ADVANCED ENERGY SYSTEMS

Light Duty CNG Vehicle Fuel Composition Study

Topical Report, GTI Project Number 20245

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Introduction

GTI undertook a study for Southern California Gas Co. to support state-level initiatives to modify the California Air Resources Board (CARB) natural gas vehicle (NGV) fuel specification. A key consideration in CARB's proceedings on proposed NGV fuel quality changes is whether such proposed changes will negatively impact vehicle operation as well as air quality in the State of California – in particular, areas in Southern California which are under continued pressure to improve air quality.

GTI conducted a study focused on assessing the light-duty NGV market sector to understand the potential impact from proposed changes in the CARB NGV fuel quality standard.

Summary of Efforts

Task 1 – Quantify Light-Duty Vehicle Population in California

The goal of this effort was to assemble demographic data on the makes and models of light-duty compressed natural gas (CNG) vehicles currently operating in the State of California and – to the extent possible – identify the proportion of "high technology" and "low technology" NGVs products in the population. "Low technology" vehicles include products such as aftermarket bi-fuel vehicles that may not have the same level of sophistication (e.g., adaptive learning) as found in modern original equipment manufacturer (OEM) products.

GTI had initial discussions with Steve Sokolsky of Bevilacqua-Knight, Inc. GTI was aware that Mr. Sokolsky had recently conducted independent work on behalf of a California-based company looking at light-duty NGV fleet populations in California. GTI had seen information on high-level population estimates and concluded this was a direct pathway to obtain the requisite light-duty CNG vehicle data. Before initiation of the project, Mr. Sokolsky indicated the information being sought was available. Subsequently, BKI indicated they were actually not able to obtain the more detailed breakdown information on the type of light duty vehicles sought for this work. The extent of information provided is as illustrated in Table 1 and Figure 1).

Table 1: BKI California NGV Market Composition

Total California NGVs:	29,765
Light-duty (<8500 GVWR):	20,419
Medium-duty (8501-26000 GVWR):	5,489
Heavy duty (>26000 GVWR):	3,857

Source: BKI

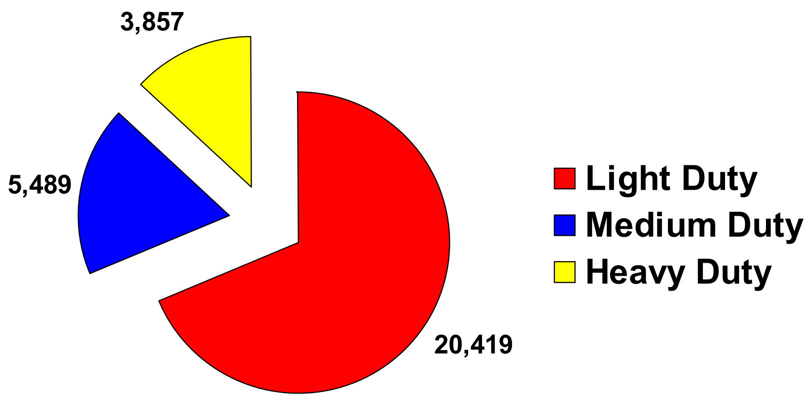


Figure 1: California NGV Market Composition (Source: BKI)

Based on this, GTI initiated its own efforts to locate these data. In an effort to obtain more detailed vehicle information, GTI contacted other potential information sources, including:

- California Air Resources Board (Mr. Gary Yee; 916-327-5986, gyee@arb.ca.gov)
- California Department of Motor Vehicles (Mr. Steven Mackay, 946-657-7825, SMackay@DMV.CA.gov; Mr. Richard Wright 916-657-7825, rwright@dmv.ca.gov)
- USDOE Energy Information Agency (Ms. Cynthia Sirk, cynthia.sirk@eia.doe.gov)
- Individual vehicle OEMs

Obtaining quantitative information from individual vehicle OEMs proved unproductive and was abandoned as a primary pathway.

Responses from Mr. Gary Yee at CARB provided the following email response:

> *"There is a cumulative total of about 21000 light duty/medium duty CNG vehicles that were sold in California. We have a break down but I have to check to see if this is considered confidential."*

The number of CARB vehicles – 21,000 – is consistent with the number provided by BKI. However, the CARB information included both light and medium-duty vehicles, which BKI projected to be closer to 26,000 vehicles. The difference may be more attributable to differences in the definition of light-duty vs medium-duty vehicles (i.e., weight class limits[1]). We will work to clarify this information with the additional data supplied by CARB.

A subsequent information request was made to see if CARB could make this "confidential" information available to GTI. Their response was that they would need to ask permission from vehicle manufacturers before releasing this type of information.

[1] Appendix C contains a description of CARB weight classification

We received a positive response to CARB and they supplied a database showing vehicle sales by year, manufacturer, and vehicle type. Table 2 and Table 3 contain a summary of these data organized by GTI.

Table 2: CARB Passenger Car and Light-Duty Truck Data (Source: CARB)

Passenger Cars

Company	Model Year	Model	Sales
Ford	1997	Contour	330
Ford	1998	Contour	111
Ford	1999	Contour	36
Ford	2000	Contour	308
Ford	1996	Crown Victoria	23
Ford	1997	Crown Victoria	61
Ford	1998	Crown Victoria	19
Ford	1999	Crown Victoria	34
Ford	2000	Crown Victoria	282
Ford	2001	Crown Victoria	68
Ford	2002	Crown Victoria	221
Ford	2003	Crown Victoria	175
GFI	1996	Contour	20
GFI	1997	Contour	268
GFI	1998	Contour	138
GFI	1999	Contour	207
GFI	2000	Contour	119
Honda	1998	Civic GX	216
Honda	1999	Civic GX	136
Honda	2000	Civic GX	214
Honda	2001	Civic GX	300
Honda	2002	Civic GX	450
Honda	2003	Civic GX	500
IMPCO/GM	1998	Cavalier	5
Quantum/GM	1999	J car (Cavalier)	130
Quantum/GM	2000	J car (Cavalier)	13
Quantum/GM	2001	J car (Cavalier)	704
Quantum/GM	2002	J car (Cavalier)	700
Quantum/GM	2003	J car (Cavalier)	700
Toyota	1999	Camry	125
Toyota	2000	Camry	125
Toyota	2001	Camry	98
		Total:	6836

Light-Duty Trucks

Company	Model Year	Model	Sales
Chrysler	1994	Caravan/Voyager	34
Chrysler	1995	Caravan/Voyager	250
Chrysler	1996	Caravan/Voyager	250
GM	2001	Chevy/GMC Pick-up	20
GM	2002	Chevy/GMC Pick-up	10
GM	2003	Chevy/GMC Pick-up	TBD
		Total:	564

Table 3: CARB Medium Duty Vehicle Data (Source: CARB)

Medium-Duty Vehicles

Company	Model Year	Model	Sales	Company	Model Year	Model	Sales
Chrysler	2003	Ram Van	34	Quantum	1997	C Truck	73
Chrysler	1999	Ram Van/ Wagon	132	Quantum	1998	C Truck	19
Chrysler	2000	Ram Van/ Wagon	81	Quantum	1999	C/K Truck	41
Chrysler	2001	Ram Van/ Wagon	124	Quantum	2000	C/K Truck	186
Chrysler	2002	Ram Van/ Wagon	74	Quantum	2001	G Van	70
Ford	1997	Econoline	28	Quantum	2002	G Van	75
Ford	1998	Econoline	47	Quantum	2002	T 800	100
Ford	1998	Econoline	10	Quantum	2002	T 800	5
Ford	1999	Econoline	61	Quantum	2003	T 800	100
Ford	1999	Econoline	50	Quantum	2003	T800 box delete	25
Ford	2000	Econoline	138	Freightliner	1998	FLN	1
Ford	2001	Econoline	196	Freightliner	1999	FLN	1
Ford	2002	E-Series Cutaway	200	Freightliner	2000	FLN	5
Ford	2003	E-Series Cutaway	200	Freightliner	2000	FLN	1
Ford	2002	E-Series Van/Wagon	125	Freightliner	2001	FLN	16
Ford	2003	E-Series Van/Wagon	188	Freightliner	2001	FLN	4
Ford	1995	F-Series	27	Freightliner	2002	FLN	30
Ford	1997	F-Series	56	Freightliner	2003	FLN	50
Ford	1998	F-Series	67	Freightliner	1997	MB bus	16
Ford	1998	F-Series	46	Freightliner	1998	MB bus	11
Ford	1999	F-Series	70	Freightliner	1999	MB bus	8
Ford	1999	F-Series	286	Freightliner	2000	MB bus	12
Ford	2000	F-Series	229	Freightliner	2001	MB bus	12
Ford	2000	F-Series	124	Freightliner	2002	MB bus	15
Ford	2001	F-Series	209	Freightliner	2003	MB bus	7
Ford	2001	F-Series	291	Freightliner	1997	Safe-T-Liner	16
Ford	2002	F-Series	126	Freightliner	1998	Safe-T-Liner	13
Ford	2002	F-Series	286	Freightliner	1999	Safe-T-Liner	39
Ford	2003	F-Series	188	Freightliner	2000	Safe-T-Liner	15
Ford	2003	F-Series	312	Freightliner	2001	Safe-T-Liner	1
GFI	1996	E-Van	15	Freightliner	2002	Safe-T-Liner	68
GFI	1998	E-Van	23	Freightliner	2003	Safe-T-Liner	64
GFI	1999	E-Van	137			Totals:	7056
GFI	1995	F-150	27				
GFI	1996	F-150	5				
GFI	1998	F-150	145				
GFI	1999	F-150	315				
GFI	2000	F-150	245				
GFI	2001	F-150	100				
GFI	2002	F-150	247				
GFI	2003	F-150	285				
GFI	2002	GM-610	80				
GFI	2003	GM-610	318				
GM	*2002*	Chevy/GMC Van	10				

Table 4 provides a summarized version of these data by vehicle type and vehicle manufacturer. There is a difference between the number of vehicles originally (and informally) cited by CARB (21,000) and the number contained in this database (14,000). The difference may be attributed to either conversion vehicles not captured in the CARB reporting database, newer sales not yet in the database (i.e., 2004 and 2005 sales were not included in the CARB data), or perhaps inclusion of heavy-duty vehicles in the originally reported estimate (or a combination of these factors).

Table 4: CARB NGV Sales Data (Light & Medium Duty up to 14,000 lb GVWR)

Passenger Cars	6,836
Light-Duty Trucks	564
Medium-Duty Trucks	7,056
Totals:	14,456
Total (less Freightliner):	14,051

Passenger Cars - By Model	
Contour	1,537
Crown Victoria	883
Civic	1,816
Cavalier	2,252
Camry	348
	6,836

Light/Medium Trucks	
Freightliner	405
GM	1,102
Ford	5,104
Chrysler	445

GTI also began an inquiry through the California Department of Motor Vehicles. Ultimately, we contacted Mr. Steven Mackay who is with the Registration Automation Development group at the DMV in Sacramento. Mr. Mackay provided the composite registration data shown in Figure 2.

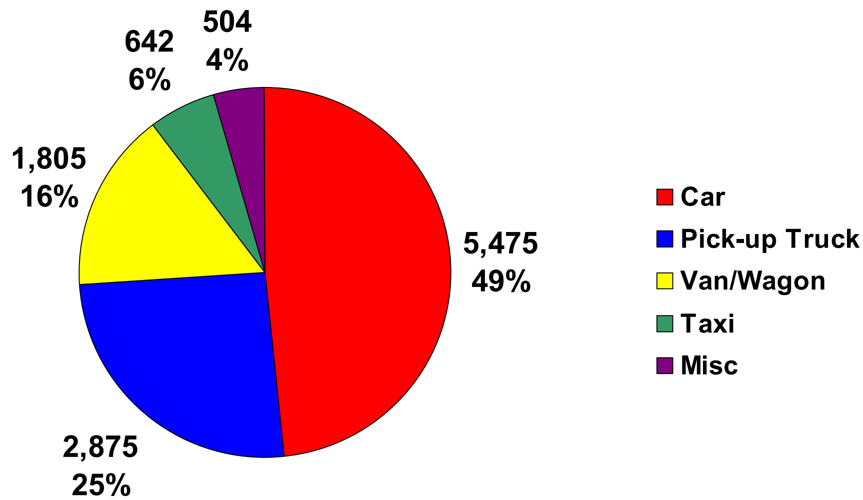
FEE PAID, APPORTIONED (PRORATE/IRP) & EXEMPT TOTALS

BODY TYPE CODE-DESCP	CODE-A ALCOHOL	CODE-B BUTANE	CODE-D DIESEL	CODE-E ELECTRIC	CODE-G GASOLINE	CODE-M METHANOL	CODE-N NATURAL	CODE-P LPG	CODE-Q HYBRID	TOTALS
0-REGULAR		183	80,466	70,289	17,168,691	697	5,475	389	69,973	17,396,030
A-AMBULANCE			3,855	1	3,529			1		7,386
B-BUS		6	36,714	776	30,268	10	5,691	434	55	73,954
D-DUMP		5	39,793	4	16,159		599	113	3	56,676
E-PNL DLRY			248	3	3,748		3	1		4,003
F-FLAT BED		17	52,421	144	83,793		40	359	4	136,778
G-TRACTOR		2	128,259	6	4,197		20	21	2	132,507
H-CHASSIS		3	16,291		31,565		47	52	6	47,984
J-HOUSECAR		5	31,198	16	322,968	1	29	86	4	354,307
K-TANK		3	9,356		3,909	2	8	318		13,596
L-LOG BUNK			524		584			2		1,110
N-TRANS MIX			6,980		1,078			2		8,060
P-PU/BOX		59	320,989	813	4,236,746	13	2,870	728	418	4,562,646
Q-SCHL BUS		1	9,630		848	85	72	1		10,635
R-REFRIG			7,315		1,517		2	57		8,891
S-STAWAG		15	11,894	608	3,080,407	30	697	110	168	3,093,929
V-VAN		16	74,842	66	342,929	4	1,108	590	31	419,586
W-TRANSPORT			3,649	5	11,721		3	9		15,387
X-TAXI			93	1	19,035		642	2	19	19,792
Y-MISC		15	102,001	3,280	167,995	8	504	530	136	274,469
Z-SPL EQIP			7,167	1	4,561		3	26	1	11,759
TOTALS	0	340	943,652	76,013	25,536,188	748	17,813	3,831	70,820	26,649,405

Figure 2: California DMV Registration Information

The California DMV registration data is more conservative (i.e., lower) than the BKI information. These data indicate there are approximately 17,800 registered NGVs in the state. Of these, the estimated number of light-duty vehicles is around 11,300 vehicles. This is approximately 63 percent of the total NGV vehicle registrations in the CMV database. [Note the

BKI data indicated about 68 percent of the population were light-duty



vehicles].

Figure 3Figure 3 shows a breakout of the mix of light-duty natural gas vehicles shown in the California DMV database. One item of note is the category labeled "Taxi." Since a large portion of these vehicles are likely to be Ford Crown Victoria vehicles, this category might otherwise be combined with the Car category.

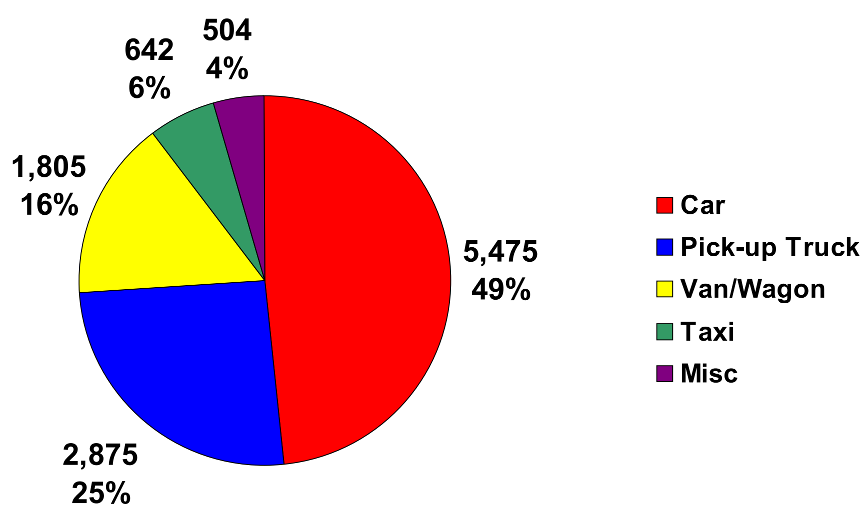


Figure 3: Estimated LD-NGV Vehicle Mix in California (Source: GTI/CA-DMV)

Questions were posed to the California DMV regarding the comprehensiveness of the registration database and whether bi-fueled vehicles are considered as gasoline vehicles or as natural gas vehicles. Their email response is included in Appendix A. From this response, it would appear that the DMV believes this database is comprehensive and that bi-fuel vehicles are shown as registered natural gas vehicles.

A final information source was the US Department of Energy – Energy Information Agency (www.eia.doe.gov). Buried within this website are USDOE-EIA estimates of the number of alternative fuel vehicles. Figure 4 shows data on the estimated number of AFVs by fuel type.

Nationally, there are an estimated 133,000 CNG vehicles, of which approximately 68.6 percent are light-duty vehicles.

	2001				2002				*2003*			
Fuel	**Light Duty**	**Medium Duty**	**Heavy Duty**	**Total**	**Light Duty**	**Medium Duty**	**Heavy Duty**	**Total**	**Light Duty**	**Medium Duty**	**Heavy Duty**	**Total**
Liquefied Petroleum Gases (LPG)	124,790	53,634	6,629	**185,053**	124,877	55,671	**7,132**	**187,680**	*125,110*	*57,873*	*7,455*	***190,438***
Compressed Natural Gas (CNG)	84,077	15,041	12,733	**111,851**	87,340	18,449	**15,050**	**120,839**	*91,231*	*24,525*	*17,232*	***132,988***
Liquefied Natural Gas (LNG)	381	0	2,195	**2,576**	452	0	**2,256**	**2,708**	*463*	*0*	*2,567*	***3,030***
Methanol, 85 Percent (M85) \a\	7,819	0	8	**7,827**	5,865	0	**8**	**5,873**	*4,911*	*0*	*6*	***4,917***
Methanol, Neat (M100)	0	0	0	**0**	0	0	**0**	**0**	*0*	*0*	*0*	***0***
Ethanol, 85 Percent (E85) \a\ \b\	100,287	15	1	**100,303**	120,809	140	**2**	**120,951**	*133,634*	*140*	*2*	***133,776***
Ethanol, 95 Percent (E95) \a\	0	0	0	**0**	0	0	**0**	**0**	*0*	*0*	*0*	***0***
Electricity\c\	17,056	445	346	**17,847**	31,926	671	**450**	**33,047**	*44,334*	*674*	*648*	***45,656***
Non-LPG Subtotal	**209,620**	**15,501**	**15,283**	**240,404**	**246,392**	**19,260**	**17,766**	**283,418**	***274,573***	***25,339***	***20,455***	***320,367***
Total	**334,410**	**69,135**	**21,912**	**425,457**	**371,269**	**74,931**	**24,898**	**471,098**	***399,683***	***83,212***	***27,910***	***510,805***

Figure 4: USDOE-EIA National AFV Statistics

Separately, USDOE-EIA estimates there are approximately 24,990 NGVs in operation in California – though this information is not broken out by weight class. Using a nominal value of 65 percent as the proportion of LDVs, this would imply a California light-duty NGV population of about 16,200 vehicles.

Table 5 summarizes findings regarding the vehicle population estimates for light-duty NGVs in California from different sources.

Table 5: Composite Estimate of NGVs in California

	Light Duty NGVs	Total NGVs
BKI	20,419	29,765
CARB	21,000* (14,051)**	
CA-Dept. Motor Vehicles	11,300	17,800
DOE – EIA	16,200***	24,990

* Original estimate of "light and medium duty" per CARB.

** Number reported in CARB manufacturer sales database, includes medium-duty vehicles up to 14,000 lb GVWR. Excludes 2004 and 2005 sales figures.

** GTI estimate using nominal 65 percent share for LDVs

The most conservative estimate of the number of light-duty NGVs in California are based on using the California Department of Motor Vehicle registration database: 11,300. A clarifying question posed by GTI to the DMV regarding how bi-fuel vehicles are categorized indicates such vehicles are to be coded in the DMV database under the natural gas category. The reliability of this categorization process is unknown, but one could expect uncertainty – particularly in aftermarket conversion vehicles.

Therefore, at the present time, the most conservative estimate is about 11,300 light duty vehicles, with a nominal value around 16,000 taken by averaging the information from the California DMV, BKI, CARB, and DOE-EIA.

The CARB data is helping in providing insights into the number and type of light-duty vehicles. If one excludes Freightliner products from CARB sales, the number of sales reported to CARB by Ford, Chrysler, GM, Honda, and Toyota (and affiliates) is 14,000 vehicles. Adding in an estimated 2,000 vehicle sales per year for 2004 and 2005 would push this number up to 18,000 vehicles – some of which could be classified as medium-duty products. The issue of retirements or used vehicle sales which may transfer to another state is not clearly addressed in the CARB database, leading to a possible overstatement. As noted previously, aftermarket vehicle conversions not associated with a major vehicle OEM (that is, the OEM and their designated upfitter) may result in an understatement if they are not reported to CARB.

Based on the above, we draw the following conclusions:

- The total number of NGVs in California is likely in the range of 20,000 to 27,000 vehicles (all weight classes)
- The number of light-duty NGVs in California (8500 lb GVWR or less) is likely in the range of 13,000 to 18,000 vehicles.
- The light-duty vehicle mix is estimated as:
    - 52 to 56 percent of light-duty vehicles are passenger cars such as the Honda Civic, Ford Crown Victoria, Chevy Cavalier, Toyota Camry, etc.
    - 26 to 30 percent are light-duty trucks such as the Ford F-150 and similar GM products
    - 16 to 18 percent are vans/wagons (including the Chrysler Minivan and full size vans such as the Ford E-Series, Dodge Vans, and similar GM products).

With this, we believe Figure 5 provides a reasonable estimate of the light-duty NGV market mix in California.

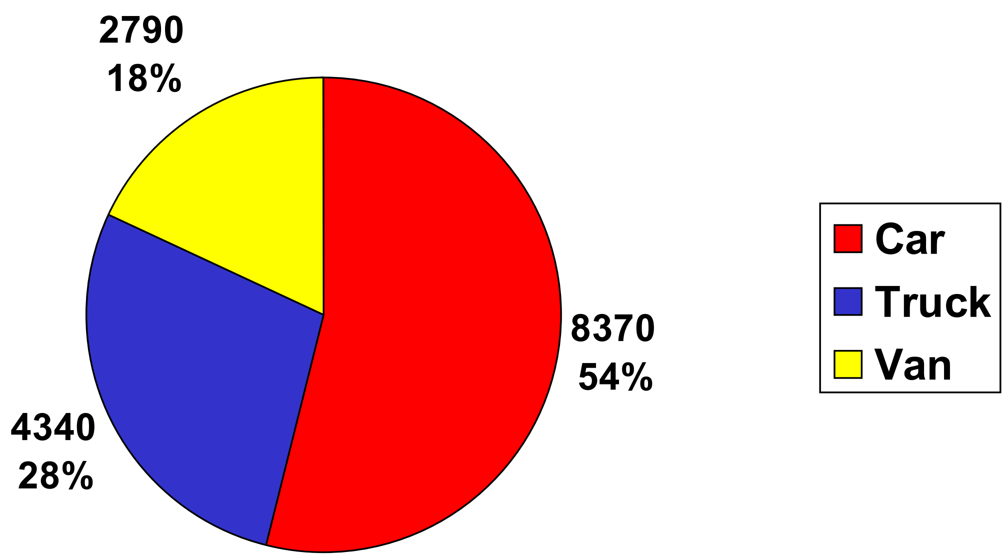


Figure 5: Composite Estimate of California LDV NGV Population

Task 2 – Analytical Assessment of the Impact of Proposed Natural Gas Composition Changes

In this task, GTI was to provide additional background to support SoCal Gas' recommendations regarding: 1) exempting light-duty vehicles from the CARB NGV fuel specification and 2) ultimately eliminating the CARB NGV fuel specification entirely for light-duty vehicles.

Table 6 and Table 7 summarize the mainstream light-duty vehicles that were introduced and sold in the market place over the past decade by OEM vehicle manufacturers, including Ford, Chrysler, GM, and Honda. Many of these vehicles were engineered as dedicated, natural gas only vehicles. Some vehicles were offered as bi-fuel vehicles that could operate on either natural gas or gasoline. All of these vehicles are conventional naturally aspirated, spark-ignited (Otto Cycle) engines.

Table 6: Light Duty NGV Passenger Cars

Honda Civic	1.7L; 100 hp @6100 rpm
Ford Crown Victoria	4.6L; 175 hp @4500 rpm
Ford Contour	2.0L (bi-fuel)
Chrysler Minivan	3.3L
Chevy Cavalier	2.2L; 115 hp @ 5200 rpm (bi-fuel)
Toyota Camry	2.2L; 115 hp @ 5200 rpm

Table 7: Light Duty NGV Trucks and Vans

Ford F-150 Pickup	5.4L; 260 hp @4500 rpm (4700 lbs GVWR); 4.9L & 5.4 L (bi-fuel)
Ford Econoline Van	5.4L; 260 hp @4500 rpm (7700 lbs GVWR); 4.9L & 5.4 L (bi-fuel)
GMC Sierra/Chevy Silverado Pickup	6.0L; 280 hp @5000 rpm (up to 8500 lb GVWR)
GMC/Chevy Van	5.7L; (8500 lb GVWR)
Dodge Ram Cargo Van	5.2L; 200 hp @4400 rpm (7700 lbs GVWR)
Ford E-Series Van	5.4L; 225 hp @4500 rpm (up to 8700 lb GVWR)

There are only two vehicles in this population mix that had increased the engine compression ratio over the standard gasoline vehicle engine design. These are shown in Table 8.

Table 8: NGVs With Increased Compression Ratio

Vehicle	Standard Gasoline Compression Ratio	NGV Compression Ratio
Honda Civic	9.4:1	12.5:1
Ford Crown Victoria	9:1	10:1

When looking at the impact of gas composition on a vehicle, there are three primary areas of concern:

- Vehicle drivability (user and vehicle OEM concern)
- Vehicle engine knock potential (user and vehicle OEM concern)
- Vehicle emissions impact (regulatory and vehicle OEM concern)

Of these, two are an area that vehicle drivers could potentially immediately recognize an impact from significant changes in fuel composition. Vehicle drivability concerns could manifest themselves in several ways, including start-up problems, rough idle problems, acceleration/stumble problems, and maximum torque or horsepower problems.

In order to simultaneously satisfy customer, regulatory, and warranty cost requirements, modern light-duty vehicles have evolved to a highly sophisticated level of control technology. This type of technology is also being employed in modern light-duty vehicles operating on natural gas.

Figure 6 shows the control system schematic for Honda's natural gas-powered Civic GC CNG vehicle (obtained from SAE Paper 2002-21-0032). The pertinent features of the fuel control strategy include air sensors (IAT for intake air and MAP for manifold air pressure) used in feed-forward control logic, fuel sensors (pressure and temperature) used in feed-forward control logic, pulse-width modulated fuel injectors, and dual upstream/downstream oxygen sensors used in feed-back control logic. Potentiometric oxygen sensors in the exhaust and related algorithms contained in the PCM (powertrain control module) are used to provide very accurate air/fuel ratio control. Input air and fuel sensors provide first order adjustments for changes in air and fuel properties. The oxygen sensors and PCM feed-back control algorithms provide for adaptive control adjustments that compensate for changes in air properties (e.g., humidity) and fuel properties (e.g., chemical composition). As changes in natural gas fuel properties occur, the PCM undergoes an adaptive learning process where it adjusts internal parameters to reflect actual fuel properties. This adaptive learning process is continuous throughout the life of the vehicle and typically has fairly broad parameters for adjustment.

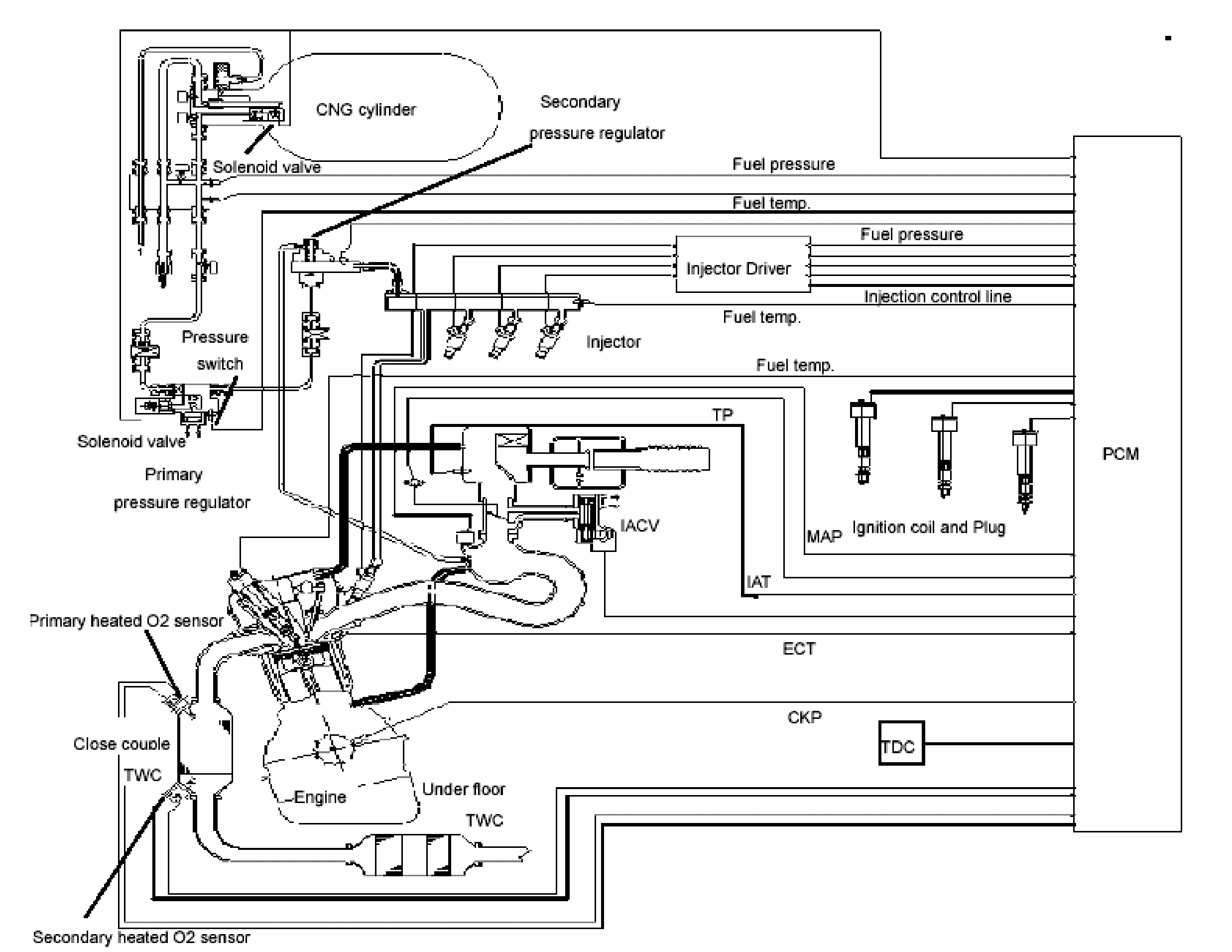


Figure 6: Honda CNG Vehicle Control Schematic (SAE Paper 2002-21-0032)

Given the state of adaptive control algorithms being used in CNG light-duty vehicles, vehicle drivability is not viewed as a primary concern. Most all drivability issues can be addressable through the use of advanced electronic controls. In GTI's experience in conducting gas quality testing programs for several different vehicle OEMs, their primary drivability issues are traced back to trace levels of water or lubricating oils that may be present in natural gas. The previously cited Honda SAE paper reinforces this viewpoint by citing fuel quality concerns only related to water and oil creating functional fuel injector problems (e.g., sticking, plugging with ice, etc.).

Figure 7 provides illustrative data from Honda contained in SAE Paper 2000-01-1863. The lower graph shows Honda's viewpoints about international norms for natural gas composition. Of note are the higher Wobbe Number values experienced in Japan and the lower Wobbe Number values potentially encountered in Europe (relative to typical U.S.-based values). The Civic GX is available in both Japan and Europe. These data indicate the Civic GX has a potentially broad range of authority in terms of operating on higher and lower Wobbe Number fuels.

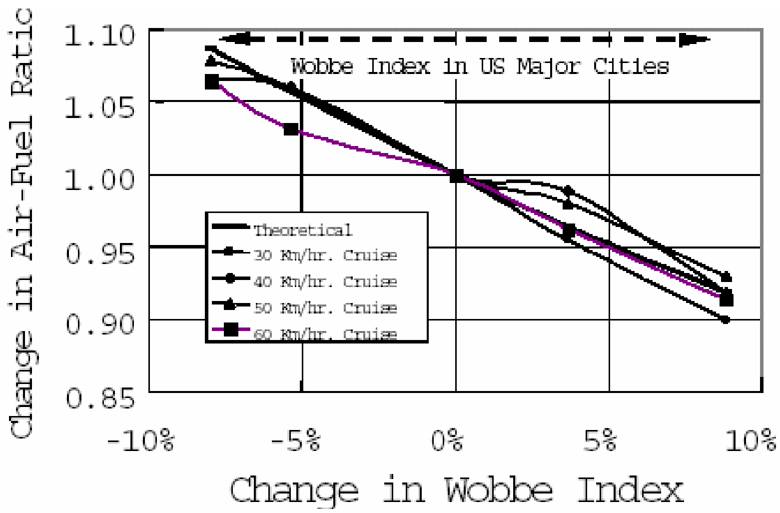


Figure A1. Air-Fuel Ratio vs. Wobbe Index

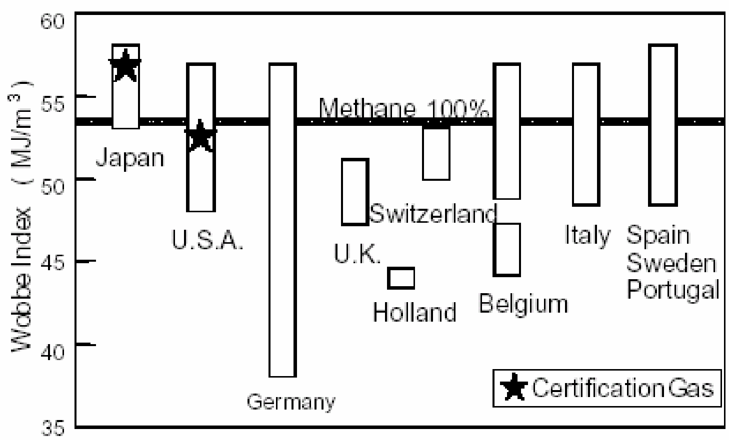


Figure 2. Wobbe Index of Natural Gas

Figure 7: Honda Natural Gas Example Operational Range and International Gas Composition Ranges (Source: SAE 2000-01-1863)

Engine knock or pre-ignition problems can potentially result from the presence of higher non-methane hydrocarbons in natural gas. Examples include higher levels of ethane, propane, butanes, and heavier hydrocarbons. These types of gases are often referred to as "rich gases" and can be found in various parts of the world, the US, and in California. In particular, certain in-state producers in the Central Valley region and off-shore producers have been identified as supplying natural gas with methane levels in the range of 80-90 percent, with relatively high levels of ethane and propane (when compared to the national or state average).

The potential for engine knock increases with:

- Higher compression ratios (or higher engine brake mean effective pressure, BMEP)
- Higher levels of non-methane hydrocarbon gases

- Higher engine loads
- Hotter ambient temperatures

Compression ratio, torque, and horsepower are terms often used to categorize or characterize a reciprocating engine. As a first-order estimate, a naturally aspirated reciprocating engine will be more prone to engine knock as the compression ratio increases.

Another size-independent measure of specific engine power is brake mean effective pressure, or bmep. Using BMEP allows us to compare engines of vastly different sizes, torque levels, and horsepower ratings. BMEP is closely aligned with engine torque, but on a size independent basis. For a four-stroke reciprocating engine, engine power is related to BMEP by the following relation:

$$P_{kW} = k * (BMEP * V_d * N)$$

Where P_{kW} is power output in kW, BMEP is in psi, V_d is engine displacement in liters (L), N is speed in revolutions per minute, and $k=5.75*10^{-5}$ for these units. Using this equation, it is possible to calculate the BMEP of a natural gas engine.

Based on data from Heywood[2], typical naturally aspirated spark-ignited (i.e., gasoline) engines have BMEP levels of 110-135 psi at their maximum power ratings. Based on the information from Table 6 and Table 7, the following is a summary of the BMEP ratings of existing light-duty NGVs in the market (Table 9).

Table 9: Light Duty NGV BMEP Ratings

Vehicle/Engine	BMEP Rating (psi)
Honda Civic (1.7L)	125
Ford Crown Victoria (4.6L)	110
Chevy Cavalier (2.2L)	130
Ford F150 (5.4L)	139
GMC (6.0L)	121
Dodge (5.2L)	113

These values are consistent with conventional spark-ignited gasoline BMEP ratings and should therefore be highly consistent with using fuels rated between 87 and 93 Octane (i.e., gasoline-type fuels).

Figure 8, Figure 9, and Figure 10 show different natural gas compositions starting from a typical natural gas (93% methane), a richer natural gas (86% methane), and a still richer natural gas composition (81.6% methane). These more extreme gases can exist with in-state natural gas

[2] Heywood, John B., "Internal Combustion Engine Fundamentals," McGraw-Hill Publishing Co., pp 50-51 (1988).

production within California or with imported LNG (depending on source and degree of mixing with other natural gases in the pipeline).

Table 10: Three Example Gas Compositions

Gas Type	% Methane	Octane Number	Methane Number	Stoichiometric A/F Ratio
Average Gas	93%	130	93	16.7
Rich Gas 1	86%	121	80	16.4
Rich Gas 2	81.6%	116	73	16.3

Component	Mole Percent	Results:	
Methane	93.40	Higher Heating Value (BTU/scf)	1032.3
Ethane	3.20	Lower Heating Value (BTU/scf)	931.0
Propanes	0.69	Lower Heating Value (BTU/lb)	20,363
n-Butane	0.25	Specific Gravity	0.5971
i-Butane	0.00	Ideal Density (lb/scf)	0.04557
n-Pentane	0.10	Real Gas Density (lb/scf)	0.04565
i-Pentane	0.00	Wobbe Number (HHV)	1336.0
Hexanes (+)	0.06	Wobbe Number (LHV)	1204.9
Nitrogen (N2)	1.50	Hydrogen/Carbon Ratio	3.884
Hydrogen (H2)	0.00	Est. Octane Rating (MON) [Gas data]	131.0
CO2	0.80	Est. Octane Rating (MON) [H/C ratio]	130.8
Water (H2O)	0.00	Methane Number (MN) [CARB]	93.3
Air	0.00	Stoichiometric A/F Ratio	16.736
		Molecular Weight	17.292
		Gasoline Gallon Equivalent (scf/gal)	122.4
Total:	100.00	Gasoline Gallon Equivalent (lb/gal)	5.580

Figure 8: Average Natural Gas (Octane Number 130/Methane Number 93)

Component	Mole Percent	Results:	
Methane	86.00	Higher Heating Value (BTU/scf)	1076.8
Ethane	7.75	Lower Heating Value (BTU/scf)	972.9
Propanes	2.50	Lower Heating Value (BTU/lb)	20,035
n-Butane	0.25	Specific Gravity	0.6338
i-Butane	0.00	Ideal Density (lb/scf)	0.04837
n-Pentane	0.00	Real Gas Density (lb/scf)	0.04844
i-Pentane	0.00	Wobbe Number (HHV)	1352.6
Hexanes (+)	0.00	Wobbe Number (LHV)	1222.1
Nitrogen (N2)	3.50	Hydrogen/Carbon Ratio	3.755
Hydrogen (H2)	0.00	Est. Octane Rating (MON) [Gas data]	120.9
CO2	0.00	Est. Octane Rating (MON) [H/C ratio]	122.4
Water (H2O)	0.00	Methane Number (MN) [CARB]	79.6
Air	0.00	Stoichiometric A/F Ratio	16.438
		Molecular Weight	18.356
		Gasoline Gallon Equivalent (scf/gal)	117.2
Total:	100.00	Gasoline Gallon Equivalent (lb/gal)	5.668

Figure 9: Rich Natural Gas (Octane Number 121/Methane Number 80)

Component	Mole Percent	Results:	
Methane	81.60	Higher Heating Value (BTU/scf)	1108.9
Ethane	10.40	Lower Heating Value (BTU/scf)	1003.0
Propanes	4.00	Lower Heating Value (BTU/lb)	19,836
n-Butane	0.00	Specific Gravity	0.6596
i-Butane	0.00	Ideal Density (lb/scf)	0.05034
n-Pentane	0.00	Real Gas Density (lb/scf)	0.05041
i-Pentane	0.00	Wobbe Number (HHV)	1365.3
Hexanes (+)	0.00	Wobbe Number (LHV)	1235.0
Nitrogen (N2)	4.00	Hydrogen/Carbon Ratio	3.678
Hydrogen (H2)	0.00	Est. Octane Rating (MON) [Gas data]	115.9
CO2	0.00	Est. Octane Rating (MON) [H/C ratio]	118.3
Water (H2O)	0.00	Methane Number (MN) [CARB]	73.0
Air	0.00	Stoichiometric A/F Ratio	16.294
		Molecular Weight	19.103
		Gasoline Gallon Equivalent (scf/gal)	113.7
Total:	100.00	Gasoline Gallon Equivalent (lb/gal)	5.721

Figure 10: Richer Natural Gas (Octane Number 116/Methane Number 73)

Figure 11 shows a relationship between Octane Number (a figure that consumers recognize) and Methane Number (MN, a unique value developed by AVL over 30 years ago for rating the knock resistance of gaseous fuels). As shown, typical natural gas mixtures are much higher in Octane

Number than gasoline. For comparison, “high performance” aviation or racing fuels fall in the range of 100 to 110 Octane Number – which is below what a “rich” natural gas will exhibit.

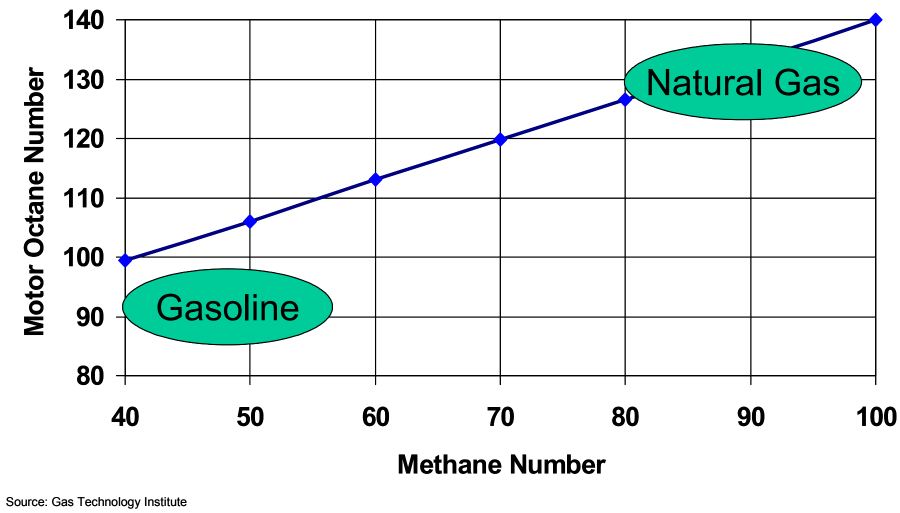


Figure 11: Comparison of Octane Number and Methane Number

Based on these values, even highly enriched natural gas compositions have Octane Ratings that well exceed those associated with gasoline Octane Ratings. Since the compression ratios and BMEP ratings of light-duty NGVs in the market are substantially similar to those of the gasoline vehicles upon which they were derived (including NGVs with somewhat increased compression ratios), there is essentially no concern these vehicles will experience engine knock with natural gas mixtures having higher hydrocarbons even at Methane Numbers as low as 65.

This situation with respect to BMEP ratings on light-duty vehicles can be contrasted with heavy-duty natural gas vehicle engines. These powerplants are highly turbocharged to increase their BMEP rating (Table 11). They can operate at these high levels of BMEP without experiencing knock by using lean-burn combustion – that is, there is much more excess air per unit of fuel when compared to a typical stoichiometric light-duty NGV engine. The excess air helps lower peak temperatures near the top of the compression stroke – thereby lowering the propensity for autoignition (or knock). With advanced controls and – in many cases, by using knock sensors – these high-performance heavy-duty engines are now approved by manufacturers to use natural gas compositions with a Methane Number as low as 65.

Table 11: Heavy-Duty Engine Horsepower and BMEP

Engine	Horsepower	BMEP
Cummins 8.3L (C engine)	280 hp @ 2400 rpm	182
Cummins 5.9L (B engine)	230 hp @ 2800 rpm	180
Deere 8.1L	285 hp @ 2200 rpm	207
DDC 8.5L (Series 50)	320 hp @ 2400 rpm	204

Figure 12 shows the comparison of light-duty NGV engines along with the BMEP ratings of heavy-duty (turbocharged, lean-burn) NGV engines made by Cummins, Deere, and DDC. This graphic clearly illustrates the much higher BMEP ratings associated with heavy-duty (diesel derivative) turbocharged natural gas engines compared to light duty (gasoline derivative) naturally aspirated natural gas engines. The average light-duty NGV BMEP rating is 123 psi while heavy-duty NGVs average 193 psi BMEP (or 60% higher specific performance from these heavy-duty NGV engines).

Based on this situation, we believe there is essentially no concern over knock problems occurring in light-duty NGVs

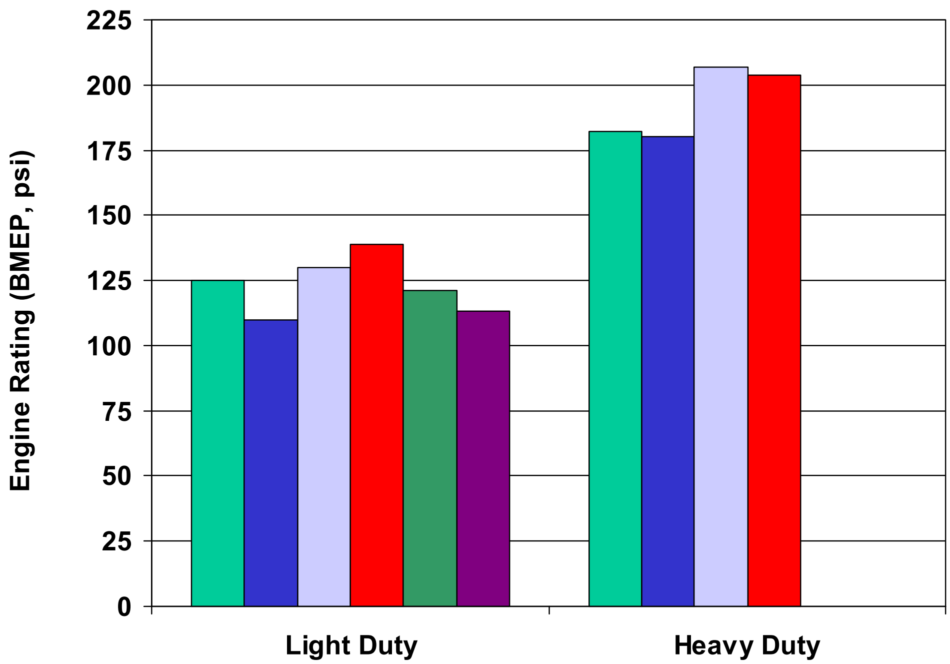


Figure 12: BMEP Rating of Light and Heavy Duty NGV Engines

Task 3 – OEM Vehicle Manufacturer Survey

GTI conducted a brief survey of OEM vehicle and aftermarket bi-fuel system manufacturers to gauge their response to the ability of in-service vehicles they produced to 1) operate satisfactorily on proposed boundary condition natural gas compositions and 2) whether they anticipate appreciable emission impacts from proposed NGV gas composition changes.

Appendix B contains a sample of the survey questions posed to these manufacturers.

Surveys were sent to representatives from the following companies:

- Baytech (upfit/aftermarket)
- DaimlerChrysler (OEM)
- Ford (OEM)
- General Motors (OEM)
- Teleflex GFI (upfit/aftermarket)
- Honda (OEM)

Due to changes in personnel and other factors, it was difficult to get direct responses from some companies. In two circumstances, responses were received from personnel who were directly involved in their NGV engineering programs but who are not presently employed by these firms. We feel their direct experience enables these individuals to address the technical issues outlined in the survey. As of this report, one manufacturer indicated an intent to complete the survey but have not yet done so.

1. Is your company familiar or involved with proposed changes to the CARB Compressed Natural Gas Vehicle Fuel Specification?

Not Familiar	Somewhat Familiar	Somewhat Involved	Very Involved
	5	0	0
Respondent Comments None.			

Generally, the respondent companies indicate they are not following the proposed CARB rulings very closely (though it is possible others in the company may be more aware).

2. Does your company support using gas composition limits (e.g., % methane, ethane, etc – as in the current CARB standard) or physical properties for limits on NGV fuel requirements (as has been proposed by various parties)?

Gas Composition Limits	Physical Property Limits
2	3

Respondent Comments

Co. B: Gas composition limits are preferable as they address the secondary implications of function brought on by the presence of the other constituents. Given that all of our products were developed to the currently standards the full implications of the change would have to be studied because it is not just the vehicles going forward that will be affected but also the customer experience of vehicles already in the field. If changes are needed to make older vehicles capable of using the new fuel without customer compromise then that would be an issue.

Co. C: This would seem (editorial: that is, physical properties) to be a sensible approach if there is some cost benefit realized via e.g., a reduction in fuel gas testing requirements. The proposed specs seem appropriate for fuel gas. As a general rule, OEMs prefer performance-based standards (rather than design based). Following this tradition, it would seem that the new proposed specs would be supported.

Co. E: No comments.

Co. F: Will this raise an issue with respect to the certification fuel? We are concerned about the implications if true on testing and emissions certification costs. We can now run tests using pipeline gas – would be much more expensive if a pre-blended fuel is needed for the test fuel. Also, some states are adopting CARB standards. What are the implications of this if CARB changes this standard?

3. Please check the appropriate box(es) for features of light-duty NGVs your company produced for the California market?

Closed-loop emission controls with oxygen sensor and 3-way catalyst	On-Board Diagnostics (OBD) for emission compliance	Adaptive vehicle engine controls
5*	5*	5*
Respondent Comments Co. B: Our vehicles employed all control system attributes necessary to comply with the then current regulations for light duty vehicles including but not limited to in use useful life testing and OBD. Fuel quality can have a significant implication on these aspects particularly things like misfire detection. Co. C: I'm confident there would be minimal if any (i.e., unmeasurable) effect on drivability for vehicles employing feedback (stoichiometric) fuel controls and 3-way catalysts, like those used on our NGVs. I have no experience with NGVs that do not employ these controls technologies, but anticipate no major drivability impact on those either. Co. E: No comments Co. F: No comments		

* All respondents, including two upfit/aftermarket companies, responded that their control systems employ each of these advanced control features.

4. Setting aside the issue of tailpipe emissions, do you expect vehicle drivability issues to arise from proposed changes to the CARB CNG fuel specification (as shown in attached tables)? Please check the appropriate box and add any comments.

No Opinion/ Not Sure	No Problems Expected	Some Possible Issues	Problems Very Likely
2	2	1	

Respondent Comments

Co. A: I don't think the main physical properties proposed (i.e., MN, Wobbe#) will impact vehicles we have in the field, provided there are still limits on sulfur and water, and perhaps, compressor oil as well.

Co. B: Without testing every application and potential consequence and gathering data, my opinion is irrelevant.

Co. C: I recommend that testing be conducted to address knock and/or fuel economy effects. I would not expect either of these to be significant issues. Knock has not been an issue with CNG because of the lower-than-optimal compression ratios typically employed by the gasoline-based engines…Newer (gasoline) vehicles employ knock sensing hardware that could address that issue should it arise…I remain confident that the proposed change in fuel specs would have little if any impact on emissions or on any OBD system that might be employed, as long as sulfur content remains insignificant.

Co. E: Possible impacts will depend on how quickly adaptive fuel control responds to a change in gas composition. If the gas composition varies widely from station to station, there could be an impact on emissions and possible drivability, but the emissions compliance margins are usually so high it is unlikely to affect OBD II systems with false MILs. If the gas composition changes are small from day to day, probably little impact. Europe is already living with variable gas composition. Might be interesting to learn of their experience.

Co. F: Needs to be evaluated/unknown.

The respondents were fairly uniform in suggesting that additional testing could/should be used to address the question of whether the proposed changes in fuel composition would impact vehicle drivability. Given the manufacturer's potential exposure (even if such vehicles our outside the standard warranty), this response is an expected position. The vehicle and equipment manufacturers do not directly benefit from the proposed changes, but may believe there may be inherent uncertainty or risks. In this respect, there is little motivation on the part of a vehicle OEM to be particularly supportive of the proposed changes. From the manufacturer's perspective, objective test data – likely by an independent third party – may be the most direct means of addressing this topic.

CONCLUSIONS

The results of this study found a number of different potential information sources for the number of light-duty NGVs in the State of California. Information from the California ARB, based on sales reports from manufacturers, is an excellent source of information to estimate the number of vehicles and, most importantly, the types of vehicles. These data may not be comprehensive, however, due to aftermarket vehicles, vehicle retirements, and vehicle sales that may result in out-of-state transfer of vehicles.

The California Department of Motor Vehicles appears to have another excellent source of information on vehicle registrations by fuel type. More time would be needed to investigate how this information is gathered and whether there are possible areas (e.g., aftermarket bi-fuel vehicles) that may not be accurately reflected. It appears this data is vehicle specific, though that level of information was not provided by the DMV.

Based on our review, we estimate the number of light-duty NGVs in California (8500 lb GVWR or less) is likely in the range of 13,000 to 18,000 vehicles. The light-duty vehicle mix is estimated as:

- 52 to 56 percent of light-duty vehicles are passenger cars such as the Honda Civic, Ford Crown Victoria, Chevy Cavalier, Toyota Camry, etc.
- 26 to 30 percent are light-duty trucks such as the Ford F-150 and similar GM products
- 16 to 18 percent are vans/wagons (including the Chrysler Minivan and full size vans such as the Ford E-Series, Dodge Vans, and similar GM products).

Our technical assessment indicates that the changes proposed in the new fuel requirements should not pose an issue with respect to engine knock – one of the most serious considerations from a user perspective.

More qualitatively, there should not be serious issues with vehicle drivability. This conclusion is based on years of experience at GTI investigating vehicle fuel quality issues and conducting sponsored testing programs for several major vehicle OEMs. The primary focus of fuel-related drivability has centered heavily on the effects of water and compressor oil carryover. Water and trace compressor oil have caused operational problems, including freezing and plugging of the fuel delivery system and sticking of fuel injectors. Survey responses from several manufacturers support this position, but others (understandably) are somewhat less committal and would prefer for controlled testing to be conducted.

Our survey of manufacturers indicates a generally low level of direct involvement or awareness on the issue of the proposed changes in the CARB CNG fuel specifications.

Survey results indicate that all of the manufacturers state that their NGV products are equipped with advanced control features, including:

- Closed-loop emission controls with oxygen sensor and three-way catalysts
- On-board diagnostics for emissions compliance

- Adaptive vehicle engine controls

Importantly, these advanced control system features provide the technical framework for these vehicle engines to adapt to changes in natural gas fuel composition. Detailed information regarding the adaptive control logic is proprietary and not available in the public domain. By inference, however, the comments by several vehicle OEMs would indicate a level of comfort with the ability of these vehicles to accommodate a broader range of compositions and fuel properties.

APPENDIX A: CALIFORNIA DMV RESPONSE TO DATABASE QUESTIONS

Response from Mr. Richard Wright, CA DMV to GTI Questions

Q. How would you characterize the comprehensiveness of your vehicle registration database and the information on the number of natural gas vehicles? For example, does this truly cover all registered vehicles in the State? What is the potential that some vehicles are not accurately recorded?

A. The counts we provided you were from a monthly statistical report that counts records for a wide variety of monthly reports. Obviously some records will not be counted monthly because of errors on the records themselves. The report does count all records on the Vehicle Registration Database however it is a picture in time that is only valid for the moment it is run. It may not have records from the IRP database that have not updated the IRP file in the VR database but the number of Natural Gas heavy duty trucks is not that large.

The number of error records monthly is less than one tenth of one percent of the vehicles. Additionally, we use a software product from RL Polk that decodes the motive power of the vehicle from the VIN. This software is used on all originals [whether new cars or previously registered elsewhere. When the VIN is keyed the software fills in the fields for Make, Year Model and Motive Power. The motive power field is changeable but a technician would not have a reason to change what generates unless he/she has documentation to show it is something else. So in answer to your question may some vehicles be incorrectly registered, the answer is yes but we have done our best to mitigate the errors.

Q. Another related question regards vehicles that are commonly referred to as bi-fuel...that is, they can operate on either gasoline or natural gas. How would these be categorized?

A. They would all be registered as "G" for gas. That decision was made by the Bureau of Automotive Repair which oversees the SMOG certification programs.

APPENDIX B: VEHICLE MANUFACTURER SURVEY

G A S   T E C H N O L O G Y   I N S T I T U T E

1700 South Mount Prospect Road | Des Plaines, Illinois | 60018

William Liss
Executive Director
T: 847 768 0753 **F**: 847 768 0501
william.liss@gastechnology.org

Dear NGV Market Participant

Gas Technology Institute (GTI) has been asked by a stakeholder in the California NGV market to gather information on proposed changes in the California Air Resources Board Compressed Natural Gas Vehicle specification.

In particular, this inquiry relates to your perspective on whether proposed changes to the ARB CNG fuel specification would have an impact on light-duty NGVs currently in the marketplace.

Please take a moment to review the attached brief survey. We would appreciate your feedback on this topic. Please feel free to include any additional comments. Due to potential concerns over confidentiality or other considerations, we will report information in a manner that does not reference back to individual companies. That is, information will be reported as a composite picture.

Thank you for your consideration of this request.

Sincerely,

Bill

Survey on Proposed Changes to CARB Compressed Natural Gas Vehicle (NGV) Fuel Specifications on Light-Duty NGVs

5. Is your company familiar or involved with proposed changes to the CARB Compressed Natural Gas Vehicle Fuel Specification? Please check the appropriate box and add any comments.

Not Familiar	Somewhat Familiar	Somewhat Involved	Very Involved
Comments			

6. Does your company support using gas composition limits (e.g., % methane, ethane, etc – as in the current CARB standard) or physical properties for limits on NGV fuel requirements (as has been proposed by various parties)? Please check the appropriate box and add any comments.

Gas Composition Limits	Physical Property Limits
Comments	

7. Please check the appropriate box(es) for features of light-duty NGVs your company produced for the California market?

Closed-loop emission controls with oxygen sensor and 3-way catalyst	On-Board Diagnostics (OBD) for emission compliance	Adaptive vehicle engine controls
Comments		

8. Setting aside the issue of tailpipe emissions, do you expect vehicle drivability issues to arise from proposed changes to the CARB CNG fuel specification (as shown in attached tables)? Please check the appropriate box and add any comments.

No Opinion/ Not Sure	No Problems Expected	Some Possible Issues	Problems Very Likely
Comments			

Current California Air Resources Board CNG Fuel Specification

Specifications		Value
Hydrocarbons (expressed as mole percent)	Methane	88.0% (min.)
	Ethane	6.0% (max.)
	C3 and higher HC	3.0% (max.)
	C6 and higher HC	0.2% (max.)
Other Species (expressed as mole percent unless otherwise indicated)	Hydrogen	0.1% (max.)
	Carbon Monoxide	0.1% (max.)
	Oxygen	1.0% (max.)
	Inert Gases (Sum of CO_2 and N2)	1.5-4.5% (range)
	Sulfur	16 ppmv (max.)
	Water	a
	Particulate Mater	b
	Odorant	c
[a]The dewpoint at vehicle fuel storage container pressure shall be at least 10°F below the 99.0% winter design temperature listed in Chapter 24, Table 1, Climatic Conditions for the United States, in the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Handbook, 1989 fundamentals volume. Testing for water vapor shall be in accordance with ASTM D 1142-90, utilizing the Bureau of Mines apparatus.		
[b]The compressed natural gas shall not contain dust, sand, dirt, gums, oils, or other substances in an amount sufficient to be injurious to the fueling station equipment or the vehicle being fueled.		
[c]The natural gas at ambient conditions must have a distinctive odor potent enough for its presence to be detected down to a concentration in air or not over 1/5 (one-fifth) of the lower limit of flammability.		

DRAFT California Air Resources Board CNG Fuel Specification

Methane Number	80 (73**) minimum
Wobbe Number	TBD (editorial: maximum may be ~1400)
Inert Gases	4.0%
C_4+ and higher hydrocarbons	1.5% maximum

** Regional allowance for MN = 73.

Additional notes:

- The Methane Number is an anti-knock index value analogous to Octane Number.
- Other specifications to be based on (or defer to) CPUC Rule 30 or Rule 21 for natural gas utilities

§ 1900. Definitions.

(a) The definitions in this section supplement and are governed by the definitions set forth in chapter 2 (commencing with section 39010), part 1, division 26 of the Health and Safety Code. The definitions set forth in the applicable model-year new vehicle certification and assembly-line test procedures adopted in this chapter are hereby incorporated by reference.

(b) In addition to the definitions incorporated under subdivision (a), the following definitions shall govern the provisions of this chapter.

[Definitions applicable only to warranty or recall provisions not in this compilation are not set forth]

* * * *

(4) "Gaseous fuels" means any liquefied petroleum gas, liquefied natural gas, or compressed natural gas fuels for use in motor vehicles.

(5) "Heavy-duty engine" means an engine which is used to propel a heavy-duty vehicle.

(6) "Heavy-duty vehicle" means any motor vehicle having a manufacturer's gross vehicle weight rating greater than 6,000 pounds, except passenger cars.

* * * *

(8) "Light-duty truck" means any 2000 and subsequent model motor vehicle certified to the standards in section 1961(a)(1) rated at 8,500 pounds gross vehicle weight or less, and any other motor vehicle rated at 6,000 pounds gross vehicle weight or less, which is designed primarily for purposes of transportation of property or is a derivative of such a vehicle, or is available with special features enabling off-street or off-highway operation and use.

(9) "Medium-duty vehicle" means any pre-1995 model year heavy-duty vehicle having a manufacturer's gross vehicle weight rating of 8,500 pounds or less; any 1992 through 2006 model-year heavy-duty low-emission, ultra-low-emission, super-ultra-low-emission or zero-emission vehicle certified to the standards in section 1960.1(h)(2) having a manufacturer's gross vehicle weight rating of 14,000 pounds or less; any 1995 through 2003 model year heavy-duty vehicle certified to the standards in section 1960.1(h)(1) having a manufacturer's gross vehicle weight rating of 14,000 pounds or less; and any 2000 and subsequent model heavy-duty low-emission, ultra-low-emission, super-ultra-low-emission or zero-emission vehicle certified to the standards in Section 1961(a)(1) or 1962 having a manufacturer's gross vehicle weight rating between 8,501 and 14,000 pounds.

* * * *

(11) "Passenger car" means any motor vehicle designed primarily for transportation of persons and having a design capacity of twelve persons or less.