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A FIELD STUDY OF THE EFFECTS OF THE HYDROGEN GENERATING SYSTEM ON POWER, FUEL ECONOMY AND EMISSIONS IN GASOLINE AND DIESEL ENGINES

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ABSTRACT

The fractional addition of hydrogen to air entering the combustion chamber improves combustion and thermal efficiency, reduce gaseous emissions and decrease fuel consumption. Hydrogen gas enhances the flame properties of the air-fuel mix and catalyzes the combustion of the hydrocarbon fuel. Since 1993, a system to generate hydrogen and oxygen gases onboard through the electrolysis of water has been developed and refined. The energy for the electrochemical reactions is supplied from the battery/alternator circuit. Hydrogen and oxygen gases produced by the system are never stored, but delivered to the air intake by a vacuum pump. An electronic process controller varies the energy input to maintain constant flow of gases produced while an electronic safety module ensures the safe operation of the system. Performance impact has been documented for a full range of engine sizes, ages, fuel and vehicle types. Emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbon (HC) were observed under loaded conditions on a dynamometer and no-load conditions at time of installation. Percent opacity, a direct measure of carbon particles emitted in diesel engines, was also investigated. Detailed fuel logs obtained from users and computer downloads were analyzed. Power and torque were measured using a number of inertial and hydraulically loaded chassis dynamometers available in Edmonton and Calgary.

INTRODUCTION

Fractional addition of hydrogen as a fuel supplement to various hydrocarbon fuels for the internal combustion engines was researched in the early 70s at the onset of the energy crisis. During the 90s, this technology was revisited due to environmental concerns related to air pollution by vehicle emissions. Hoehn (1974) found decreased fuel consumption, lowered exhaust temperatures plus reduced CO and NOx emissions in ultralean conditions. Gallaghar and MacAlister (1993) hypothesized that hydrogen was a combustion stimulant that increased the rate of molecular cracking of large hydrocarbons. Another theory is that the high temperature in the combustion chamber produce of nascent (atomic) hydrogen and oxygen radicals. These radicals cause a chain reaction to ignite all primary fuel molecules simultaneously. Hydrogen has high flame speed, wide flammability limits, and low activation energy. Hydrogen speeds up rates of initiation and propagation of flames, reducing initiation delay and combustion periods (Jingding, 1997).

The HGS project initiated in Arizona in 1993. Twelve external agencies tested the patented design. Reduction in HC emissions varied from 8.3 to 69%, CO from 3 to 91% and NOx emissions varied for a 5% reduction to a 16% increase. One opacity test showed a 34% reduction. Three dynamometer tests showed an average 4.1% increase in horsepower. Fuel economy increases varied from 2% to 31%. These initial results were widely variant. The HGS product has undergone many developments since 1996. Figure 1 shows current version of the hydrogen generating system. The following outlines our field research in 1997 and 1998.

HC, CO & NOx EMISSIONS TESTING

Baseline no-load emission readings are stored at steady-state engine speeds using the Snap-On emission 5 Gas Analyzer model MT3505. After installation of the HGS, the engine is started and the HGS unit is turned on. When the engine reaches normal operating temperature, post emission tests are carried out according to a procedure elaborated by the manufacturer of the HGS. No-load CO, HC and NOx emissions tests were performed consistently on 49 vehicle installations in 1997 of various applications including passenger vehicles, light and heavy duty trucks, motorhomes, forklifts and a Zamboni. Three of these vehicles used diesel fuel, three used propane fuel and the remaining used gasoline. NOx results are not included in this analysis, as this emission should be tested under load.

Table 1- No Load Emissions Test upon Installation

Number Vehicles	Percent (%)	Observed HC (ppm)	Observed CO (%)
22	45	Reduced at all rpm	Reduced at all rpm
4	8	Increased at all rpm	Increased at all rpm
11	22	Reduced at all rpm	Increased at some rpm
12	25	Increased at some rpm	Reduced at some rpm

Nearly half of all installations displayed an immediate reduction in HC and CO under no-load conditions. This offers a quick way to check the operation of the HGS. Half of the installations show emissions increases or no effect under no-load emissions testing. Until the engine stabilization period is complete, slightly increased emissions may be measured. Chill (1998) hypothesizes that *"Hydrogen's affinity for Carbon would start the cleaning action almost immediately. The exhaust stroke can only flush (but not burn) carbon and other deposits loosened. An exhaust emissions test will show what the hydrogen is doing now."*

From February to March 1997, HC, CO and NOx gaseous emissions were measured under load on three test vehicles in controlled environment, using a chassis dynamometer. Two vehicles used gasoline fuel and one used diesel. Significant reductions of HC and CO emissions were observed under load.

A 5.8 L GMC Suburban was tested on a Dynojet chassis dynamometer equipped with a Snap-On Gas Analyzer. CO and HC were significantly reduced under load at all engine speeds as seen in Fig. 2 and 3. A 1996 Ford Crown Victoria was loaded on a Clayton (SUN) Model 820-9 chassis dynamometer with a Snap-On Gas Analyzer. CO was reduced to nearly zero at all engine speeds tested except 2500 rpm. This included a reduction from 2.85% to 0.06% CO at 2000 rpm attributed to the HGS. HC was reduced at all engine speeds tested. For example, at 2000 rpm, the HC dropped from 65 ppm to 8 ppm. A 1995 International 4700 Diesel truck was tested on a Taylor Model 719 hydraulically loaded dynamometer. Emissions were monitored using a Biosystems PhD Ultra Gas Analyzer. Both CO and NOx were significantly reduced under no-load emissions testing. Load testing showed a significant reduction in CO over the entire range of engine speeds. NOx was not reduced by the HGS, it remained at 35 to 59 ppm throughout the loaded tests.

OPACITY TESTING

Opacity or particulate density readings are based on percent light transmission between two photocells with clean air 0%. The black elemental carbon core of a soot particle has a 95% influence on opacity (Colorado, 1986). Due to the unavailability of chemiluminescence and diluted exhaust infrared meters (McCormick et al, 1998) measuring devices in Alberta particulate matter was investigated with snap acceleration tests. The Wager Model 6500 Opacity meter ensures an accuracy of +/-1% and follows SAE J1667 recommendations. SAE J1667 is the diesel emissions procedure used in California, Nevada, Utah, Washington, Colorado, and will be used in Arizona and Ontario in the spring of 1999.

Two 7.3L Ford F-250 trucks were tested with the Wager Opacity meter in September of 1998. Baseline opacities of 1.3 and 1.8% were reduced to 0.3%. Considering this low range values and that the meter is only accurate to 1%, the Ford results are inconclusive. The percent opacity for a 1991 GMC 1500 Turbo diesel truck was recorded for 7 hours without the HGS and 3 hours with the HGS feeding hydrogen and oxygen gases into the air intake. As can be seen from Fig. 4, the HGS resulted in a rapid drop in opacity after one hour of operation. After 3 hours, the HGS reduced the opacity by nearly ten percent. Extrapolation of the HGS graph after 3 hours would indicate a further reduction in opacity, but this could not be determined experimentally.

A diesel van tested in Calgary on April 30 (Chill, 1998) demonstrated drastic changes in opacity after only 40 minutes with the HGS running. Opacity snapshot readings were taken for five different rpm under no-load. Both streams of the dual exhaust were sampled and found to have widely varying opacities. The average opacity of the right exhaust decreased from an average of 62% to 20% after 40 minutes of HGS. The HGS was turned off and the opacity further fell to 12%.

G. Gallagher (1986) noted that loaded mode opacity tests performed at Colorado State University sometimes produced very high, rapidly changing opacity values. Gallagher (1986) attributed this to *"oxidation of the exhaust system deposits and/or a scouring action caused by exhaust system deposits broken loose by thermal transients during the test"*. After 40 minutes with the HGS on, Chill (1998) turned the HGS system off to test the cleaning affect of the HGS. The left exhaust's average opacity of 39% fell to 13 % after 40 minutes of HGS operation with the HGS off during the test. The range of the opacities also decreased after adding the HGS. The HGS system helps to maintain a more consistent emissions cycle, and makes permanent changes to the condition of the engine.

MILEAGE AND FUEL ECONOMY FIELD TESTING

All HGS users were asked to keep a consistent fuel type and re-fueling routine and record average vehicle speeds, rpm, idle time, weather conditions, load and terrain along with fuel volumes and distances. Thirty-three complete, consistent fuel logs were analyzed for performance. Six of the vehicles used diesel fuel, the remaining gasoline. Vehicles included small, mid to large passenger vehicles, vans, sport utility vehicles, light and heavy duty trucks pulling trailers, a 3 ton dump truck, a motor home and a stationary generator. A large amount of empirical data quoting mileage increases without adequate backup was not used in this analysis.

Fuel savings were calculated with eqn. (1) or (2). A sample of the detailed fuel savings data can be found in Table 2. Table 3 summarizes the fuel savings for the 33 vehicles sampled.

$$FS\,\% = \frac{\text{baseline L/km} - \text{HGS L/km}}{\text{baseline L/km}} * 100\% \qquad (1)$$

$$FS\,\% = \frac{\text{baseline gpm} - \text{HGS gpm}}{\text{baseline gpm}} * 100\% \qquad (2)$$

Table 2- Detailed Fuel Savings with Current Prototype

1. 1994 Ford Bronco, V8, 5.0 L Engine

	# Fills	mpg	L/100 km
Baseline	7	14.7	19.5
With HGS	14	22.6	12.8
% Savings		53.7	34.3

2. 1998 Volvo VN Diesel 12.7 L Highway Tractor

	# Fills	mpg	L/100 km
Baseline	3	6.2	46
With HGS	13	7.35	38.4
% Savings		18.5	15.6

Table 3 – Fuel Savings by Engine Size

Number Of Vehicles	Engine Size (L)	Model Years	Fuel Savings (%)	Standard Deviation (%)
7	1.8-3.3	1984-1995	20.7	4.1
6	3.4-4.3	1974-1997	20.8	15.6
8	5.0-5.2	1986-1996	24.9	8.5
4	5.6-5.9	1992,1996	12.4	8.7
3	7.3,7.5	1995, 1996	24.0	6.8
5	12.0,12.7	1995-1998	13.4	1.8
33	**1.8-12.7**	**1974-1998**	**20.0%**	**9.2%**

Fuel savings varied from 4.2 to 42.6%, averaging 20.0%. Three quarters of the vehicles sampled had fuel savings between 10 and 25%. The HGS system performed well over the entire range of engine sizes, and suffered the most variance in the 3.4 to 4.3 L range. In this range a 1974 Jeep equipped with a first generation HGS realized much lower savings than two 1994 Ford vehicles equipped with the newer HGS prototype. A Cummins stationary generator recorded higher fuel savings than a motor home of the same engine size. High standard deviations in the field data indicate that all variables were not tightly controlled. Both small personal cars and large diesel highway trucks suffered low standard deviation and fuel savings can be predicted with more confidence.

DYNAMOMETER TESTING

In February, 1997 and April 1998, six vehicles were tested for maximum brake horsepower and torque. The Dynojet Model 248-H chassis dynamometer rated at 1200 hp (894 kW) was used for six of the ten runs. Energy drawn from the drive wheels of a vehicle is stored in a rotating drum of known mass. By measuring the acceleration of the drum and the vehicle engine rpm, horsepower and torque can be calculated (Dynojet.com, 1998). None of the dynamometers used were equipped with a Micromotion mass meter to determine fuel consumption values

Each run included six identical loading schedules performed on the same day, three as a baseline and three with HGS unit on for one hour. A government agency used a different chassis dynamometer to test three of these same test vehicles. The company also hired an external consultant to complete detailed testing and evaluation of two of these vehicles (Chill, 1998). The results obtained are summarized in Table 4.

Table 4- Summary of Dynamometer Results

Vehicle	Power Before	Power After	% Gain	Torque Before	Torque After	% Gain
1995 International 4700, 7.3L						
	192.9	201.5	4.4	209.4	214.8	2.6
	128.9	138.6	7.5			
1994 GMC ½ Ton, 5.0 L						
	192.9	201.3	4.4			
	126.3	129.4	2.5	210.8	215.0	2.0
	197.1	201.1	2.0			
1995 IHC 3 Ton Diesel Dump Truck, 7.3 L						
	127.9	138.6	8.4			
	132.5	134.7	1.7			
1990 GMC Suburban, 5.7 L						
	156.0	163.9	5.1	244.4	270.3	10.6
1994 Ford Bronco, 5.0L						
	151.1	162.5	7.6	219.6	225.2	2.5
1989 GMC Diesel Box Van, 6.2 L						
	94.1	100.1	6.3	166.0	176.2	6.1
AVERAGES		**5.5% power** +/-2.2		5.3%**torque** +/- 3.7		

The average brake horsepower and torque increase on all six vehicles over ten separate dynamometer tests was five percent. The average horsepower and torque match closely, but does not occur in each run. The average increases for the three vehicles supervised by an external consultant (Chill, 1998) was 6.3% horsepower increase and 6.4% torque increase. An independent test conducted by Environment Canada (FTP /UDDS) on a new Ford Crown Victoria showed no performance change after the system was installed. Fig. 5 displays peak horsepower for the GMC Suburban as resulted from rpm-Power/Torque profiles presented in Fig. 6.

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CONCLUSIONS

Performance impact of the hydrogen generating system is widely variant and dependent on following variables:

- type of fuel
- type of engine
- condition of the engine
- operating conditions
- operating parameters of the engine
- duty cycle

Summarizing results presented in this paper, following observations can be made:

a) The hydrogen generating system reduces CO and HC emissions under loaded conditions. Half of the vehicles tested under no-load at installation will demonstrate CO, HC and NOx reductions. NOx reductions at no load are not as meaningful as loaded emissions test. The one loaded NOx test performed did not show reduction by the HGS.

b) HGS reduced Snap Acceleration percent opacity by ten percent. Tests are inconclusive if baseline opacity is below 5%. Average live opacity readings were reduced 26 to 38%, but ranges during trials have wide variance. Opacity can produce widely varying value unless strict procedures are followed. A variety of opacity testing including SNAP, idle, high-idle, steady-state and diesel-lug down testing is recommended.

c) The HGS provides an average fuel savings of 20.0% +/- 9.2% on a wide variety of engine sizes, ages, manufacturers and applications. The two classes with lower deviation are small gasoline cars, averaging 20.7% fuel savings, and large highway diesel trucks, averaging 13.4% fuel savings.

d) Dynamometer testing showed an average increase of 5.5% horsepower and 5.4% engine torque. Further testing with dynamometers equipped with emissions analyzers and fuel consumption rates is recommended. The HGS appears to react well under steady-state load rather than a transient UDDS drive cycle.

Further field research is required in order to evaluate the performance impact of the HGS, with higher level of accuracy. In order to substantiate the claims, engines will be grouped in classes, ensuring appropriate number of samples and further development of the testing methodologies.

NOMENCLATURE

CO – carbon monoxide gas
gpm – gallons per mile = 1/mpg
HC – unburned hydrocarbons
HGS – Hydrogen Generating System
NOx – nitrogen oxide gaseous emissions
mpg – miles per gallon
pm – part per million by volume
UDDS – urban dynamometer driving cycle.

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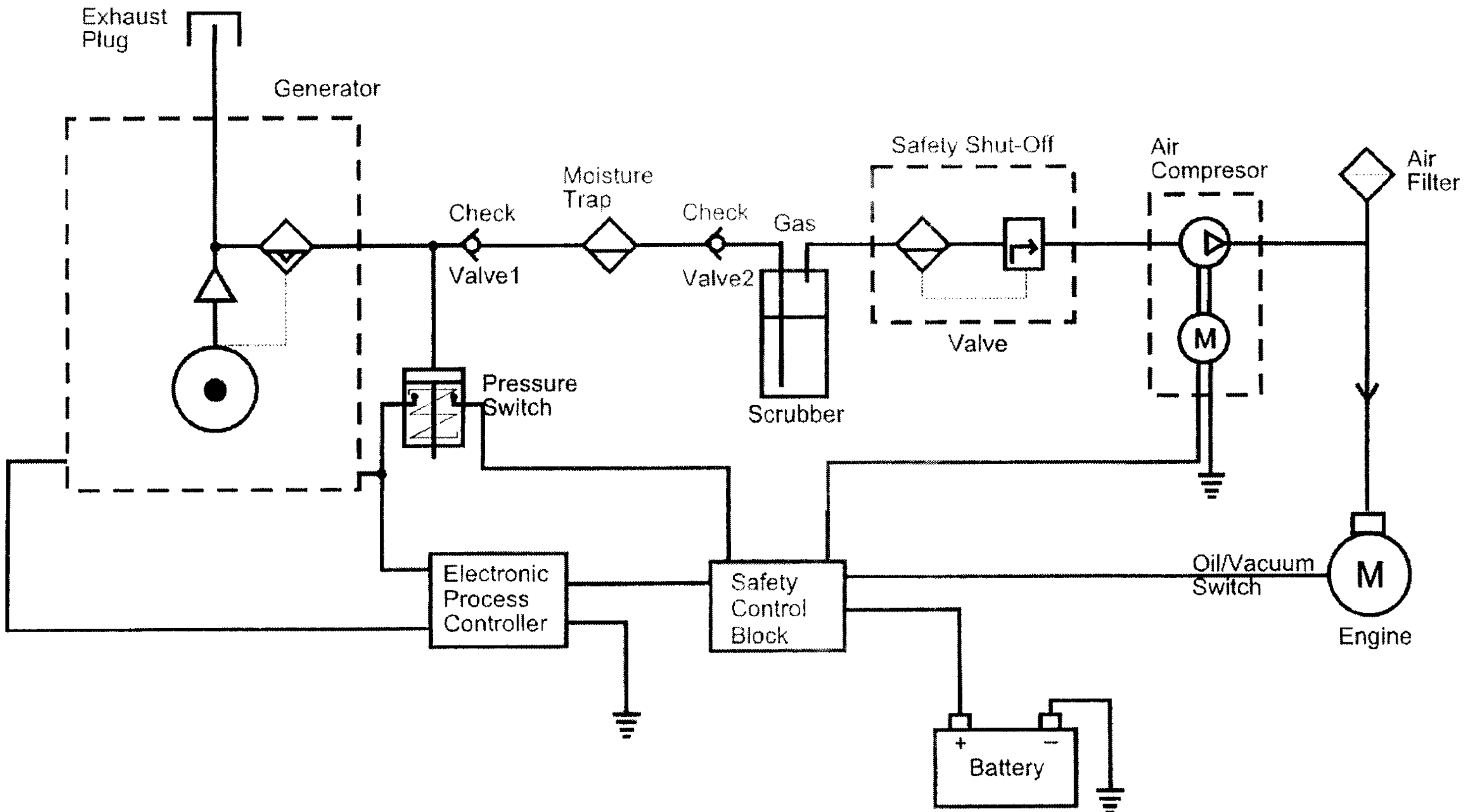

Fig. 1 Hydrogen Generating System

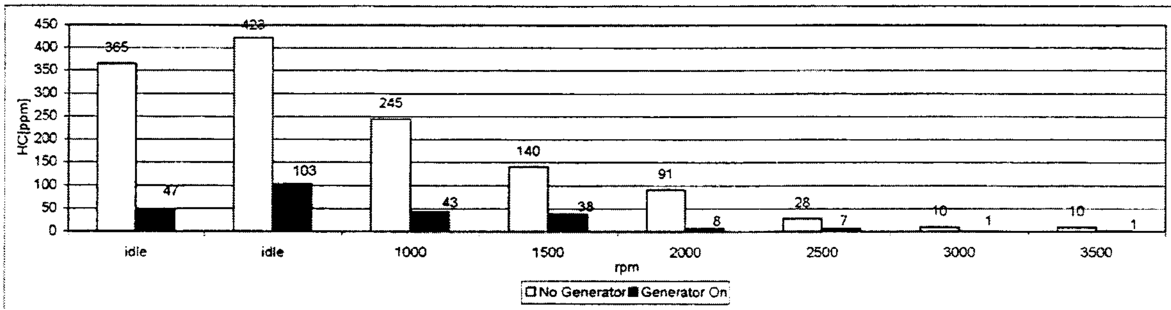

Figure 2 - 1990 GMC Suburban HC Emissions

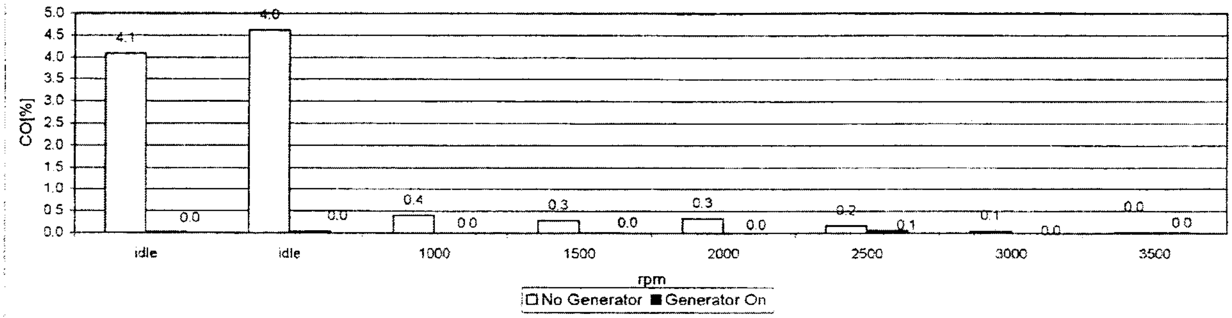

Figure 3 - 1990 GMC Suburban CO Emissions

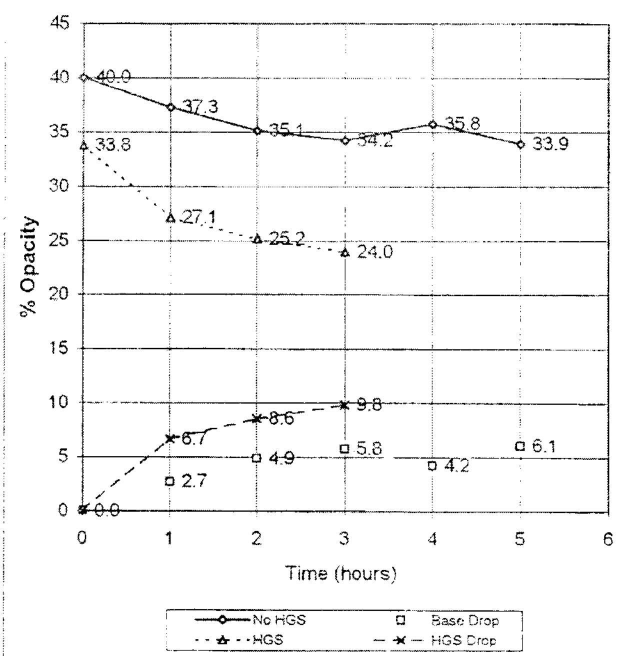

Figure 4 - Opacity Data, 91 GMC Turbo

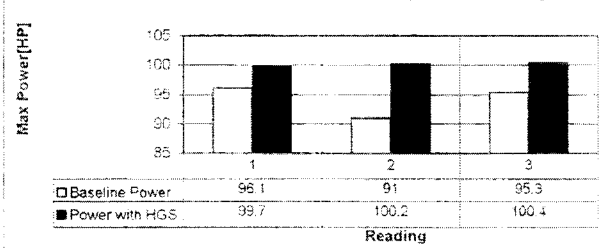

Figure 5 - HorsePower Increase on 89 GMC Diesel

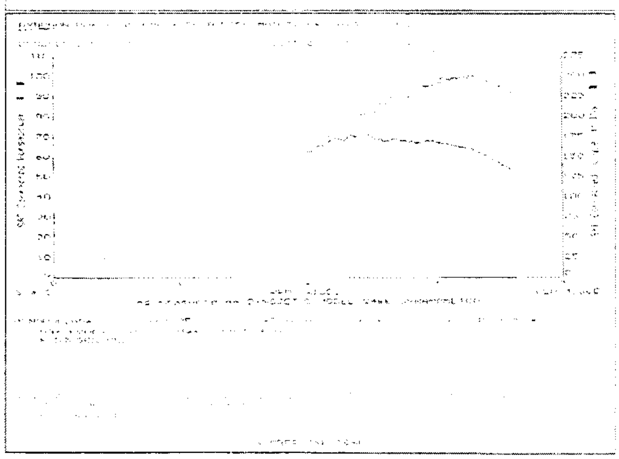

Figure 6 - Dynojet Run with HGS for 89 GMC Diesel