COMMERCIALIZATION OF HEAVY DUTY NATURAL GAS ENGINES

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INTRODUCTION

The purpose behind the participation of California energy and air quality agencies in the creation and expansion of alternative fuel low emission vehicle markets is to support public policy goals for fuel diversity in the transportation market and improved air quality. Remarkable advances in commercializing natural gas vehicles have occurred in some heavy-duty market segments, but the levels of future market growth needed to achieve the public policy goals will require improved economics for truck purchasers. These improved economics seem to require a combination of more efficient engines, economic return from reduced emissions, and lower equipment and fuel prices.

Fuel efficiency is very dependent on driving patterns. Available Otto cycle spark-ignited and throttled natural gas engines yield lower fuel economy at low load and idle operating on congested urban streets and freeways than the diesel engines that they compete with. This means that long haul and any other trucking sectors that can minimize low load and idle operation become preferred target markets where the fuel economy disadvantages of spark-ignited natural gas engines can be minimized. However, this will require widespread natural gas availability servicing the principal corridors used by long-haul trucking.

There are some fundamental conflicts that can frustrate attempts to create large and sustainable markets for heavy-duty natural gas vehicles. The long-haul truck market typically operates at 10,000 miles per month or higher with medium- to high-load duty cycles. The duty cycles that characterize this market allow current spark-ignited natural gas engines to operate at their best fuel efficiency, although this is at best 15 percent lower than typical diesel efficiency. Theoretically, the large quantities of relatively inexpensive natural gas fuel consumed could result in a large enough fuel cost savings to amortize the current high engine and vehicle differential prices. Unfortunately, this long-haul market also requires a dense network of CNG or LNG fuel stations outside of the major air quality challenged urban areas. It is very difficult to economically justify the large investments necessary to create such a dense and widespread fueling network when there are only very limited numbers of near-term customers (the chicken and egg problem so familiar to alternative fuel supporters). Natural gas fueling stations also require high utilization to be able to amortize their high capital costs and dispense fuel that will be inexpensive enough to compete effectively with diesel fuel despite less efficient engines.

Heavy duty diesel sources have been targeted by California air quality districts as the last major source of photochemical oxidant air pollution (principally NO_x as a precursor to Ozone) with the potential for relatively low cost control. Inventories of mobile source nitrogen oxide (NO_x) emissions in California's South Coast and Sacramento Air Basins show about half or more comes from heavy duty diesel trucks. This reflects considerable success in achieving up to 98 percent reductions in NO_x emission levels with improved emission control technology in light duty vehicles. A large portion of the heavy duty truck emissions is not controllable by regulation of locally-based sources, because it comes from long-haul trucks that are often not based in the local district and thus difficult to control with local regulation. Indeed, there is real concern that tougher regulations can force relocation of trucking firms that are economically important to the local community. The size of the targeted heavy duty market segments is also large enough to support both the commercialization of heavy duty natural gas vehicles and the necessary widespread natural gas (primarily LNG) fueling station network.

This paper will describe the major types of heavy duty natural gas engine technologies, current results of demonstrating several examples in trucks, and the results of economic payback analysis. It will discuss the need for improved fuel efficiency (in actual duty cycles typical of major market segments) along with a reduction in federal highway fuel excise taxes for LNG and a return on the purchaser's investment in lower emission engine technology in order for heavy duty natural gas engines to achieve their economic potential in trucking markets.

ENGINE TECHNOLOGIES

There are three basic types of heavy duty natural gas engines currently available: spark-ignited stoichiometric, spark-ignited lean bum, and pilot-ignition dual fuel.

Spark-ignited stoichiometric engines provide the lowest NO_x emissions, as low as 1/5 that of modem diesels, but at the cost of the lowest fuel economy, perhaps half that of modern diesels in typical truck duty cycles. Examples of these engines are:

- The Caterpillar G3306 engine, a 10 liter engine based on a widelymarketed mechanical diesel engine, includes an oxygen sensor and closed loop computer feedback technology to control the air/fuel ratio at stoichiometric to allow a three-way catalyst to effectively control NO_x in addition to HC and CO. This engine is certified at 0.7 g/bhp-hr NO_x, the lowest available. This engine has received only very limited commercial market acceptance, likely due to both low fuel economy and high heat rejection.

- The Tecogen (ThermoPower) 7000 and 7000T engines are converted Chevrolet 427 CID (7 liter) gasoline engines. They include a three-way catalyst, but are open loop without an oxygen sensor and computer feedback system to precisely control the air-fuel ratio at stoichiometric.

Spark-ignited lean burn engines: the majority of the current market offerings, provide intermediate fuel economy, perhaps 2/3 of modem diesels in typical truck duty cycles, with NO_x emissions as low as 1/3 that of modern diesels. Examples of these engines are:

- The Cummins natural gas engines use this principle. The latest generations of L10, C8.3, and B5.9 series natural gas engines incorporate advanced oxygen sensor and closed loop computer feedback technology with central fuel metering systems to maintain lean air/fuel ratios near the lean limit.

- The John Deere 6081 (8.1 liter) and 6068 (6.8 liter) engines and the Mack E-7G (12 liter) engine utilize advanced lean bum oxygen sensor and closed loop computer feedback technology.

- The Detroit Diesel Series 50G (8.5 liter) (currently available for trasit markets without oxygen senso feedback control) and 60G (12.7 liter) engines are projected to become available for automotive marketrs in 1998 with advanced lean bum oxygen senso and closed look computer feedback technology.

A more sophisticated type of oxygen sensor and computer feedback technology is required to measure the oxygen *quantity* at lean air/fuel ratios rather than the more common stoichiometric sensor and feedback systems (in gasoline passenger cars and light trucks) that merely monitor the *presence or absence* of oxygen.

Pilot-ignition dual fuel: engines provide NO_x emissions from 1/2 to equal that of modern diesels, with fuel economy nearly equal to modern diesels. An example of this type of engine is:

- The Clean Air Partners/Power Systems Associates/ Caterpillar dual fuel engines use this principle. The technology developed by Clean Air Partners and produced by Power Systems Associates (a major Caterpillar dealer) involves modifications to a range of Caterpillar diesel engines that maintain the Caterpillar warranty. The technology includes automotive type port fuel injectors for natural gas with the conventional diesel fuel direct injection system injecting just enough diesel fuel to ignite the natural gas intake charge. Improved versions of Caterpillar 3126 (7.2 liter 190 and 250 hp), C10 (10 liter 275 and 350 hp), and C12 (12 liter - 350, 400, and 425 hp) dual fuel engines are expected to be certified this year to the ARB optional NO_x emission standards of 2.5 g/bhp-hr.

EARLY SUCCESSES

The most notable early successes of natural gas heavy duty engines have been in the transit bus market. The Federal Transit Agency (FTA) provides funds from gas tax revenues to pay for 80 - 85 percent of the purchase price of transit buses for public transit districts. Transit agencies have been able to obtain FTA funding to cover the higher capital costs of alternative fuel engines, fuel storage systems, and to some extent the necessary fueling infrastructure. Transit districts thus do not need to amortize the higher capital costs with fuel cost savings or economic return from emission bene fits.

Cummins has been notably successful in taking advantage of this public support for natural gas to enter the transit market previously dominated by Detroit Diesel Corporation (DDC) with their two stroke diesel engines. Over 135 million cumulative miles experience have been achieved on over 1,500 natural gas Cummins L10G engines, initially the L10-240G, later the L10-260G, and most recently the L10-300G (280 hp transit rating), primarily in the transit market[1].

DDC responded to the Cummins market challenge with a Series 50 four stroke diesel engine that is a four cylinder, 8.5 liter version of the very successful six cylinder Series 60 12.7 liter truck diesel engine. DDC also developed a natural gas version, the *Series 50G, that is* available in 250 and 275 hp transit ratings. The previously market-dominating DDC two stroke diesel engines have not been certified to California transit emission standards (without particulate traps) since 1990[2].

There have also been substantial sales of heavy duty natural gas engines in municipal refuse collection service and schoolbuses. Engines include the Cummins C8.3G and L10G series, the DDC Series 50G, the Mack E-7G, the Tecogen TecoDrive 7000 and 7000T, and the John Deere 6081.

DEMONSTRATION EXAMPLES

The California Energy Commission has cosponsored several demonstrations of heavy duty natural gas engines in a variety of truck applications. Cosponsors include the South Coast Air Quality Management District, Southern California Gas Company, the U. S. Department of Energy, the National Renewable Energy Laboratory (NREL), the American Trucking Associations Foundation's Trucking Research Institute, Ventura County APCD, and Santa Barbara County APCD.

The relative fuel efficiencies of the demonstration spark-ignited lean burn engines described below are remarkably consistent. The 25 - 40 percent loss of efficiency that appears to characterize these engines in typical truck duty cycles needs to be recognized as a formidable barrier to their commercialization in trucking markets. The Caterpillar and Detroit Diesel engines are prototypes that may not include potential fuel efficiency improvements. Some recent engine improvements in other engines may show improved relative fuel efficiency, but reliable data confirming this is not yet available.

- Vons Caterpillar G3406LE (14 liter - 350 hp) - 30 percent lower BTU fuel economy compared to a mechanical 3406B diesel in the same service[3]. The duty cycle was relatively high load, pulling high gross weights over Grapevine pass. Caterpillar decided not to commercialize this engine due to both the lack of sufficient market demand to justify significant further development efforts and the availability of the dual fuel engine option.

- L.A.. Times DDC S60G (12.7 liter -370 hp) - 35 to 40 percent lower BTU fuel economy compared to electronic DDC S60 diesels in the same service 4. The duty cycle is medium load, pulling medium gross weights in frequently congested roadways primarily on the Los Angeles regional freeway system.

- Wal-Mart DDC S60G (12.7 liter -370 hp) - 29 to 33 percent lower BTU fuel economy compared to electronic DDC S60 diesels in the same servic[5]. The duty cycle was relatively high load, pulling medium gross weights over various open road highways including the Grapevine pass.

- Jack B. Kelley Cummins LIO-30OG (10 liter - 300 hp) - 25 percent lower BTU fuel economy compared to diesels in the same service [6]. These are high load operating vehicles hauling LNG and other cryogenic gases on rural highways. This is a private commercial demonstration with some NREL fundng.

- City of Long Beach Cummins L10260G (10 liter - 260 hp) - 30 perent lower BTU fuel economy compared to mechanical Cummins LI0 diesels in the same service [7]. These are refuse packer trucks that collect municipal waste from homes and deliver to a central solid waste recovery facility. This demonstration of three natural gas trucks is funded by a DOE Grant.

ECONOMIC ANALYSIS OF NATURAL GAS TRUCKS

The author performed an analysis of natural gas truck economics to determine the ability of currently available engines and fuel systems to amortize higher vehicle prices with lower cost fuel and emission incentives. The payback analysis for natural gas trucks illustrated in the Appendix includes a range of assumptions for duty cycle efficiencies, monthly mile age accumulation, emission benefits, and incentives for emission benefits. The analysis presented assumes a$35,000 capital cost increase for natural gas engines and fuel systems, 2 g/bhp-hr NO_x emission levels in comparison to 4 g/bhp-hr for diesels (required for trucks in 1998), a 10 percent annual cost of capital (hurdle rate), $1.50 per gallon diesel and $.50 per gallon LNG retail price, and either no value for NO_x emission reductions or a $10,000 per ton of NO_x emission credit.

At 10,000 miles per month, common in long-haul trucking, and the 30 percent efficiency loss typical of current engines (in demonstration fleets), nearly 14 years is required for payback without emission credits. This can be reduced to 2.4 years with emission credits. For a fleet that can achieve 15,000 miles per month, with a 30 percent efficiency loss, payback ranges from nearly 7 years without credits to about a year and a half with credits. For a fleet that can achieve 20,000 miles per month, with a 30 percent efficiency loss, payback ranges from about 5 years without credits to about a year with credits. Obviously, different efficiency and fuel price assumptions lead to different results, but these assumptions appear to reflect future possibilities with some optimism for low LNG prices and stable diesel prices. The $0.50 per gallon LNG price could represent fuel from a nearby liquefaction plant with the Federal Excise Tax (FET) reduced to CNG levels as proposed in pending Federal tax legislation. Although other assumptions can be modeled, it is difficult to project economic competitiveness without improvements in engine efficiency and emission incentives.

LNG price forecasts incorporate three elements for discussion: location, tax rates, and utilization. LNG is transported by cryogenic truck tanker from production plants to fuel stations, and production locations are not generally located close to fuel stations needed for California demonstrations. Siting new production plants to minimize the haul distance to needed fuel stations will be a critical element in achieving competitive pricing.

Federal fuel excise taxes are currently at a level that penalizes LNG (and LPG and methanol) compared to CNG, diesel, gasoline, and ethanol on a BTU content basis. There are efforts underway in the U.S. Congress to either normalize the tax rate per BTU or establish rates for alternatives that would initially be lower than conventional fuels (potentially zero since electricity currently has no excise tax). The present varied tax rate structure for different fuels appears to reflect the relative political strength of various alternative fuel constituencies and the failure of alternative fuel proponents to work together for mutual benefit.

Lastly, the price of LNG and any other alternative will be somewhat sensitive to fuel station utilization. The higher the fuel station investment per BTU delivered, the more sensitive that station's economics is to utilization. LNG fuel station investment is lower than CNG, but higher than the other liquid fuels, giving it an intermediate sensitivity to utilization.

Attainment of the necessary market growth to accomplish fuel diversification goals will be delayed until sufficient economic improvements occur to meet the needs of the targeted heavy duty natural gas truck customers.

ECONOMIC INCENTIVES FOR NO_x REDUCTION

The opportunity to achieve an economic return from lower emissions is also a critical element in projecting a successful economic basis for trucking industry investment in natural gas vehicles. Currently, purchasers of lowemission heavy duty natural gas engines do not receive any direct economic benefit from the lower emissions. Some trucking companies may be able to justify the higher prices in return for image improvement (sometimes called "green marketing"), but it is difficult to see this occurring on a large enough scale to achieve the necessary air quality improvement without commensurate direct economic benefits.

Some pioneering air quality agencies have pursued establishment of market mechanisms for emission credit trading to provide the needed direct economic benefits, but difficulties in providing the necessary accurate documentation of actual emission benefits have prevented achievement of effective market success.

Another approach is to provide public funding to purchase emission benefits. This has been proposed in AB 1368 to the California Legislature that would provide funds to pay the additional purchase cost of low emission heavy duty vehicles up to a value of $12,000 per ton of NO_x reduced. Since major reductions in NO_x from heavy duty vehicles are required by the California State Implementation Plan, the bill would essentially pay for the emission reductions needed for attainment. Tougher emission standards for 2004 are not projected to be sufficient or in time to achieve attainment, particularly in the Sacramento area where attainment is required by 2005 (the South Coast Air Basin has until 20 10). Attainment is projected to require early adoption of all possible alternative fuel and low emission technologies and the bill would encourage such early adoption.

IMPROVING TECHNOLOGY

In recognition of the need to improve the efficiency of heavy duty natural gas engines, the American Trucking Associations Foundation's Trucking Research Institute (TRI), with funding by the U. S. Department of Energy, the South Coast Air Quality Management District, and the Gas Research Institute, has initiated a program to cost-share the development of improved fuel efficiency engines with original equipment manufacturers. The California Energy Commission, the California Air Resources Board, and other organizations are considering cofunding of the TRI administered program.

Proposals from original equipment manufacturers (Caterpillar, Cummins, John Deere, and Mack) include some very interesting and pioneering fundamentally new future technologies, in addition to substantial near-term improvement of existing technologies. Technologies proposed include direct injection compression ignition (diesel like) technology, improved feedback control for SI engines, electronic fuel metering for each cylinder to reduce maldistribution and facilitate skip fire, improved high-energy ignition for leaner mixtures, and camless valve actuation for complete timing flexibility.

CONCLUSIONS AND RECOMMENDATIONS

1. Currently available heavy duty natural gas engines are significantly less fuel efficient than the diesel engines they are competing with in representative truck duty cycles with substantial idle and light load operation.

2. Natural gas, primarily LNG, will not become economically competitive in heavy duty truck markets until some combination of improved engine efficiency in customer duty cycles, lower engine and fuel system prices, lower fuel prices, and emission credits becomes available. Lower engine and fuel system prices can be anticipated when scale economics and competitive pressures occur. Lower fuel prices can come from reduced FET and from local LNG facilities that can provide shorter haul distances.

3. Organizations with responsibility for attaining air quality standards that are significantly impacted by emissions from heavy duty trucks should pursue ways to improve the economics of natural gas trucks by finding ways to provide economic benefits to truck purchasers in return for emission benefits.

4.Organizations with responsibility to improve fuel diversity in transportation markets should pursue ways to improve the economics of natural gas trucks by finding ways to increase the fuel efficiencies of heavy duty natural gas engines and reduce natural gas, principally LNG, prices and FET rates.

LEGAL NOTICE

The views and conclusions expressed in this document are those of the author and should not be interpreted as necessarily representing the official policies of the Energy Commission or the State of California.

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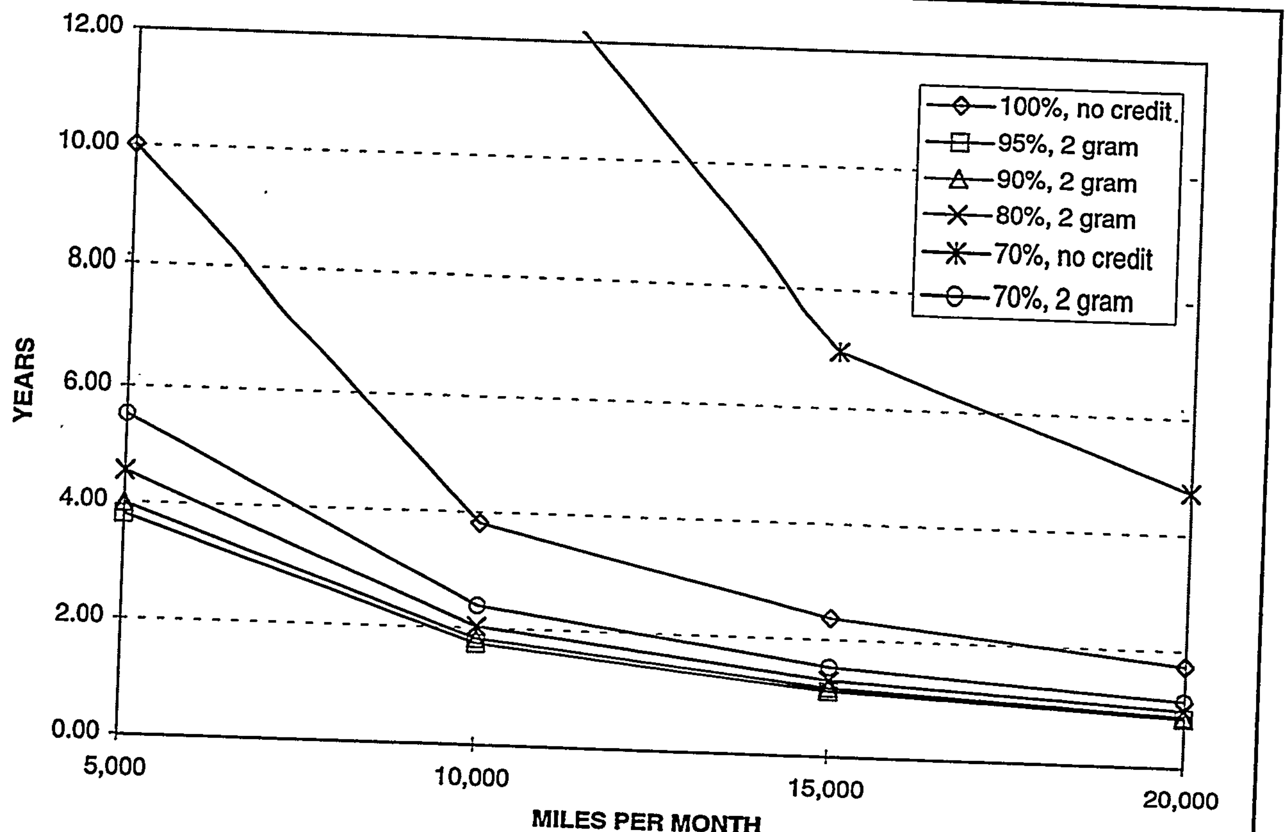
7. City of Long Beach, Federal Grant DE-FG51-94R900029, Monthly operating data reported to the NREL Alternative Fuels Data Center.

APPENDIX - NATURAL GAS TRUCK AMORTIZATION



MILES/MO	100%, no credi	95%, 2 gram	90%, 2 gram	80%, 2 gram	70%, no credit	70%, 2 gram
5,000	10.01	3.80	3.99	4.54		5.51
10,000	3.81	1.72	1.80	2.01	13.90	2.38
15,000	2.37	1.11	1.16	1.30	6.96	1.52
20,000	1.72	0.82	0.86	0.96	4.72	1.12
Efficiency % of diesel	100%	95%	90%	80%	70%	70%
NOx g/bhp-hr LNG	2	2	2	2	2	2
NOx g/bhp-hr DSL	4	4	4	4	4	4
CF-LNG (mi/bhp-hr)	4.1	4.1	4.1	4.1	4.1	4.1
CF-DSL (mi/bhp-hr)	4.3	4.3	4.3	4.3	4.3	4.3
NOx g/mi LNG	8.2	8.2	8.2	8.2	8.2	8.2
NOx g/mi DSL	17.2	17.2	17.2	17.2	17.2	17.2
NOx $/ton	$0	$10,000	$10,000	$10,000	$0	$10,000
Diesel mpg	6.9	6.9	6.9	6.9	6.9	6.9
LNG mpg	4.002	3.8019	3.6018	3.2016	2.8014	2.8014
Diesel price	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50
LNG price	$0.50	$0.50	$0.50	$0.50	$0.50	$0.50
Interest rate	10.00%	10.00%	10.00%	10.00%	10.00%	10.00%
LNG gal	0.58	0.58	0.58	0.58	0.58	0.58
Cap. Cost Differential	$35,000	$35,000	$35,000	$35,000	$35,000	$35,000