A Comprehensive Summary of Industrial Truck Engine Emission Data Compared by Fuel

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ABSTRACT

Historically, the industrial truck industry has been plagued by misleading and often conflicting reports on the relative emissions of various fuels. This has led many of the estimated 95,000[1] end-users in this market to switch between those fuels without the benefit of accurate, 'apples-to-apples' information. The purpose of the study is to provide a comprehensive, literature review of the emission studies to-date, with a critique of the merits of each.

BACKGROUND

In 1990 Clark Material Handling Company prepared a CNG Project Review based on an emission study conducted by Bryan S. Memmott on a Mitsubishi powered lift truck. To our knowledge, this was the first published data comparing LPG and natural gas for forklifts. It reported carbon monoxide emissions almost twenty times higher on propane compared to natural gas fuel delivery systems. Unfortunately this was widely promoted as a basis for switching to natural gas. This report was later corrected in a second study[2] explaining that the propane values were based on an 'as delivered' engine that was subsequently found to lack a balance line between the air cleaner and the atmospheric vent of the propane pressure regulator as well as an incorrect second stage diaphragm spring[2].

In 1994, Southwest Research Institute and the Alternative Fuel Research and Education Division of the Texas Railroad Commission completed a comprehensive study of LPG and CNG fuel configurations for forklifts to determine the emission levels attainable in the laboratory[3]. It compared seven open and closed loop carbureted combinations on a Nissan H20, 4-cylinder engine. It included tests with and without a catalyst using three different test cycles, including the current ISO 8178 C2. Only two of the seven tests are included here (Table 1). They represent the closest duplication of conditions for LPG and CNG. These were closed-loop, without catalyst, carbureted systems but provide early documentation of the negligible differences in tailpipe emissions in a controlled study.

Table 1. Summary of Cycle C2 Emissions

Summary of Cycle C2 Emission Results (Brake Specific Emissions gm/hp-hr)					
Test No.	Fuel	THC (NMHC)	CO	NOx	l
E	LPG	2.5	15	12	~0.99
H	CNG	3.0 (0.3)	12	9	0.99-1.00

Source: Southwest Research Institute

In 1995 Columbia Gas of Ohio asked Mr. Memmott to conduct a third study. Six different tests, with various fuel systems and fuels revealed even smaller differences between properly installed and adjusted gaseous fuel conversions. Quoting from the conclusion of that report, " Test 3 has shown that propane can deliver performance with low exhaust emission, in fact, lower than natural gas…"

In 1999, at the Providence, RI Forklift Summit, the Propane Education and Research Council sponsored a study by Dr. Mark Delucchi, University of California at Davis, that reported favorable emissions for LPG in his 'Total Fuel Cycle Analysis of Emissions of Urban Air Pollutants and Greenhouse Gases'[4]. Summarizing from his abstract, "LPG from natural gas appears to have among the lowest lifecycle emission of urban air pollutants, and, perhaps, relatively low lifecycle emission of greenhouse gases." Using his modeling, Table 2 predicts for the year 2005.

Table 2. Pollutant Emissions From the "Upstream" Fuel Cycle, from Feedstock Production Through Fuel Dispensing (grams/10^6-BTU-Fuel Dispensed)

FUEL	Ethanol	LPG	LPG	LPG	Diesel	CNG	RFG	MeOH	EtOH	CH2
Feed Stock	W50/G50	NG	Oil	Oil	Oil	NG	Oil	NG	Com	NG
CO2	-17,862	4,504	7,568	11,557	12,713	9,262	19,714	30,264	67,849	83,251
NMOC's	31.50	9.40	16.70	26.10	17.50	7.00	52.20	25.20	235.70	9.40
CH4	195.60	123.00	125.10	127.80	132.80	313.10	153.30	28.70	205.00	375.50
CO	144.10	24.00	28.10	33.40	39.90	30.00	39.10	59.10	210.60	50.20
N2O	12.40	0.20	0.30	0.50	0.80	0.40	0.70	1.20	36.90	1.90
NOx	187.60	43.20	49.20	57.10	59.40	72.00	72.90	154.10	467.80	163.90
PM	41.20	2.50	20.40	43.70	46.00	4.00	44.40	9.60	199.70	10.90
CO eqv.	-8,474	7,489	10,448	14,300	15,647	16,785	23,251	37,115	83,763	92,008

Source: Institute of Transportation Studies

PRESENT:

Current projects would first include the University of Alberta paper 'Tailpipe Emissions Comparison Between Propane and Natural Gas Forklifts' by Dhaliwal and Checkel[5]. The most often quoted statistics from that study were, "…NGV converted forklifts produced lower emissions (*than LPG*) by 97% CO and 84% NOx." This study utilized a weighted eight-mode duty cycle that more closely simulates actual forklift operation. The study compared an open loop, carbureted LPG system with two-way catalyst technology to a computer controlled, closed-loop, fuel injected NGV system with a three-way catalysts. While the authors were clear in explaining the differences, this was a classic comparison of old LPG technology with the latest NGV technology. The study went on to examine the effect of various fuel system malfunctions and emissions degradation over time, but those results were largely lost in the initial bias of the design. They did qualify the results saying, "…tests have proven with a well tuned truck engine and properly calibrated fuel system either LPG or NGV will produce low emissions without sacrificing good performance."

In 2002, Southwest Research Institute on behalf of the California ARB and the South Coast Air Quality Management District conducted the most recent study[6]. Their results were reported in the September issue of Off Highway Engineering published by the Society of Automotive Engineers. Several engines and test cycles were selected. This was a substantive comparison of gasoline and LPG. A range of emissions reduction technologies was employed including air/fuel ratio and spark timing optimization, and three-way catalysts in a closed-loop fuel systems. Using the ISO 8178-C2 seven mode test typical of the variable speeds of a forklift and isolating just the engines run on gasoline and and LPG, the results can be seen in Table 3 (a, b and c).

Table 3a. Gasoline BASELINE (Open Loop)

GASOLINE Engine BASELINE (Open-Loop) Emissions (g/kW-h)	HC	NOx	HC+NOx	CO	BSFC (kg/kW-h)
Engine B	2.0	11.2	13.2	21.9	0.353
Engine C	5.1	10.4	15.6	68.0	0.376
Avg. (C2)	**3.6**	**10.8**	**14.4**	**45.0**	**0.365**

Table 3b LP Engine BASELINE (Open-Loop)

LPG Engine BASELINE (Open-Loop) Emissions (g/kW-h)	HC	NOx	HC+NOx	CO	BSFC (kg/kW-h)
Engine B	1.3	15.7	16.9	9.9	0.321
Engine C	2.3	15.4	17.7	11.8	0.329
Avg. (C2)	**1.8**	**15.6**	**17.3**	**10.9**	**0.325**
	(<50%)	(>31%)	(>17%)	(<75%)	(<11%)

Table 3c. Engine OPTIMIZED LPG Results

Engine B OPTIMIZED LPG Results (g/kW-h) Description	HC	NOx	HC+NOx	CO	BSFC (kg/kW-h)
Baseline	1.3	15.7	16.9	9.9	0.321
Closed-Loop/OEM catalyst	0.5	0.5	0.7	4.0	0.349
" " w/new calibration	0.3	0.7	1.0	7.9	0.341
" " w/larger catalyst	**0.3**	**0.0**	**0.3**	**5.5**	**0.336**

Source: Southwest Research Institute

Additional tests were conducted to measure unregulated emissions (formaldehyde, acetaldehyde, benzene, 1,3-butadlene and styrene) and 250 hour durability, but the conclusion was, "…that low emissions-meeting CARB LSI standards-could be obtained with a properly operating control system."

Table 4.

Manufacturer	Model Year	Engine Disp.	Engine Models	Fuel Types	Certification Values HC+Nox (std 3.0)	Certification Values CO (std 37.0)
Ford Power Products	2001	4.20	ESG 642	Gas	0.6	17.6
	2002		LRG 425	Gas/NG,LPG/NG	.05	5.7
	2001	2.50		Gas,/LPG,Gas/LPG	.04	12.5
	2002			Gas/NG, LP/NG	0.1	14.6
Mitsubishi	2001	2.36	4G64	LPG	0.2	1.1
	2002			LPG	0.3	0.8
Impco	2001	5.70	GM5.7L/AH	LPG	0.6	6.3
	2002	3.00	GM 3.0L	LPG	0.2	5.2
Nissan	2002	2.50	H25 Nissan/TCM/Komatsu	Gas, LPG	0.5	9.9
	2002	2.00	H20 Nissan/TCM/Komatsu	Gas/LPG	0.4	5.6
NACCO (NMHG)	2001	2.0,2.2	FE ZH02, FEH09R	LPG	0.7	19.9
	2002	2.0,2.2	FE ZH02, FE H09R, F2 ZH03	LPG	0.8	19.9
	2002	3.00	GM 3.0L	LPG	0.6	10.4
Jasper	2001	7.50	Jasper 460	LPG	0.6	0.6
Toyota	2001	2.20	4Y, 4YH	LPG	2.6	7.2
	2001	4.30	GM6-262, GM6-262H	LPG	1.1	8.0
MCFA	2001	2.0,2.35	4G83, 4G64	LPG	1.4	17.5
	2002	2.0,2.35		LPG	1.5	15.2

Source: California Air Resources Board

Current California Air Resource Board data is summarized in Table 4. This represents the most comprehensive emission data set to date. This data is as of August 2002. Ford Power Products and Nissan successfully certified using gasoline (underlined). Mitsubishi, Impco, NACCO, Jasper Toyota and MCFA all chose propane for certification. It is important to note that none of the OEM's chose to certify CNG fuel systems in 2001 or 2002.

These tests were made using the C2 steady state, 7-mode drive cycle with the current certification values of 3.0 g/hp-hr for HC plus NOx and 37.0 g/hp-hr for CO (see details in Appendix A). New regulations published by the EPA in September 2002 will require additional transient cycle testing for certification.

The transient tests, like over-the road drive cycles, will require additional engine control strategies and ongoing research to reach cut-points of 2.7 g/hp-hr HC and NOx and 4.4 g/hp-hr CO effective in 2007. Due to the long history with the ISO 8178 and it's international implications, the C2 cycle will still be used. It will be combined with the new transient test cycle with each weighted equally.

The ideal way to compare tailpipe emissions using different fuels would be introduce them using the same fuel delivery system on the same engine. One manufacturer has done just that with a dual fuel throttle body injection system capable of running either gasoline or propane. The most recent data comes from Zenith Fuels Systems, Inc. and is shown in Table 5. Their laboratory used the California ARB emission cut-points and the steady state C2 drive cycle. Both fuels were tested on three popular industrial truck engines using the Zenith Electronic Engine Management System-ZEEMS.

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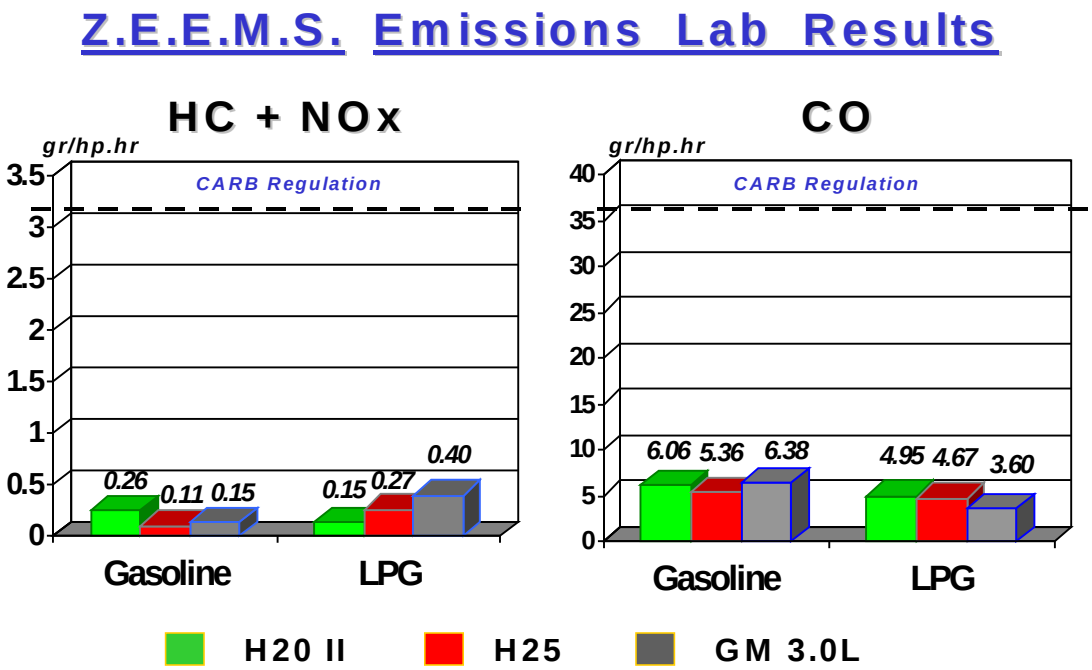
Table 5.



Source: Zenith Fuel Systems Inc.

Last, present day Life Cycle Analysis (LCA) can be found in the 2002 World LP Gas Association's 'Clearing the Air' A Technical Guide on Autogas (LPG) – Emissions, Test Methods, Standards and Technology[7]. It utilizes a renowned LCA model titled 'Greenhouse gases, Regulated Emissions, and Energy use in Transportation' (GREET) ver. 1.5 developed by Michael Wang at the Argonne National Laboratory (Table 6 and 7). The GREET model estimates both upstream and Total Fuel Cycle energy consumption, greenhouse gases and emissions for both short and long term scenarios. Upstream is defined as the fuel processing from feedstock to the dispenser. Downstream emissions are from the dispenser through the engine and into the atmosphere. Again LPG emerges favorably.

Table 6. Upstream fuel cycles: Energy efficiencies of natural gas based fuel cycle stages

FUEL	FUEL-CYCLE STAGE	ENERGY EFF. (%)	TOTAL EFF. (%)
Natural Gas	Recovery Processing	97.0(1) 97.5(2)	(1)*(2)*(3)*(4)
CNG	Transportation and distribution Compression and storage	97.0(3) 95.0(4)	87.2
LP Gas	Production Transportation, storage and distribution	96.5(3) 97.9(4)	89.3

Source: Argonne National Laboratory

Table 7. Upstream fuel cycles: Energy efficiencies of petroleum based fuel cycle stages

Source: Argonne National Laboratory

FUEL	FUEL-CYCLE STAGE	ENERGY EFF. (%)	TOTAL EFF. (%)
Crude Oil	Recovery Transportation and storage	98.0 (1) 99.5 (2)	(1)*(2)*(3)*(4)
Conventional Gasoline	Refining Transportation, storage and distribution	85.0 (3) 98.5 (4)	81.6
Reformulated Gasoline	Refining Transportation, storage and distribution	86.0 (3) 98.5 (4)	82.6
LP Gas	Refining Transportation, storage and distribution	93.5(3) 97.9(4)	89.3
Conventional Diesel	Refining Transportation, storage and distribution	89.0(3) 98.6(4)	85.6
Reformulated Diesel	Refining Transportation, storage and distribution	87.0(3) 98.6(4)	83.6

Total Fuel-Cycle of energy consumption, greenhouse gases and emissions are shown in relative numbers compared to gasoline vehicles. Since LPG is produced both from petroleum and natural gas, it is included in both fuel cycles. Efficiencies of both processes are summarized in the tables above. In terms of energy efficiency, LPG has the highest total energy efficiency (89.3%) in the upstream fuel-cycle. This is an important part of the propane story.

CONSLUSION

When gaseous fuels are compared accurately, differences in tailpipe emissions from similar industrial truck engines are negligible. Propane has an advantage over all other fuels, including electricity, when the upstream emissions are examined, as described in two popular Life Cycle Analysis models.

REFERENCES

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2. Bryan Memmott; The Second LPG/CNG Fork Truck Emission Test Detailed Version, 1994
3. Charles Urban; Southwest Research Institute Report No. 08-6944, March 1995
4. Mark Delucchi; Institute of Transportation Studies, UCD-ITS-RR-97-22, February 1997
5. Dhaliwal and Checkel; Society of Automotive Engineers; #2000-01-1865, 2000
6. Ulmet, White, Stout, Salardino; Society of Automotive Engineers; #2002-01-1752, 2002
7. World LP Gas Association; Emissions, Test Methods, Standards and Technology, 2002

ACRONYMS AND ABBREVIATIONS

ARB: Air Resources Board

BSFC: Brake Specific Fuel Consumption

CH2: Compressed Hydrogen

CNG: Compressed Natural Gas

CO: Carbon Monoxide

EPA: Environmental Protection Agency

EtOH: Ethanol

G50: 50% grain

ISO: International Standards Organization

λ: Lambda – Stoichiometric A/F ratio

LPG: Liquid Petroleum Gas

MeOH: Methanol

NG: Natural Gas

NGV: Natural Gas Vehicle

NMHC: Non-methane Hydrocarbons

NOx: Oxides of Nitrogen

OEM: Original Equipment Manufacturer

THC: Total Hydrocarbons

W50: 50% wood