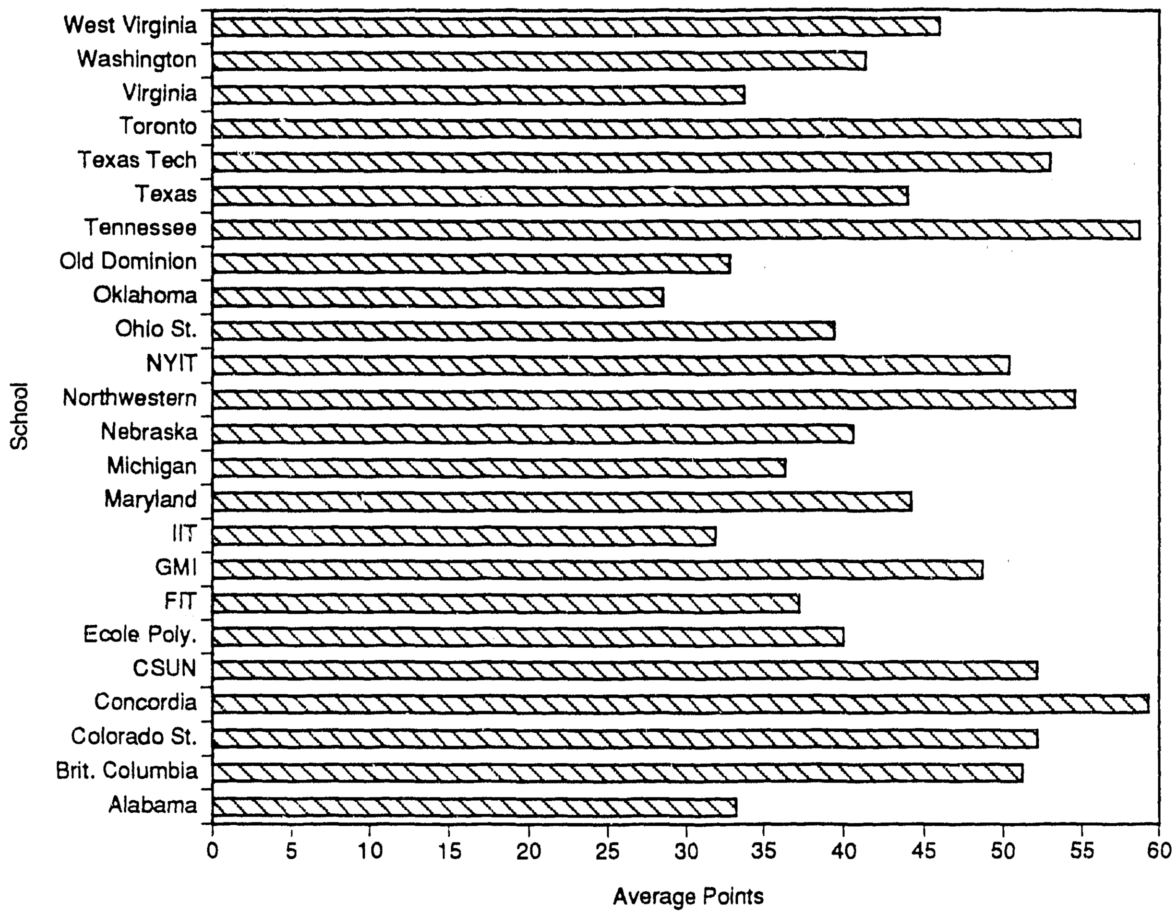

Figure 11. Results of the Oral Presentation Event

Table 9 Oral Presentation Judges

Norman Malcosky, Columbia Gas
Frank Ament, General Motors Corporation
Dr. Harvey Klein, Ford Motor Company
Vaughn R. Burns, Chrysler Corp.
Jerry Allsup, U.S. Department of Energy
John Christie, General Motors of Canada Ltd.
Norm Yale, Gas Research Institute
Burt Mason, Metropolitan Transit Authority
Gordon Larsen, Mountain Fuel
John W. Sayre, Automotive Natural Gas, Inc.
J.J. Haddon, Gas Marketing
S. Poredos, Union Gas Limited
Mike R. Gutirrez, Public Service Co. of Colorado
D.R. Gates, Chevrolet-Pontiac, Canada Group
G.P. McCarbery, General Motors Corporation

ROAD EVENTS - On Sunday, Day Four of the competition, the teams met at the Capital in Oklahoma City for the start of a 200-mile road rally to test the performance of the NG conversions, their fuel economy, and the driving skills of the competitors. An excellent test of their performance in everyday driving, this event put the trucks on a preplanned route over public roads at controlled speeds. Teams drove in ordinary traffic within the legal speed limit. Observers from the Oklahoma Region of the Sports Car Club of America (SCCA) scored vehicles for arriving early/late at secret checkpoints along the route. The SCCA officials who set up the rally also measured its length to the hundredth of a mile. To determine the road rally fuel economy, each CNG truck was filled to a temperature-corrected 3000 psi by Oklahoma

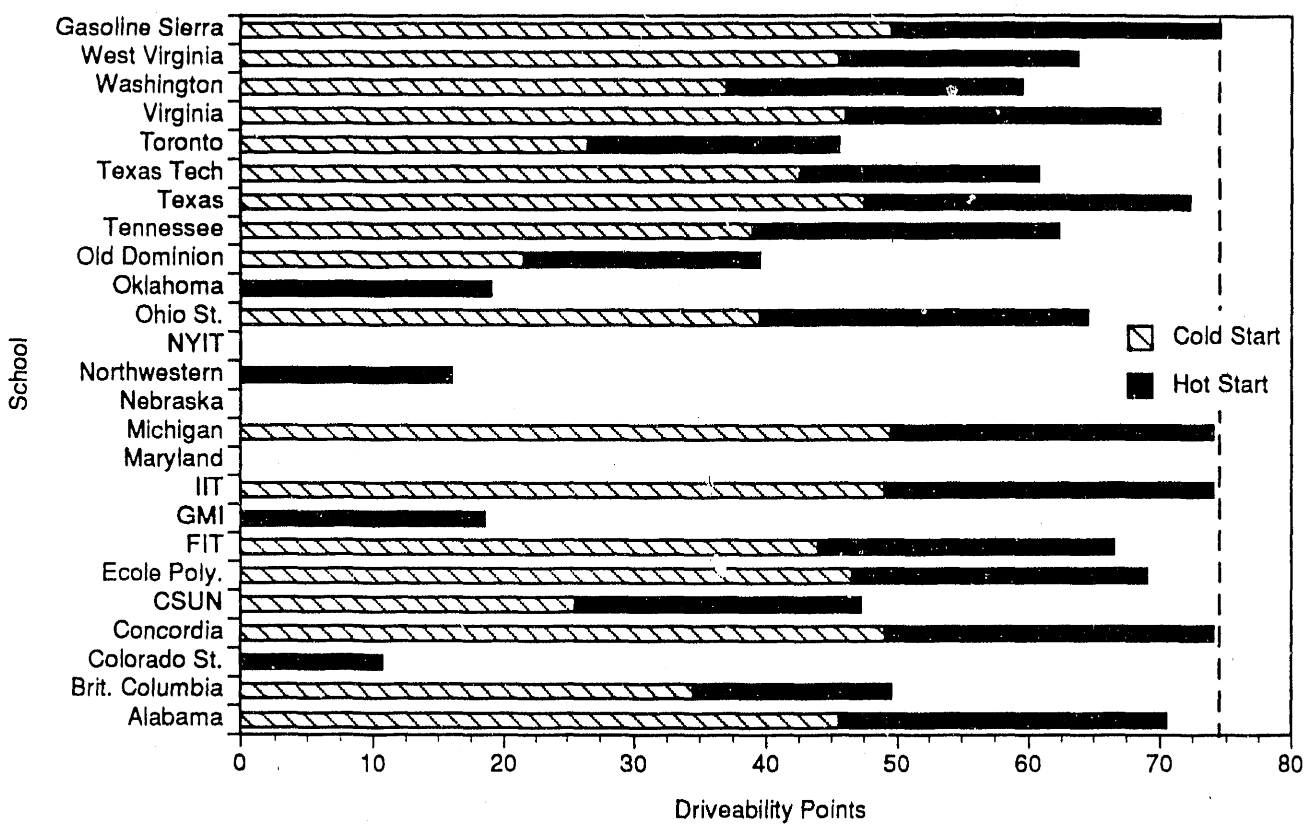

Figure 12. Results of the Driveability Events

Natural Gas at the start of the rally. Precise starting fuel pressures and temperatures were recorded by truck; the LNG teams also started this event with full tanks of fuel. Samples of both fuel types were taken so that their energy content could be evaluated and used in the fuel economy calculations.

The rally was not without its drama, with the competitors encountering a bicycle race along part of the same route as their rally. Changes to signage and typographical errors in the rally instructions led to several of the check points being excluded from the final scores. The half-way point of the rally was at a park on a lake outside of Norman. The teams had an hour break with a catered lunch. Several teams with fuel consumption problems obtained additional fuel (under the watchful eyes of event organizers); again, pressures and temperatures were recorded.

The rally ended back at the University of Oklahoma campus, where fuel pressure and tank temperature of the CNG-powered trucks were again measured. The LNG vehicles were refueled using a dewar that was weighed before and after the fuel was loaded into the three LNG-powered entries. Fuel economy was then calculated for the road rally using known tank sizes for the CNG trucks and the weight of the LNG used over the course of the rally. Every competitor except one bested the gasoline-powered control truck in fuel economy during this event. Washington University led all the schools with nearly 69% better fuel economy than the control vehicle. Close behind were West Virginia University and the University of Tennessee in second and third place, each delivering better than 60% better fuel economy compared to the control vehicle. Colorado State University excelled in the road rally, easily winning this event, with the Universities of Alabama and British Columbia in second and third place. The complete scores for these two events are shown in Figures 14 and 15.

Robert Larsen

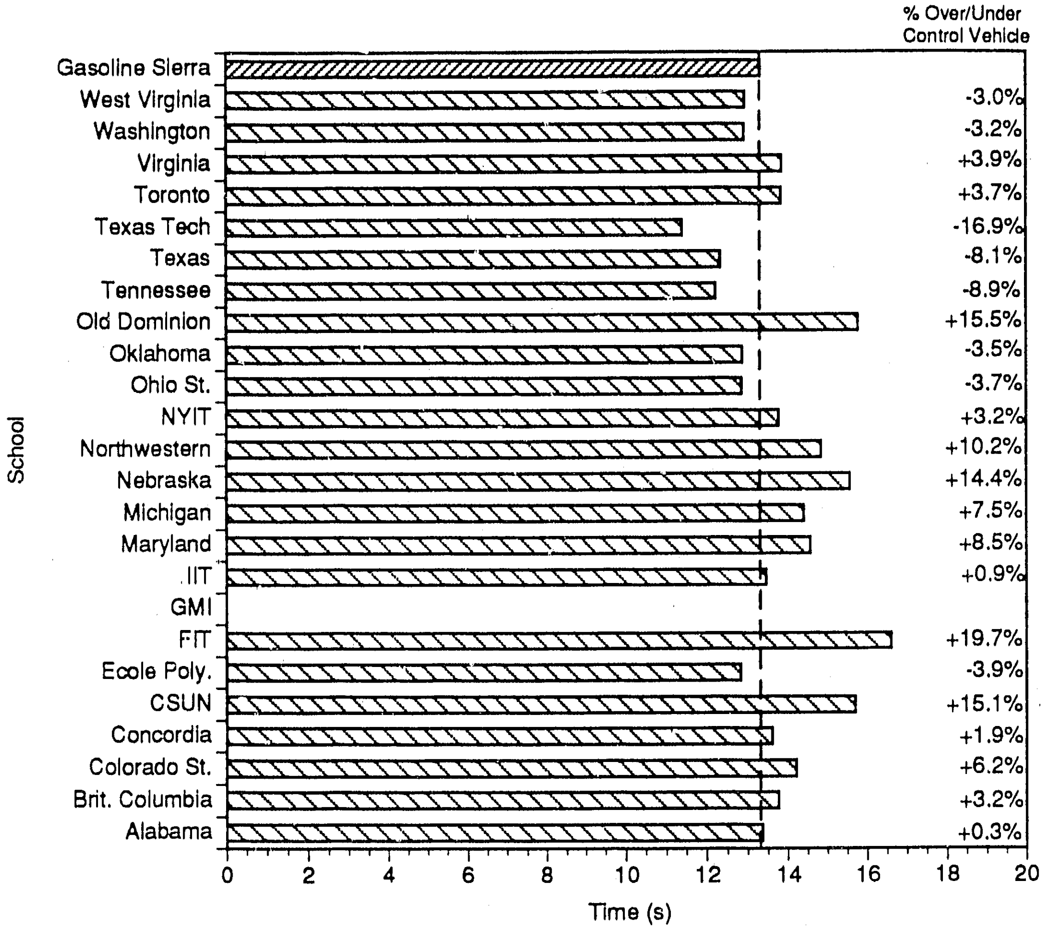

Figure 13. Results of the Acceleration Event

On Day Five, the trucks competed in an endurance event from Norman to Lake Murray, near Marietta, Oklahoma, and back to Norman. The 240-mile route was run almost entirely on an interstate highway at a steady 45 mph to provide near-ideal operating conditions. As part of the event's rules, this distance had to be run without refueling or teams would face penalties. The start of this event was similar to that of the rally, where Oklahoma Natural Gas again fueled all the vehicles to a temperature-corrected 3000 psi and the LNG vehicles were filled to their capacity.

We were delighted to see the truck from GMI rolling up early in the morning for the first time in the competition. The truck had been brought down overnight from Bartlesville, where it had been suffering from mechanical problems incurred before the emission testing several weeks earlier. After hours of working on an engine that would not retain its coolant, a cracked cylinder head was replaced and the truck joined the competition at last. Because of its late arrival, however, it was not completely filled with fuel. As soon as it arrived, it was attached to the slow-fill refueling system set up for the competition.

Because of the need to keep all the trucks in a long caravan at a controlled speed for over a hundred miles each way on the interstate, an escort of two Oklahoma State Patrol cars was provided. All the competing vehicles were equipped with CB radios so that communications could be maintained. During the planning of the event, concerns were expressed about the ability to keep 24 trucks together at a fixed speed on a highway for nearly 250 miles. These concerns were unfounded, as the students handled themselves in an

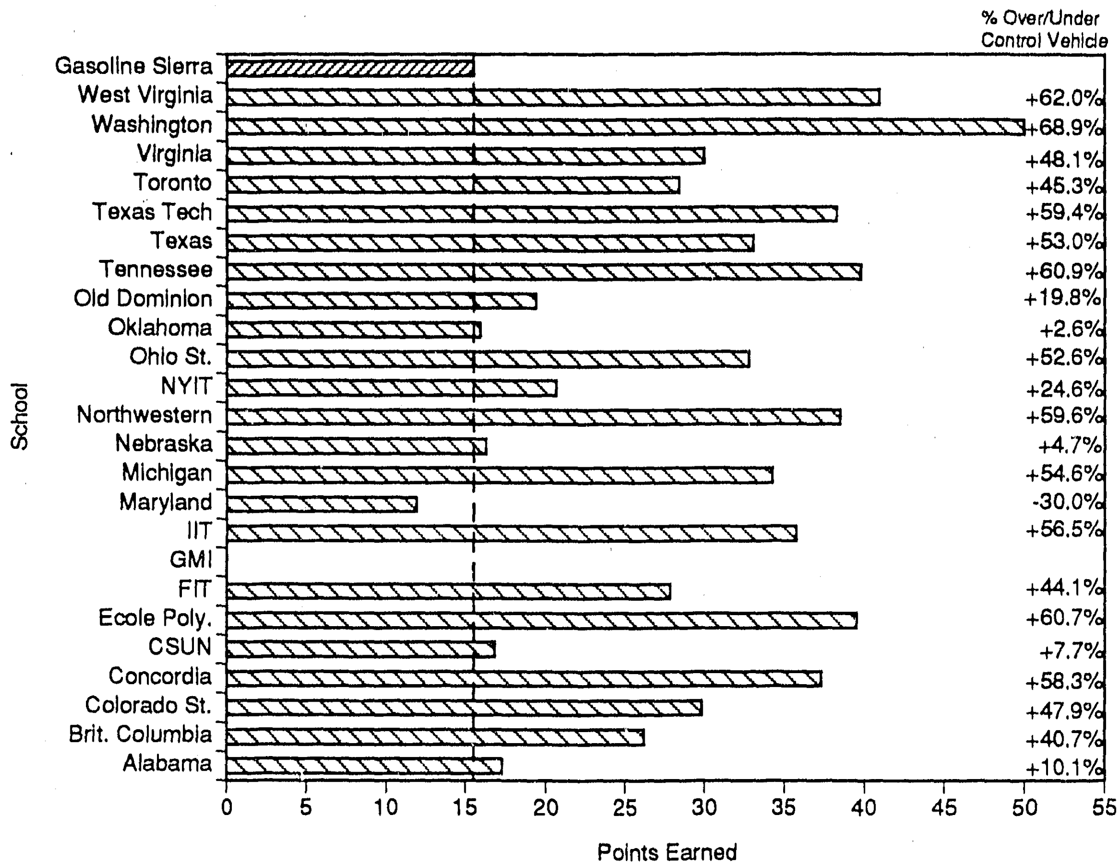

Figure 14. Road Rally Fuel Economy Event

exemplary fashion along the route. The GMI team got off to a late start, leaving Norman about 40 minutes behind the field due to their need to have a full tank of fuel. They soon caught up to the slow-moving caravan and joined the event; their arrival was quickly broadcast over the CB network. The CB radios not only provided a means for official communication but also provided a way for the teams to fend off the boredom of driving 45 mph for so long.

Lake Murray was a welcome relief for all the participants, serving as a beautiful backdrop for another excellent lunch and some watersports activities during the break between legs of the event. After a rest of about an hour and twenty minutes, teams switched drivers, and the caravan reformed to head back to Norman. The return trip was uneventful, except for the mounting tension around whether the trucks could drive the entire 240-mile trip without refueling. After the safe return of the caravan to Norman, only the Nebraska and GMI trucks ran out of fuel en route, both within ten miles of the finish. Each incurred 75 penalty points. The GMI team calculated it was their rush to catch up with the field that pushed their fuel supply too far. Fuel temperature and pressure were again measured for the CNG teams at the end of the event to compute their endurance fuel economy; LNG trucks were refueled and their fuel use determined by weighing the refueling dewar. The results of this event showed that 17 schools outperformed the gasoline-powered control truck in endurance fuel economy. Delivering over 40% better fuel economy than the control vehicle, the Washington University truck again bested the competition using a small (305-cid) engine and a lean-burn conversion approach. Both Colorado State and Concordia Universities achieved a 40% improvement and tied for second place. The complete scores for this event and their relationship to the control vehicle appear in Figure 16.

Robert Larsen

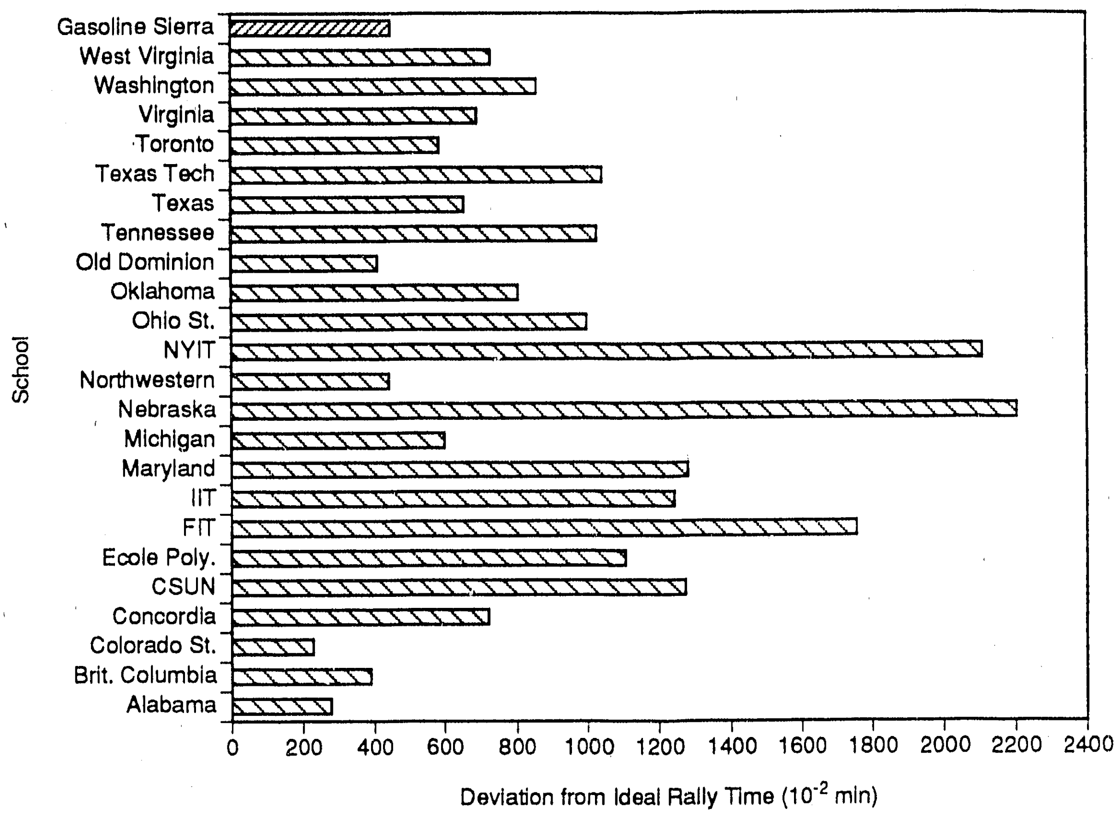

Figure 15. Results of the Road Rally Event

CLOSING DAY - On the final day of the Natural Gas Vehicle Challenge, the trucks competed in the weight pull event to test usable power output in combination with the transmission and final drive ratios. It was planned to use a sled that progressively loaded the pulling pickup by applying the sled's brakes. When the brakes locked on the sled before the event, an alternative was devised. Trucks were loaded with 1000 pounds in their beds, then timed while pulling a 2000-pound trailer from a standing start over a 200-foot asphalt course. This arrangement is shown in Figure 17. The trucks strained against the heavy load, but when the event ended, the supercharged truck from Texas Tech University made it look easy with the only time under seven seconds. It was followed by the trucks from Washington University and the University of Tennessee. In all, seven competitors out-performed the control truck. The complete results of this event are shown in Figure 18.

Final Results - When all the results were totaled, the overall winner of the NGV Challenge was the University of Tennessee, with 560.8 points, followed by Colorado State University, Concordia University, Ecole Polytechnique (the University of Montreal's engineering school), California State University at Northridge, and Texas Tech University. Table 10 shows the top five scoring teams by event; the intense level of competition is apparent from the large number of teams that performed exceedingly well in different events. The overall winner (Tennessee, Figure 19), interestingly enough, won no event outright, but performed consistently well in every event.

Winners of other awards were as follows:

Best Conversion . . . . Colorado State University
Best Emissions . . . . California State - Northridge

Robert Larsen

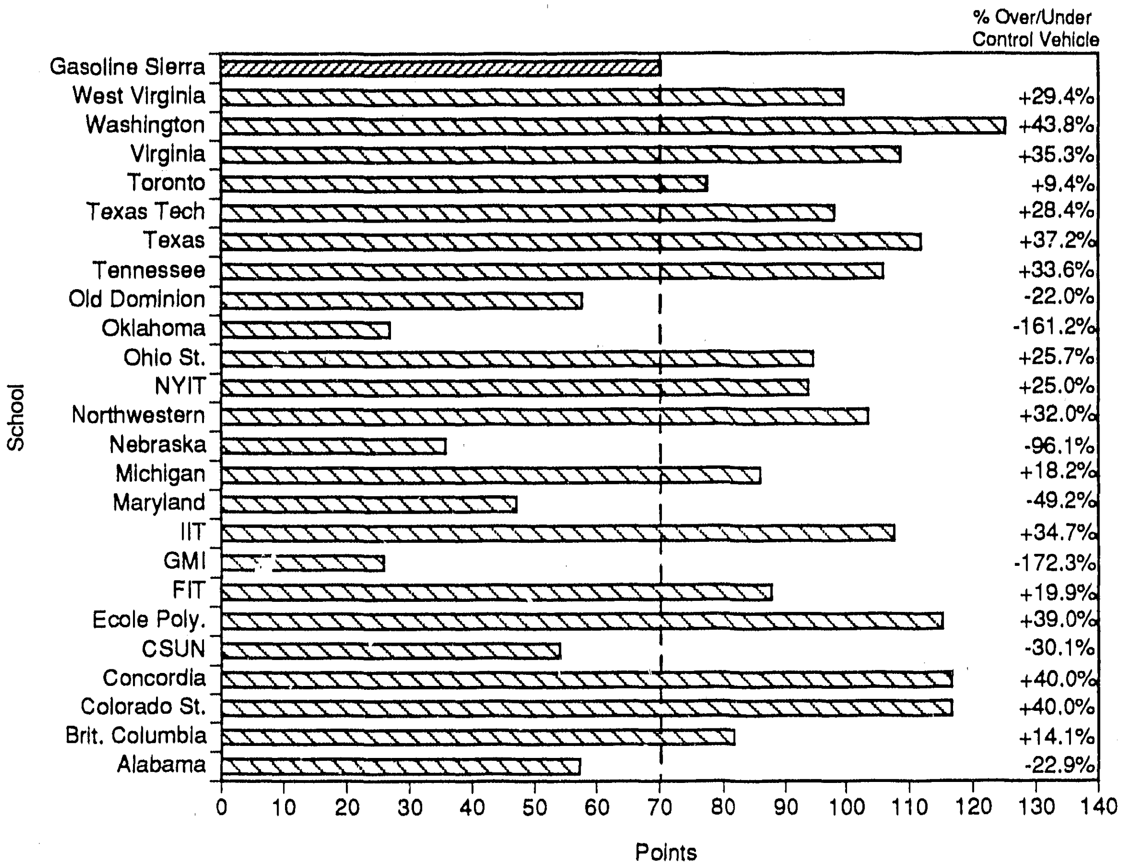

Figure 16. Results of the Endurance Fuel Economy Event

Figure 17 The weight-pull event simulated real-world truck utility.

Lowest Combined
Engine-Out
Emissions . . . . University of Tennessee
Best Fuel Economy . . .Colorado State University

As stated in the rules for the competition, only vehicles that had passing scores on emissions were eligible for the Best Conversion and Best Fuel Economy awards. This rule was established because of the legal requirements to attain promulgated emissions levels before a vehicle can be produced. Based on this restriction, the Colorado State team's performance won them both awards.

Several additional awards were made to teams that displayed high levels of sportsmanship and a "never-say-die" attitude in the face of adversity. Four teams were awarded the Spirit of the Event Award for exemplary sportsmanship: Colorado State University, New York Institute of Technology, Washington University, and West Virginia University. GMI Management

Robert Larsen

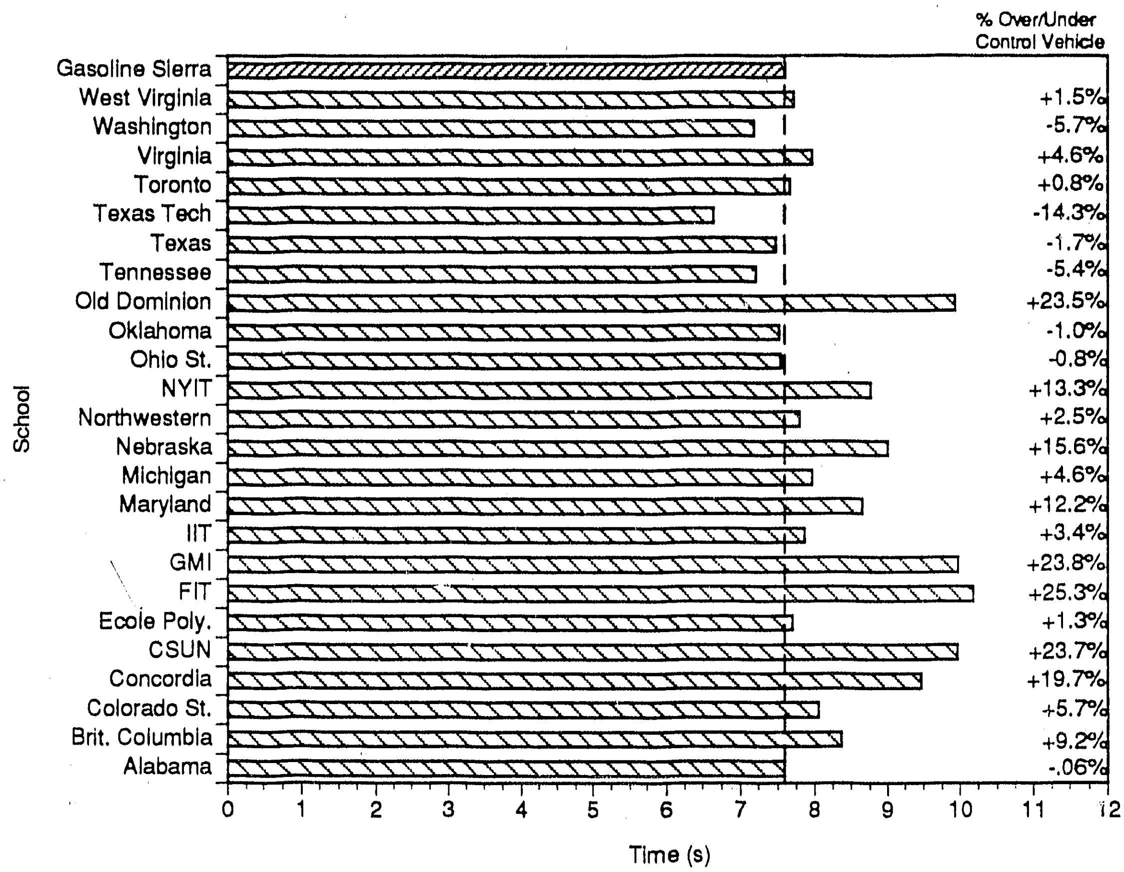

Figure 18. Results of the Dead Weight Pull Event

and Technological Institute was chosen as the winner of the Press on Regardless Award, with Runner Up awards given to Texas Tech and Ecole Polytechnique for surviving accidents with their vehicles on the way to the competition and to the University of Nebraska for rebuilding their engine after a failure less than one week in advance of the event.

The awards were made at a victory banquet sponsored by the American Gas Association at the conclusion of the sixth day of competition. Representatives from the Allied-Signal Catalyst Company awarded the Best Emissions trophy and presented a check that doubled the cash award to $3,000. AC Rochester made a similar presentation for the Lowest Engine-Out Emissions award. Mr. Joe Tucker of Oklahoma Natural Gas received a surprise award from the American Gas Association Technical Committee for his efforts to advance NGV technology. Without Joe's tireless efforts and Oklahoma Natural Gas's support, the NGV Challenge could not have occurred. All through the banquet, the teams showed excellent spirit and congratulated the winners and themselves for completing a rigorous competition.

Observations and Conclusions - The NGV Challenge was successful because it produced advanced NGV technology and demonstrated the potential of natural gas to deliver performance similar to, or in some cases better than, the production gasoline-powered control vehicle. However, if the production truck had competed in all the events, it would have been the overall winner of the competition. This result should come as no surprise, given the extensive development of gasoline-powered vehicles in general and this production truck specifically. It does point out the difficulty of bringing any alternative fuel technology up to the level now considered adequate for production.

In addition, there were other factors that must be considered when reviewing the

Table 10 The Top Five Placing Teams by Event

Event	Place: 1st	2nd	3rd	4th	5th
Static Events					
Design Report	Univ. of British Columbia (47.0)	Colorado State (46.6)	Univ. of Nebraska (43.5)	Univ. of Maryland (41.0)	Cal St. Northridge Texas Tech (36.8)
Oral Presentation	Concordia Univ. (59.3)	Univ. of Tenn. (58.7)	Univ. of Toronto (54.9)	Northwestern Univ. (54.5)	Texas Tech. (53.0)
Design Inspection	Texas Tech (48.9)	Univ. of Maryland (47.5)	Colorado State (46.1)	Cal St. Northridge (45.7)	Univ. of Tenn. (42.1)
Total Static Events	Colorado State (144.9)	Univ. of British Col. (139.1)	Texas Tech. (138.7)	Cal St. Northridge (134.7)	Univ. of Tennessee (134.0)
Performance Events					
Cold Start	Univ. of Michigan (59.0)	Concordia Univ. (56.0)	Univ. of Virginia Ill. Inst. of Tech. West Virginia Univ. Univ. of Texas (53.0)	Univ. of Tenn. (48.0)	Florida Inst. of Tech (44.0)
Acceleration	Texas Tech (50.0)	Univ. of Tenn. (45.6)	Univ. of Texas (44.2)	Ecole Polytechnique (41.5)	Ohio State Univ. (40.4)
Weight Pull	Texas Tech (50.0)	Washington Univ. (45.3)	Univ. of Tenn. (44.1)	Univ. of Texas (41.5)	Univ. of Oklahoma (40.2)
Rally	Colorado State Univ. (50.0)	Univ. of Alabama (41.1)	Univ. of British Col. (29.3)	Old Dominion Univ. (27.9)	Northwestern Univ. (25.8)
Cold Driveability	Univ. of Michigan (49.5)	Ill. Inst. of Tech. Condordia (49.0)	Univ. of Texas (47.5)	Ecole Polytechnique (46.5)	Univ. of Virginia (46.0)
Hot Driveability	Concordia Univ. Ill. Inst. of Tech. Ohio State Univ. Univ. of Alabama (25.0)	Univ. of Texas (24.7)	Univ. of Michigan (24.5)	Univ. of Virginia (24.0)	Univ. of Tennessee (23.2)
Total Performance	Univ. of Texas (228.3)	Univ. of Tenn. (211.0)	Univ. of Michigan (204.3)	West Virginia Univ. (203.5)	Ill. Inst. of Tech. (200.9)

Table 10 (Cont'd)

Event	Place: 1st	2nd	3rd	4th	5th
Fuel Economy Events					
FTP	Ecole Polytechnique (75.0)	Washington Univ. (74.7)	West Virginia Univ. (63.2)	Univ. of Alabama (60.0)	Texas Tech Univ. (57.4)
Rally	Washington Univ. (50.0)	West Virginia Univ. (41.0)	Univ. of Tennessee (39.8)	Ecole Polytechnique (39.5)	Northwestern Univ. (38.5)
Endurance	Washington Univ. (125.0)	Colorado St. Univ. Concordia Univ. (116.6)	Ecole Polytechnique (115.2)	Univ. of Texas (111.9)	Univ. of Virginia (108.6)
Total Fuel Economy	Washington Univ. (249.7)	Ecole Polytechnique (229.7)	Concordia Univ. (208.6)	West Virginia Univ. (203.7)	Colorado St. Univ. (203.2)
Emissions Event	Calif. State Univ. (175.0)	Colorado St. Univ. (50.0)	Univ. of Tennessee Northwestern Univ. (25.0)		

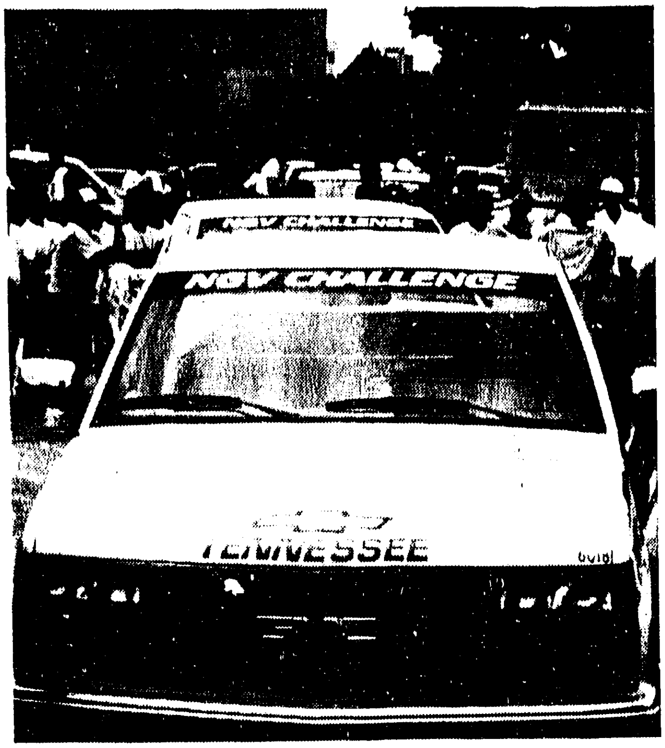

Figure 19 University of Tennessee entry, the overall winner, at the Oklahoma state capitol.

performance of the student-converted vehicles. First and foremost is the limited amount of time that was available to the teams to perform their conversions. Teams had less than four months to execute and refine their designs, a very short time to do a conversion demanding considerable systems development and integration. The lack of time forced many teams to utilize existing conversion hardware, most of which has been in use for decades without modification. Some of this hardware had significant limitations in its ability to deliver the precise fuel control required for strict emissions standards and good driveability and performance. It should be noted that the winning team used a mechanical mixer modified for closed-loop operation, indicating the potential of existing hardware if used with modern electronic controls.

Teams that tried some more advanced after-market hardware discovered that some of the existing engine controller and fuel management systems were not well developed for natural gas, despite their manufacturers' claims to the contrary. A significant amount of research and development on these systems was done by the teams, and some clever combinations with other fuel management systems were used to achieve fuel control over the entire engine operating range.

It was also clear that the two teams who had access to prototype production gaseous fuel injection systems had an advantage over the rest of the field. One of these teams did considerable work to address fuel distribution problems with the original design, essentially converting a TBI unit into a port injection system. This work undoubtedly advanced the state of the art in NG fuel systems.

The relatively poor showing on the emissions and FTP fuel economy tests illustrate how difficult it is for student teams to tailor their vehicles' engine and fuel control systems to meet today's strict standards. Most teams do not have access to emissions testing facilities, so calibration of their engine management system to meet emissions and still give good driveability is very difficult. The transient nature of the FTP exacerbated the fuel control problems of many of the teams, with excess emissions (particularly HCs) and poor fuel economy the result. In addition, the emissions table itself, established by the EPA, was more representative of passenger car standards than those of light trucks. However, when the emissions table was produced, there were no natural gas-specific emission standards or regulations, so existing standards were adapted for use in the event. No matter what the eventual emissions standards for NGVs turn out to be, it appears that total hydrocarbons may be a formidable hurdle for NGVs to clear.

Given all the limitations faced by the students, the performance of their vehicles illustrates the promise and problems of NGVs. Despite the relatively poor FTP fuel economy, the vehicles showed excellent over-the-road fuel economy, besting the baseline truck by a significant margin. In the hot and cold driveability events, about half the field demonstrated good performance, the same proportion that demonstrated cold-start capability. Acceleration and weight-pull events showed the difficulty of maintaining gasoline-type levels of power production operating on a gaseous fuel. Nevertheless, some of the teams showed increases in useable power that indicate that power can at least be maintained at baseline levels.

Finally, the NGV Challenge was a success because several hundred of the brightest student engineers in the U.S. and Canada came together with more advanced dedicated NGVs than had ever been together in one place and participated in a safe and valuable learning experience. The competition also provided a venue for national and state governments to work in partnership with vehicle manufacturers, suppliers, and utilities to develop and demonstrate the potential of alternative fuels. Many good design approaches for NGVs were demonstrated and tested against each other and a production vehicle. Given the limitations of time and the availability of suitable NG hardware, the many hours of student work gave commendable results. However, it is the opinion of the organizers and the faculty advisors that additional potential exists for improving the performance of these vehicles. To allow the schools to further apply what they learned from this event, a follow-up competition is planned for Spring 1992.

SPONSORS - Many U.S. and Canadian government agencies and companies sponsored the NGV Challenge. The U.S. Department of Energy, through Argonne National Laboratory, was the prime sponsor and organizer. Energy, Mines & Resources-Canada provided direction and funds to the competition. The State of Oklahoma provided funds that covered most of the operational expenses and hosted the competition: the Sarkey Energy Center at the University of Oklahoma provided invaluable organizational assistance and logistical support. SAE provided organizational, administrative, and public relations support. General Motors' GMC Truck Division provided the 24 pickup trucks to the schools. Technical support for the competition was donated by GM-Canada. The Gas Research Institute paid for the emissions and cold-start testing. AC Rochester paid for the engine-out emissions testing. Oklahoma Natural Gas provided the CNG refueling at no cost at NIPER and in Norman for the event. Other sponsors for the event included:

American Gas Association
Canadian Gas Association
Alagasco
Allied Signal Automotive
  Catalyst Company
Michelin Tire Company
NGV Coalition
Phillips Petroleum
Sherex
Sports Car Club of America
Texaco

The total out-of-pocket cost for the competition (not including the value of the donated trucks) was approximately $500,000, with DOE and EMR providing about half of the funds. The trucks were valued in excess of $400,000, and the donation of hundreds of hours of volunteer effort is also gratefully acknowledged. In addition, the student teams recruited many local sponsors to defray the costs of the conversions and to provide technical assistance.

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.

APPENDIX A: 1991 SAE NATURAL GAS VEHICLE CHALLENGE RULES - REVISED 5/20/91

GENERAL PROVISIONS - A student alternative fuels competition called the SAE Natural Gas Vehicle (NGV) Challenge will be held June 6-11, 1991.

The U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), Energy, Mines, and Resources - Canada (EMR), General Motors (GM), and the State of Oklahoma, are primary sponsors of this event. Schools are responsible for providing insurance for their vehicles, their traveling and some housing expenses, and for transporting their vehicles to the competition.

Emissions testing for the NGV Challenge will involve a complete Federal Test Procedure (FTP). In addition, cold starting at -20° F will be conducted. These two events require that the competing vehicles must be shipped to the designated location and must arrive by May 17, 1991. Schools are responsible for shipping the vehicles to the test site and for their on-time arrival (a 25 point late penalty per working day will be imposed).

Both emissions testing and cold start tests will be completed before the teams arrive to compete head to head. Team representatives can observe these pre-event tests at their own expense. In case of mechanical failures of the vehicles during pre-event testing, the participating schools should have contingency plans to send one or two students ("designated wrenches") to the test site to repair the vehicles, or they risk losing the points associated with the testing. The schedules for testing will be developed at a later date and will be posted on the computer bulletin board.

The organizers retain the right to change these rules as necessary to facilitate or clarify the contest. Any changes, clarifications, etc. of these rules will be posted on the ANL/DOE Student Competition computer bulletin board and sent to a single key contact person for each team. It is the team's responsibility to stay current with this information. The phone number for the bulletin board is 708/972-6199.

A. ELIGIBILITY

1. All participants must sign a standard Sports Car Club of America insurance waiver.
2. Schools must be the registered owners of their vehicles to be eligible to compete.
3. Undergraduate participation is strongly encouraged; graduate student participation is allowed, but limited to no more than 25% of the undergraduate participation. This ratio will also be applied to the drivers in the event. For example, if there are 12 undergraduate students working on the Challenge team, up to 3 graduate students may also be team members.
4. All contestants must have a valid drivers license and be student members of SAE with a valid membership card.
5. A faculty advisor or representative from the school must be responsible for the student team members and must accompany each team throughout the event or the team will be penalized up to and including disqualification. This rule will be enforced without exception. The name and phone number of the faculty advisor and a list of team members must be submitted to Bob Sechler, SAE, Educational Relations, 400 Commonwealth Drive, Warrendale, PA. 15096-0001, by December 1, 1990. Use the attached Team Data Form. This information will be used for communication, publicity, and recruiting.
6. Each team must produce evidence of insurance coverage, at a minimum of $100,000/$300,000/ $100,000 for their vehicle before beginning the Challenge.

B. CONVERSION REQUIREMENTS

The 1991 SAE NGV Challenge requires that student engineers convert a production 1991 GMC Sierra 2500 rear wheel drive pickup truck to dedicated natural gas (NG) operation. The vehicles will have 5.7 liter V8 engines, 4L60 hydraulic 4 speed automatic transmissions, and 3.73 open rear axles.

1. Fuel: The primary fuel for the NGV Challenge will be compressed natural

gas (CNG) which the event will supply; however, liquefied natural gas (LNG) powered vehicles are allowed. Teams are cautioned that they must make their own special arrangements for obtaining tanks and fuel supples for either fuel during development.

If a team elects to use LNG, they must provide sufficient certified test data to the organizers by January 5, 1991 concerning the safety of their tanks, installation, and conversion. In addition, they must work with the organizers to assure the availability of LNG fuel for their vehicle during the event and provide a sufficiently accurate method of measuring fuel usage. LNG teams must also submit certified fuel energy content (BTU) data for the fuel they use and must provide for boil off vapor containment sufficient for three weeks of inactivity at an ambient temperature of 25° C.

A minimum 250 mile driving range at an average speed of 45 mph is required; only Department of Transportation (DOT) approved or exempted, or Canadian Trade Commission (CTC) approved fuel tanks may be used; their location and number are up to the student teams. NG fuel tanks will not be supplied.

2. Engine: An engine block of the same GM design (a small block Chevrolet) must be used; other modifications to the engine are unlimited. No additional engine components will be supplied by GM, SAE, DOE, or EMR. If major engine damage occurs during conversion or the Challenge, the repair costs will be the responsibility of the college or university team.
3. Suspension: No modifications to the vehicle suspension will be allowed unless it is to compensate for the extra weight of CNG or LNG tanks. Ground clearance must be maintained at stock level.
4. Body and Aerodynamics: No modifications to the body will be allowed, including the firewall, inner fenders, or underbody, unless required to install NG conversion or emission control equipment safely. Hoods may be modified if justified for conversion safety. To encourage efficient packaging of the fuel tanks and to preserve the usefulness of the pickup truck for practical applications, teams will be penalized 50 points for each fuel tank located within the truck bed. No bed covers are allowed and the tailgate must remain in place.
5. Emissions: Vehicles must meet existing federal exhaust emissions standards for 1991 light duty trucks or incur penalty points. Teams earn points for further reducing exhaust emission levels through results of standard Federal Testing Procedure (FTP) emissions tests. Points will be awarded using brackets corresponding to emission levels of all regulated pollutants. The brackets have values for each pollutant corresponding to the difficulty of controlling emissions of the pollutants simultaneously. The brackets and their point values have been adjusted for natural gas engine operation and established by the U.S. Environmental Protection Agency (EPA) Motor Vehicle Emissions Laboratory. A listing of the brackets and their corresponding points may be found at the end of these rules. Changes to the exhaust emissions control system are allowed, but appropriate heat shielding for the catalytic converter and other relevant exhaust system components is required for safety.
6. Wheels and Tires: If a tire sponsor for the entire event is secured, teams will be required to use the supplied sponsor's tires; otherwise, the stock wheels and tires must be used in all Challenge events. Tire pressures will be limited to the maximum or minimum levels stated in the users manual. A minimum tread depth of 5/32" will be required for safety. The same wheels and tires must be used for all events.

Robert Larsen

7. Transmission and Final Drive: The automatic transmission must be used without ratio changes but may be reprogrammed to match engine operation. Changes to the final drive ratio are allowed.
8. Exhaust System: The exhaust system may be modified but must meet applicable 1990 U.S. Federal Standards for exhaust emissions and noise levels with a sound limit of 80 db. The exhaust noise will be measured using test procedures found in E9 below, and will face penalties for exceeding the sound limit. Penalties for failing to meet mandated emissions levels will be assessed as described in E2.
9. Engine Control System: Entrants are not required to use the GM engine control management system.
10. Component Deletion: Removing components or systems from the vehicles to lighten them is prohibited. No changes are allowed that would nullify compliance with federal, state, or provincial safety regulations. All trucks must have all systems that came with them in good operating condition, but systems may be modified as long as safety is not compromised.
11. All trucks and support vehicles must be equipped with a 40 channel CB radio. This is the team's responsibility.
12. All trucks must have a 5 pound minimum class ABC fire extinguisher on board and easily accessible to the driver. A remote 5 pound 1211 or 1301 halogen system is an allowable substitute.
13. Vehicle Appearance: It is required that all sponsors' logos appear on both sides of all trucks. See Figure 1 for decal placement. Other graphics are acceptable but must be in good taste. No graphics except those supplied for window application (e.g. sun shades) may appear on any window, and no obstruction of vision of any sort is allowed. Individual graphics are limited to 75 square inches. Vehicles will be white, but can be painted. The school name and number (to be assigned) must also prominently appear on the hood and both sides of the truck cab. Numbers must be 10" high minimum.
14. Any rules changes, clarifications, etc. will be posted on the student competition electronic bulletin board. It is the team's responsibility to keep current with this information.
15. Refueling fittings for CNG vehicles will be standardized and will be specified.
16. Due to the diversity of the conversions, no conversion kit will be supplied.

C. CONDUCT OF THE EVENT

1. The overriding emphasis of the Challenge and all its events is on safety. Any unsafe behavior during the Challenge will result in disqualification of the student team.
2. Safety belts must be worn at all times any of the contesting or support vehicles are in motion. 25 penalty points will be assessed for each individual not wearing a safety belt each time said individual is observed to be in violation of this rule by a Challenge official.
3. Each team must produce evidence of registration and insurance coverage at minimum of $100,000/$300,000/ $100,000 for their vehicle before beginning the NGV Challenge.
4. No changes or modifications to the vehicles will be allowed after they arrive for emissions testing except for those changes required to return them to operating condition after a breakdown. Hoods will be sealed and engine calibrations frozen at the beginning of the event. A 25 point penalty will be assessed any time the hood is opened for repair. If the hood is opened for any reason, an event official must be present.
5. One support vehicle per converted vehicle will be allowed on the rally sections of the Challenge. All support vehicles must be equipped with safety belts at all seating positions. Safety belts must be worn at all times the support vehicles are in motion. The

same penalties described in Item C2 will be applied to the support vehicle personnel.

6. No drafting of competing or support vehicles will be allowed during the endurance and rally events. Drafting is defined as following another vehicle closer than three car lengths at cruising speeds for sustained periods of time. Infractions of this rule may be reported by other competitors or by Challenge organizers. Penalty will be 10 points for each occurrence on the rally event and 25 points for each occurrence on the endurance event.
7. The organizers will provide housing, lunch, and dinner from June 6, 1991 through June 10, 1991 for eight team members plus a faculty advisor.
8. Any use of alcohol during the hours of the event or controlled substance at any time will result in immediate disqualification.

D. SCORING SCHEDULE

Event	
Emissions	
FTP emission test	250
Design	
Written design report	75
Vehicle design inspection	75
Oral design presentation	75
Fuel Economy	
Endurance event fuel economy	125
Road rally fuel economy	50
FTP fuel economy (55% city/45% highway)	75
Performance	
-20°F cold start test	50
Acceleration with 1,000 pound payload	50
Dead weight pull	50
Cold driveability & start	50
Hot driveability & start	25
Rally performance	50
Total	1000

Vehicles must arrive for emissions testing by 5:00 p.m., May 17, 1991. There is a <u>25 point penalty per working day for late arrival.</u> Absolutely no excuses will be accepted.

Points may be earned or penalty points assessed in the emissions, cold and hot driveability, acceleration, and endurance tests as described in E below. In addition bonus points can be earned for superior cold start performance.

E. DESCRIPTIONS OF NGV CHALLENGE EVENTS

1. <u>Fuel Economy:</u> Three different fuel economy measurements will be taken. Fuel economy will be calculated from the FTP emissions test, and will be used directly in the following formula to allocate the points available for that event. In the other two cases, points for each of the events will be determined by measuring the actual fuel consumed and using the following formula (let FC = the fuel consumed by your vehicle in BTU's):

$$\text{Your Score} = (3(FC/FC_{best}) - 2(FC/FC_{best})^2]$$

$$\text{X Points Available}$$

No negative points will be awarded in any of the fuel economy events.

2. <u>Emissions:</u> All cars are to be at the emissions test location by 5 pm May 17, 1991, and contain less than 1/8 tank of fuel. The Challenge vehicles must achieve U.S. federal tailpipe emissions standards for 1991 light trucks or incur penalties. Superior emissions performance will earn up to 250 points. Testing will be measured using the Federal Test Procedure (FTP). Truck fuel systems will be leak tested; teams must correct any fuel leaks before being allowed to compete. Emission performance of the vehicles will be scored on the results of all constituents according to the schedule at the end of these rules. A team's score is determined by the simultaneous control of pollutants as listed on the schedule (assigned score on the bottom line). A team is not eligible to win the Best Fuel Economy Award or the Best Conversion Award if they fail federal exhaust emissions standards. Emissions prior to the

catalyst will be analyzed and a special trophy awarded.

3. Cold Start: All vehicles will be cold start tested at -20° F in advance of the competition. To receive all the points for this event, vehicles must start within 5 seconds of cranking time and continue to run without driver intervention for five minutes. Thirty seconds after starting, the truck will be put in drive and held against the brake. No additional time beyond the initial 5 seconds will be allowed for special features to operate or to enhance starting performance before starting is initiated. All starting procedures must be automated and operate without driver participation beyond using the key to engage the starter. Each second or fraction thereof beyond the 5 seconds allowed to start will result in a three point deduction from the available points. Three bonus points will be awarded for each full second shorter than the 5 seconds allowed for vehicles to start successfully. A successful start is defined as continuous operation of five minutes without driver intervention. False starts or stalls will be penalized 10 points per occurrence. Testing will be terminated when all possibilities for earning points are exhausted. The starting procedures will be per the GM Owners Manual. If the truck starts and runs for the 30 seconds prior to engaging drive, 20 points minimum will be awarded.
4. Cold & Hot Driveability: Cold start and driveability test will be conducted early one morning at ambient temperatures. The same test will be performed at the end of the acceleration event for hot start & driveability. Points will be deducted for poor starting and drive-away faults on a 100 to 0 scale (100 being best) according to a score derived from production vehicle benchmarks. Half the raw score from these events will be used in the overall scoring for cold start & driveability points and 1/4 of the raw score will be used for the hot start and driveability.
5. Endurance Event: An endurance event emphasizing fuel economy and durability will be held. The teams will be required to maintain an average speed of 45 mph for the entire endurance event (250 mi. max.) without refueling. There must be a passenger in each vehicle for this event. Refueling will occur after the run so that fuel economy can be calculated. Each vehicle's speed will be recorded at least once (but possibly more times) per hour to ensure adherence to the set speed. Penalty points will be applied according to the following table based on your deviation from the ideal average speed. Fractions of mph will be rounded according to the following method: .1 to .5 variance rounds down; .6 to .9 rounds up (i.e. 45.5 rounds to 45; 45.6 to 46).

Your Average Speed	Penalty Points
45	0
44 or 46	25
43 or 47	75
42 or 48	125

Fuel economy will be calculated from the actual mileage driven and the amount of fuel consumed using the formula in paragraph E 1. Twenty-five penalty points will be assessed for any mechanical repairs, except tire repair, required during this and any other Challenge event. A truck that does not complete the full endurance test (250 mi. max.)without refueling will be penalized 75 points.
6. Rally Performance: A Time-Speed-Distance road rally event will be conducted on mostly rural highways. The approximately 200 mile rally will have about 55% urban and rural roads and 45% highway driving, and may have any number of checkpoints. Some roads may be good unpaved. Points will be awarded according to the following formula (let T your = your team's timing

rally score, and T min = lowest (best) team rally score).

$$\text{Your Score } \frac{\text{T min}}{\text{T your}} \times 50$$

Teams are encouraged to contact their local Sports Car Club of America (SCCA) for rally tutoring.

7. Conversion Paper: All teams must submit a written paper describing their approach for natural gas conversion and operation, emissions control, and cold & hot start and driveability. The standard SAE technical paper format must be used. A strict limit of fifteen pages, including attachments, will be enforced. Ten copies of the paper must be received by Bob Sechler, SAE, Educational Relations, 400 Commonwealth Drive, Warrendale, PA. 15096-0001, by May 24, 1991. The papers will be judged by a panel of industry and government experts and will become the basis for a published SAE paper on the conversions. A ten point per day penalty will be assessed for late papers. Absolutely no excuses will be accepted.
8. Oral Presentation: Each team must make a ten minute oral presentation of the rationale and approach to their conversion, fuel economy, emission control, and cold & hot start and driveability strategies. A five minute question and answer session will follow the presentation. The presentation should be based on the assumption that a major auto manufacturer has selected 24 engineering schools to develop a prototype NG powered vehicle for production. Your job is to convince the judges that your team did the best job, and your conversion should be produced. Visual aids are strongly recommended. The presentation will be judged on its content, format, and delivery.
9. Sound Test: A sound test will be run according the standard SAE test procedure J986b (modified for existing conditions) and limited to 80 db. Teams whose exhaust noise exceed this standard will be assessed a 5 point penalty for each db over the standard to a maximum of 50 points.
10. Design Judging: A panel of industry experts will judge each vehicle conversion for:
    Innovative design for improving fuel economy
    Innovative design for emission control
    Innovative design for improving power density
    Feasibility of design in time allowed
    Fuel storage and vehicle utility
    Cost effectiveness
    Practicality
    Level of Complexity
11. Cargo Carrying Capacity: Any fuel tanks in the truck bed will be penalized 50 points per tank.
12. Acceleration: All vehicles will be loaded with a 1000 pounds of deadweight and will be timed over a 1/4 mile*, straight line course from a standing start. The least elapsed time will receive 50 points with others receiving points according to the following formula:

$$\text{Your Score} = \frac{(\text{T min} \times 50)}{(\text{T yours})}$$

minus (your placement in the Acceleration Competition minus 1)

Each team must have two drivers, and each driver will be allowed 2 runs. The fastest run for each driver will be averaged for your teams time. All drivers must wear a helmet bearing a 1980 or later Snell Foundation sticker.

The maximum speed in returning to the start line is 10 mph. Violation will result in a 50 point penalty.

A separate award will be made for top speed achieved in the quarter mile.*

* The distance may he shorter than 1/4 mi. as dictated by existing conditions.

Robert Larsen

13. Dead Weight Pull: Trucks will be delivered with a trailer hitch installed, which may not be modified in any way (size, mounting height, bracing, ball mounting location, etc.) Vehicles will be hooked to a sled which will increase in resistance as it is pulled. The truck bed will be loaded with 1000# dead weight. The pull surface will be asphalt. The truck must attempt to pull the weight from a dead stop over a maximum distance of 100 ft. without stalling. The event judge will stop the pull when forward motion is stopped. This will be a solo event. A truck is allowed two attempts; the best will be scored.

Scoring the weight pull event: Ranking for the weight pull event will be determined by minimum elapsed time for the vehicles making a "full pull" (100 ft.). Vehicles not completing the full distance will be ranked according to the distance (nearest inch) pulled. The score will be as follows:

$$\left(\frac{\text{Your distance}}{\text{Maximum distance}} \times 50\right) - (\text{your rank in the weight pull} - 1) = \text{score}$$

No negative points will be awarded.

14. Rules Changes: Any rules changes, clarifications, etc., will be posted on the student competition electronic bulletin board. It is the team's responsibility to keep current with this information.

F. STUDENT ACHIEVEMENT AWARDS:

At least $21,000 (U.S.) in prizes will be awarded as follows:

• First place overall	$5000
• Second place	$3500
• Third place	$3000
• Fourth place	$2500
• Fifth place	$2000
• Best NG conversion (1/2 paper, 1/2 inspection)	$1500
• Lowest emissions	$1500
• Best fuel economy (avg. of three events)	$2000

The organizers reserve the right to increase the prize money for some or all of the above categories, and add awards at their discretion if resources allow.

G. NGV CHALLENGE SCHEDULE. DATES AND LOCATIONS MAY BE REVISED

REVISED 5/20/91

5/17/91	Bartlesville, OK	Trucks must arrive at NIPER by 5pm for emissions testing
5/24/91		Papers due by 5pm E.S.T.
6/06/91	8:00AM	Bartlesville: Two team representatives (min.) arrive by 8am to register
	8:30AM	Support vehicles depart (1 per truck max.)
	9:00AMT	rucks Depart: Team registration begins, Energy Center, University of Oklahoma, Norman, Oklahoma
	10:00AM	Arrive in Tulsa: (support vehicles go direct to McDonald's on Turner Turnpike-$2.50 toll) Media Event at Texaco Refueling Station (31st & Memorial Dr.)
	10:45 AM	Trucks Depart Tulsa via Tumer Turnpike ($2.50 Toll)
	11:45AM	Turner Turnpike: (Stroud): Lunch Phillips Refueling Station-Refuel, Leave 12:45PM
	2:00PM	Arrive Capital - Oklahoma City - Media Event with Governors
	4:00PM	Arrive in Norman: Vehicle Display @ Enemy Center - east lot
	5:00PM	Judges Meeting/Dinner - faculty club
	6:00PM	Reception @ Energy Center
	8:30PM	NGV Team Meeting - Energy Center
	10:00PM	Steering Committee - Residence Inn Park Vehicles-Baseball Lot

Robert Larsen

6/7/91	7:00AM	Trucks must arrive @ South Oval (Friday)Street
	8:00AM	Oral Presentations - Adams Hall Design Judging - Armory Vehicle Display - South Oval Street
	12:00PM	Lunch @ Couch Cafeteria
	1:00PM	Event Resumes
	5:00PM	Event Concludes
	6:00PM	Dinner@ Holiday Inn Team Captain Meeting Park Vehicles for fueling University of Oklahoma motor pool lot Administrators Meeting - Residence Inn
6/8/914 (Sat.)	7:00AM	Cold Driveability-Baseball lot
	9:00AM	Acceleration and Sound Test Event Begins - North Campus Airport
	12:00PM	Lunch-Media event
	1:00PM	Event Resumes Hot Driveability
	5:00PM	Event Concludes
	6:00PM	Dinner@ Holiday Inn Team Captain Meeting Park Vehicles Univ. of Okla. motor pool lot
	8:00PM	Administrators Meeting - Residence Inn
6/9/91 (Sun.)	7:30AM	Depart for Oklahoma City
	8:30AM	Arrive @ State Capitol Media event
	9:00AM	Road Rally Begins
	12:00PM (approx.)	Lunch (Meeker, Okla.)
	5:00PM	Arrive in Norman Event Concludes
	6:00PM	Dinner @ Holiday Inn Team Captain Meeting
	8:00PM	Administrators Meeting - Residence Inn Park Vehicles-Baseball Lot
6/10/91 (Mon.)	8:00-9:00AM	Vehicle Display
	9:00AM	Endurance Run to Lake Murray (past cookie factory)
	12:00PM	Arrive @ Lake Murray - Martin's Landing Lunch (swimming available)
	2:00PM	Event Resumes
	5:00PM	Arrive in Norman-park in Baseball Lot Event Concludes
	6:00PM	Dinner@ Holiday Inn Team Captain Meeting
	7:30PM	Faculty Advisors Meeting - Holiday Inn
	9:00PM	Administrators Meeting - Residence Inn
6/11/91	8:00AM	Weight Pull - Event Begins - Lloyd Noble south lot
	12:00PM	Lunch @ Lloyd Noble
	1:00PM	Event Resumes
	5:00PM	Event Concludes Tabulate Scores List Winners Vehicle Display @ OCCE
	6:00PM	Banquet@ OCCE
	7:00PM	Awards Presentation
	8:00PM	Event Concludes

Robert Larsen

APPENDIX B: REQUEST FOR PROPOSALS 1991 SAE NATURAL GAS VEHICLE CHALLENGE: A STUDENT ALTERNATIVE FUELS ENGINEERING DESIGN COMPETITION

BACKGROUND - The U.S. Department of Energy (DOE), Energy, Mines and Resources-Canada (EMR), Argonne National Laboratory (ANL), the Society of Automotive Engineers (SAE), and General Motors (GM) are again joining to organize a college and university student alternative fuels design competition. The competition employs natural gas (NG) as the alternative fuel and will be held in June of 1991. The GMC Truck Division of General Motors has agreed to donate 20 full-size three-quarter-ton pick up trucks to schools for conversion to dedicated NG use. These vehicles, a basic conversion kit, and cash grants will be awarded to 20 schools with the top proposals submitted in response to this Request for Proposals (RFP). The proposals will be evaluated by a panel of experts drawn from industry, natural gas utilities, and government.

Proposers should be aware that a follow-up event in 1992 using the same vehicles is likely. If a school's proposal should be selected for the NGV Challenge, they will also likely be invited to continue their work on advanced natural gas vehicle technology for another competition in 1992.

The proposals must be postmarked no later than June 22, 1990; this cut-off date will be strictly enforced. Ten copies of the proposal should be sent to Mr. Robert Sechler, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096-0001. The winning schools will be announced by August 15 and, will receive their vehicles, conversion kits and grants by September 7th, 1990. Any questions regarding the competition should be addressed to Mr. Robert Larsen, Center for Transportation Research, Argonne National Laboratory, 9700 S. Cass Ave., Bldg. 362 28, Argonne, IL 60439, 708- 972-3735, FAX: 708-972-3443. Answers to questions will be posted on the ANL/DOE Student Competition Electronic Bulletin Board at 708-972-6199. Questions may also be asked via the Bulletin Board; interested parties should check the Bulletin Board periodically for any updates on this and other DOE-sponsored competitions. The complete rules for the NGV Challenge will be available by September 7, 1990, the same time as the vehicles are awarded to the twenty participating schools.

OVERVIEW OF EVENT - The 1991 SAE NGV Challenge requires that student engineers convert a production 1990 GMC rear wheel drive pick up truck to dedicated natural gas (NG) operation. The vehicles will have 5.7 liter V8 engines, 4-speed electronically-controlled automatic transmissions, and posi-traction rear axles. Unlimited modifications are allowed to the engine; however, an eight cylinder block of the same GM engine design must be used. The automatic transmission must be used without ratio changes but may be re-programmed to match engine operation. Changes to the final drive ratio are allowed. Entrants are not required to use the GM engine control management system, but will be provided with a method to modify the controller to allow its use.

The 20 student teams selected by this proposal process will also receive at least $5,000 in grants to help defray the costs of conversion and participation in the event. Teams are responsible for obtaining funding in excess of the grants provided by the organizers to complete their conversion and cover other costs associated with their participation in this event.

The primary emphasis of the NGV Challenge is improved engine performance, fuel economy, and low emissions. A minimum 250 mile driving range at an average speed of 45 mph is required; only Department of Transportation (DOT) approved or exempted, or Canadian Trade Commission (CTC) approved fuel tanks may be used; their location and number are up to the student teams. NG fuel tanks will not be supplied; attached to this proposal in Appendix A is a list of tank makers which teams may contact in the preparation of their proposals. To encourage efficient packaging of the fuel tanks and to preserve the usefulness of the pickup truck for practical applications, there will be a cargo carrying event consisting of fitting as many objects as possible into the pickup bed.

Robert Larsen

The primary fuel for the NGV Challenge will be compressed natural gas (CNG). However, liquefied natural gas (LNG)-powered vehicles will be allowed. Teams are cautioned that they must make their own special arrangements for obtaining tanks and fuel supplies. If a team elects to submit a proposal based on LNG and they are chosen to compete, they must provide sufficient test data to the organizers in advance of the competition concerning the safety of their tanks and conversion. In addition, they must work with the organizers to assure the availability of LNG fuel for their vehicle during the event and provide a sufficiently accurate method of measuring fuel usage.

The over-riding concern of the NGV Challenge is safety. All vehicles will be extensively scrutinized for safety considerations before being allowed to compete.

Proposers should be aware that their vehicles must be ready to be shipped for emissions and cold start tests no later than May 13, 1991. The NGV Challenge event will begin on June 9, 1991, in Norman, Oklahoma and will conclude on June 15, 1991 in Detroit, Michigan. Vehicles and personnel will be transported from Oklahoma to Michigan as part of the event. However, proposers should realize that they will be responsible for transportation expenses to and from the event as well as housing and meals for team personnel outside a core group of eight members and an advisor.

Planned events for the competition are the following:

- Complete Federal Test Procedure (FTP) emissions test
- City and highway FTP fuel economy tests
- Evaporative emission SHED tests
- -20°F cold-start tests
- A written technical report of no more than 15 pages
- A oral presentation of 20 minutes
- A design judging inspection
- A cargo carrying capacity event
- A fuel economy road rally (time/speed/distance) event
- A fuel economy/endurance event on a closed course
- Acceleration event carrying a fixed weight
- A cold and hot start drivability event
- A dead weight pull event
- A exhaust noise measurement test

STUDENT ACHIEVEMENT AWARDS - At least $21,000 (U.S.) in prizes will be awarded as follows:

First place overall	$5,000
Second place	$4,000
Third place	$3,500
Fourth place	$3,000
Fifth place	$2,500
Best NG conversion(1/2 paper, 1/2 inspection)	$1,000
Lowest emissions(regulated constituents from FTP test, including Evaporative emissions)	$1,000
Best fuel economy(average of the three events)	$1,000

The organizers reserve the right to increase the prize money for some or all of the above categories if resources allow.

SCORING -

Event	Points
Emissions	
FTP emission test	200
Evaporative emissions SHED test	50
Design	
Written design report	75
Vehicle design inspection	75
Oral design presentation	50
Vehicle carrying capacity	50
Fuel Economy	
Endurance event fuel economy	100
Road rally fuel economy	75
FTP fuel economy(55% city/ 45% highway)	75
Performance	
-20°F cold start test	50
Acceleration with 1,000 pound payload	50
Dead weight pull	50
Cold driveability	50
Hot driveability	25
Rally performance	25
Total	1000

The exhaust noise test will be run according to standard SAE test procedure J986b and limited to 80 db. Teams whose exhaust

Robert Larsen

noise exceeds this standard will be assessed a 5 point penalty for each db over the standard to a maximum of 50 points.

Vehicles must meet existing federal exhaust emissions standards for 1990 light duty trucks or face penalty points. Teams earn points for further reducing exhaust emission levels through results of standard Federal Testing Procedure (FTP) emissions tests. Points will be awarded using brackets corresponding to emission levels of all regulated pollutants. The brackets have values for each pollutant corresponding to the difficulty of controlling emissions of the pollutants simultaneously. The brackets and their point values have been adjusted for natural gas engine operation and established by the U.S. Environmental Protection Agency (EPA) Motor Vehicle Emissions Laboratory. A listing the brackets and their corresponding points will be published in the final rules of the NGV Challenge and sent to those schools that request it for preparation of their proposal. For your proposal preparation, plan to reduce emissions of all regulated exhaust gas constituents to the lowest level possible.

A team is not eligible to win the Best Fuel Economy award if they fail to meet existing Federal exhaust emissions standards.

NGV CHALLENGE SCHEDULE -

Release RFP	4/23/9
PropOsals due to SAE	6/22/90
Proposal review process begins	6/25/90
Schools notified of proposal review results	8/15/90
Schools receive vehicles, conversion kits and grants	9/7/90
Vehicles shipped for emission testing	5/13/91
NGV Challenge begins	6/9/91
NGV Challenge ends	6/15/91

PROPOSAL REQUIREMENTS - All accredited engineering programs in the United States and Canada are eligible to submit proposals for the 1991 SAE NGV Challenge.

Proposals must be no more than 10 pages of text along with 5 pages of supporting materials (a total of 15 pages), and must be postmarked no later than June 22, 1990. Late proposals will not be considered.

Innovative engineering design will be the most heavily weighted factor in judging the proposals The sponsors are particularly interested in cost effective ways to obtain low exhaust emissions, high fuel economy and power density, and demonstrate high durability and reliability. The criteria for judging are:

Innovative design for improving fuel economy	25%
Innovative design for emission control	25%
Innovative design for improving power density	15%
Feasibility of design in time allowed	15%
Fuel storage and vehicle utility	10%
Facilities and resources available	10%

Every proposal submitted must have written statements of support from the Dean of the Engineering faculty and from a local natural gas utility. Your local natural gas utility is an invaluable source of information and technical support for your conversion; they will also provide access to fuel during the development process.

For the purposes of judging the proposals, cost effectiveness will be weighed as part of the innovation and feasibility criteria. Those proposals that employ less expensive and/or complex methods to achieve the engineering goals of the competition will be scored higher than those proposals achieving equal results with more expensive and/or complicated methods. For the competition, cost effectiveness will be judged through mandatory cost analysis sections in the written and oral reports.

Proposers must address how they will handle the licensing and insurance of the vehicles donated to them by GMC Truck Division. If the school is selected, proof of vehicle insurance at a minimum level of \$100,000/\$300,000/\$100,000 must be provided to the organizers in advance of the competition. All vehicles must be registered in the state of the school's location; proof of registration will also be required in advance of the competition.

Collaboration between schools is acceptable if both schools meet all the requirements stated in this RFP.

Robert Larsen

APPENDIX C

NGV CHALLENGE
ORAL PRESENTATION SCORING SHEET

SCHOOL:___________________________ **JUDGE:**___________________________

JUDGES: Circle the score which you feel best represents the presentation's merit for each of the following categories:

Oral Presentation (40 points)	**Poor**	**Sub-Standard**	**Average**	**Good**	**Better**	**Excellent**
Organization	0	1	2	3	4	5
Delivery	0	1	2	3	4	5
Visuals/Graphics	0	1	2	3	4	5
Time Utilization	0	1	2	3	4	5
Question Response	0	1	2	3	4	5
Overall Effectiveness	0	3	6	9	12	15

Technical Approach (35 points)

Emissions Control System	0	1	2	3	4	5
Cold Start/Drivability	0	1	2	3	4	5
NGV DesignConcept/ Practicality/Degree Design Takes Advantage of NG Properties	0	1	2	3	4	5
Engine/fuel management	0	1	2	3	4	5
Cost/Performance Tradeoff	0	1	2	3	4	5
Power Density	0	1	2	3	4	5
Fuel Economy/Range Considerations	0	1	2	3	4	5

Robert Larsen

COMMENTS:

Any Aspect Deserving Specific Follow-Up Research:

NGV CHALLENGE
DESIGN INSPECTION SCORING SHEET

SCHOOL:_______________________________ **JUDGE:**_______________________________

JUDGES: Circle the score which you feel best represents the team's design score from your design inspection for each of the following categories:

NGV CONVERSION (35 points total)

	Poor	Sub-Standard	Average	Good	Better	Excellent
Execution of Concept/ Craftmanship	0	1	2	3	4	5
Cost/Performance Tradeoff	0	1	2	3	4	5
Fuel Delivery System	0	1	2	3	4	5
Engine Management System	0	1	2	3	4	5
Degree of Complexity/ Ease of Manufacture	0	1	2	3	4	5
Fuel Storage System	0	1	2	3	4	5
Safety Considerations	0	1	2	3	4	5

EMISSIONS CONTROL SYSTEM (20 points total)

System Execution/ Craftsmanship	0	1	2	3	4	5
Innovation	0	1	2	3	4	5
Integration with Conversion	0	1	2	3	4	5
Degree of Complexity/ Ease of Manufacture	0	1	2	3	4	5

PERFORMANCE CHARACTERISTICS (20 points)

Cost/performance tradeoff	0	1	2	3	4	5
Fuel Economy Considerations	0	1	2	3	4	5
Execution of Cold Start/Driveability Modifications	0	1	2	3	4	5
Power Density	0	1	2	3	4	5

Robert Larsen

COMMENTS: ____________________

____

____

____

____

Any Aspect Deserving Specific Follow-Up Research: ____________________

____

____

____

____

NGV CHALLENGE
DESIGN PAPER SCORING SHEET

SCHOOL:______________________________ **JUDGE:**________________________________

JUDGES: Circle the score which you feel best represents the team's design score from their written report for each of the following categories:

NGV CONVERSION (35 points total)

	Poor	Sub-Standard	Average	Good	Better	Excellent
Design Concept/Practicality	0	1	2	3	4	5
Fuel Delivery System	0	1	2	3	4	5
Engine Management	0	1	2	3	4	5
Degree of Innovation	0	1	2	3	4	5
Fuel Storage	0	1	2	3	4	5
Fuel Economy/Range	0	1	2	3	4	5
Safety Design Characteristics	0	1	2	3	4	5

EMISSIONS CONTROL SYSTEM (20 points total)

System Design/Practicality	0	1	2	3	4	5
Control of Unburnt Methane	0	1	2	3	4	5
Comprehensiveness of Design- NO_x vs total HC	0	1	2	3	4	5
Degree of Innovation	0	1	2	3	4	5

PERFORMANCE DESIGN CHARACTERISTICS (20 points total)

Power Density	0	1	2	3	4	5
Cold Start Approach/ Modifications to Improve Driveability	0	1	2	3	4	5
Cost/Performance Tradeoff	0	1	2	3	4	5
Degree of Innovation	0	1	2	3	4	5

Robert Larsen

COMMENTS:

Any Aspect Deserving Specific Follow-Up Research:

END

DATE FILMED

4 / 03 / 92