(1)

CARB PUBLIC HEARING

DIESEL CERTIFICATION FUEL SPECIFICATIONS

9/22/94

Good morning. My name is Melissa Chapman. I am a Fuels Planning Engineer for 76 Products Company, a member company of Unocal Corporation. Today, however, I am representing the Western States Petroleum Association, also known as WSPA. WSPA is a trade association whose member companies are engaged in the exploration, production, refining, and marketing of petroleum and petroleum products throughout California and the western United States.

WSPA appreciates the opportunity to comment on the California Air Resources Board's proposed specifications for diesel engine certification fuel (94-9-1). We agree with Staff that the current certification fuel specifications set forth in the low aromatic diesel fuel regulation are too widely defined to truly represent commercially-available diesel fuel. We believe, however, that Staff's proposed certification fuel is also not representative of commercial fuel and will produce lower emissions than average commercial fuel. Consequently, the use of this fuel will permit certification of engines and vehicles that will fail to achieve desired emission reduction goals under real-life operating conditions.

The emissions performance of certification fuel directly influences the ability of a new vehicle or engine to meet CARB's stringent emission standards. A certification fuel that results in lower emissions than the average commercial fuel will fail to achieve the desired emissions benefits. Such failures will eventually lead to shortfalls in the attainment of air quality goals and increased pressure for additional emission controls. The emissions characteristics of certification fuel must therefore reflect the fuel commercially available in the state.

We believe that the specifications for certification fuel should match those of commercial fuel as closely as possible. Commercial fuel for motor vehicle use in California is distributed among three categories. They are: 1) 10% Aromatic Diesel Fuel, 2) Alternative Formulations, and 3) Small Refiner Diesel Fuel. A certification fuel based on the parameters of these fuels would best reflect commercial fuel and would result in certification test results which are representative of emissions produced by the in-use fleet. Since CARB is the only authority with access to these fuel parameters, we urge CARB staff to determine the actual parameters of these in-use fuels and propose a certification fuel based on the determined parameters. A certification fuel based on these parameters would best represent commercial fuel and result in the certification of engines and vehicles that will achieve desired emission reduction goals.

We do understand, however, that this is a complicated task, and may not be realistic given CARB's desired timetable. If a fuel parameter-based proposal is not feasible, we suggest using an emissions-based method to match the emissions expected from commercial fuel. This method would determine the specifications of a certification fuel which is estimated to produce emissions equivalent to a volume-weighted average of 10% aromatic diesel fuel, alternative formulations, and small refiner diesel fuel.

Based on our estimates, this method would result in a certification fuel with 10% aromatics content and a cetane of 49. (See attached table)

You can see from the slide that the 10% aromatic diesel fuel is represented by a cetane average of 52. This number was based on CARB's analysis of actual 10% aromatic diesel fuel production.

The emissions produced from alternative formulation diesel fuels have been shown to be equivalent to those produced by a reference fuel during alternative formula certification testing. All alternative formulations can therefore be represented by the reference fuel specifications of 10% aromatics content and 48 cetane.

Small refiners will soon be producing either a 20% aromatic fuel or an alternative formulation, which has been shown to have emissions equivalent to those produced by a 20% aromatic reference fuel during alternative formula certification testing. It is therefore appropriate to equate small refiner diesel fuel to this 20% aromatics, 47 cetane reference fuel. Using available equations that relate changes in aromatic content and cetane number to changes in emissions, the emissions of the small refiner reference fuel have been estimated to be equivalent to a 10% aromatic fuel with a cetane number of 45.

Relating all three categories of fuel to a corresponding emission-equivalent 10% aromatic fuel enables the calculation of a pooled cetane for a 10% aromatic fuel, which is the volume-weighted average of all three categories of commercial fuel. As you can see, this methodology results in a certification fuel with 10% aromatics and a cetane of 49 -- fully two cetane numbers below the 51 cetane midpoint of the currently proposed specification.

Finally, we believe that CARB should ensure that the certification fuel represent, to the greatest extent practicable, the emission characteristics of the average commercial fuel sold within the state. If there is to be an error, it should be on the conservative side, which will minimize any loss in estimated emission reductions. This philosophy is consistent with that used in specifying CARB Phase 2 reformulated gasoline certification fuel, which will be used to certify low-emission vehicles.

In conclusion, the proposed certification fuel is not representative of the pool of commercial fuel, but is actually cleaner burning. Our first preference is that CARB staff base the specifications on the properties of actual in-use fuel. If CARB insists on using a 10% aromatic fuel as the basis for its specifications, then we recommend using the emissions equivalency approach outlined in this presentation, which takes into account all three categories of diesel fuel produced in the state. This approach indicates that the cetane number midpoint of a 10% aromatic certification fuel should be 49, rather than 51. Using the methodologies we have outlined will lead to certification fuel specifications that are more representative of in-use diesel, and will result in a vehicle certifications that will be more representative of the in-use fleet. This process will better serve the air quality needs of California.

Thank you.

SLIDE

CALCULATION OF POOLED CETANE FOR EMISSIONS - EQUIVALENT 10 VOL % AROMATIC DIESEL

DESCRIPTION	CETANE NUMBER EMISSION - EQUIVALENT 10 % AROMATIC DIESEL	VOLUME % OF POOL	CETANE CONTRIBUTION TO POOL
10 % AROMATIC DIESEL	52	29	15.1
SMALL REFINER DIESEL	45	14	6.3
ALTERNATIVE FORMULATIONS	48	57	27.4
POOL	49	100	48.8

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WSPA
Western States Petroleum Association

Gina Grey
Managing Coordinator

September 21, 1994

Board Members
California Air Resources Board
c/o Board Secretary
P.O. Box 2815
Sacramento, CA 95812

Re: **Proposed New Specifications for Diesel Engine Certification Fuel (94-9-1)**

Dear Board Members:

The Western States Petroleum Association (WSPA) is a trade association whose member companies are engaged in the exploration, production, refining and marketing of petroleum and petroleum products throughout California and the western United States. WSPA appreciates the opportunity to comment on the California Air Resources Board's proposed specifications for diesel engine certification fuel (94-9-1).

The attached presents WSPA's comments on the above-referenced hearing. Our primary concern lies with the need for CARB's diesel engine certification fuel specifications to best represent commercial diesel fuel. WSPA believes there are two options CARB could utilize to generate certification fuel specifications reflective of current in-use/certification diesel fuel properties. In our opinion, the most appropriate method would be to generate a "composite" alternative formulation which represents all categories of diesel fuel currently produced in California. If CARB staff continues to base the certification fuel specification entirely on their analysis of 10% aromatic diesel fuel production, we suggest an alternative analysis using an "emissions equivalency approach."

Please direct questions regarding our comments to Mr. Al Jessel of Chevron (415-894-3288).

Sincerely,

505 N. Brand Blvd.. Suite 1400 • Glendale, California 91203 • (818) 543-5352 • FAX (818) 545-0954

Western States Petroleum Association
Comments on:

CARB's Proposed New Specifications for Diesel Engine Certification Fuel Proposed for Adoption September 22, 1994

One of the most important aspects of CARB's regulatory framework designed to reduce the emissions from diesel-powered vehicles, is to require certification of new vehicles and engines to meet stringent emission standards. The emissions performance of certification fuel directly influences the ability of a new vehicle or engine to meet those standards. A certification fuel which gives lower emissions than the average commercial diesel fuel will permit the certification of engines that will fail to achieve the desired emission benefit. Such failures will lead to shortfalls in the improvement of air quality and increased pressure for additional regulation. WSPA believes the emissions characteristics of certification fuel need to reflect the fuel commercially available in the state.

CARB's proposed specification for diesel certification fuel is based entirely on 10% aromatic diesel -- which represents less than one-third of the diesel available in the state -- and will permit certification of engines and vehicles which will fail to achieve desired emission reduction goals. According to the staff proposal, the certification fuel should have an aromatic content of 10 volume percent and a cetane midpoint of 51. Since the upper limit proposed on cetane is actually 55, and we have been assured by CARB staff that the proposed range includes an enforcement tolerance, we can assume, under the current proposal, the average certification fuel will actually have a cetane value between 51 and 55. The incentive for engine manufacturers to operate at the highest assumed cetane level possible (lowest emissions) is significant, as this makes certification easier.

In our opinion, there are two approaches CARB could utilize to generate certification fuel specifications which would be more representative of commercial diesel fuel. Our first, and preferred approach, is based upon fuel property measurement while the second approach is based on emissions equivalency.

Measurement of In-Use Fuel Properties

Commercial diesel fuel for motor vehicle use in California is actually distributed at this time among the three categories indicated in Table 1. The most appropriate method to generate an accurate certification fuel specification would be to use in-use/certification fuel property data and production volumes to generate a "composite" formulation. Since many of these formulations are proprietary, WSPA, as a trade organization, does not have the data to calculate the properties of the composite fuel. CARB, however, does have all the necessary data and should use this as the basis for setting certification fuel specifications which would accurately represent the majority of commercially available fuel.

TABLE 1
CATEGORIES OF CALIFORNIA DIESEL MOTOR VEHICLE FUEL

Description	Volume, bdp	Aromatics, vol %	Cetane
10 % Aromatic Diesel	45,000 (29%)	10[1]	52[1]
Small Refiner Diesel	22,000 (14%)	20[2]	47[2]
Alternative Formulations	88,000 (57%)	10[3]	48[3]

[1] Based on CARB's in-use 10% Aromatic Diesel survey results.
[2] Based on the small refiner reference fuel specification.
[3] Based on large refiner reference fuel specification (all alternative formulations are equivalent in emissions performance).

Emissions Equivalency Approach

CARB staff decided to base the certification fuel specification entirely on their analysis of in-use 10% aromatic fuels. Based upon their survey of 10% fuels, the average cetane level of this fuel was calculated to be 52. WSPA's approach attempts to include the remaining categories (i.e., alternative certified formulas) of fuel not considered by CARB. In order to do this, we have related the expected emissions performance of these categories to a fuel with 10% aromatic content and cetane levels set to achieve equivalent emissions performance. Inclusion of these two categories results in a certification fuel specification with a lower cetane than proposed by CARB staff.

The two categories of diesel fuel not considered in CARB's proposal are diesel produced under the small refiner exemption and the alternative certified formulations granted to other refiners. Since emissions increase with lower cetane and higher aromatic content, diesel produced under the small refiner exemption may have higher emissions than 10% aromatic fuel. Using available equations (i.e., from VE-1 CRC Research Program) which relate changes in aromatic content and cetane number to changes in emissions (SAE Paper 902171), we estimate the emissions performance of the small refiner reference fuel would be equivalent to a 10 vol % aromatic diesel with a cetane number of 45. As for the other-refiner alternative certified formulations, they are required to have emissions at least equivalent to, or cleaner than, benchmark reference fuel with a cetane at 48 and a aromatic content of 10 vol %.

TABLE 2
CALCULATION OF POOLED CETANE FOR EMISSIONS-EQUIVALENT 10 VOL % AROMATIC DIESEL

Description	Cetane Number Emission-Equivalent 10 % Aromatic Diesel	Volume % of Pool	Cetane Contribution to Pool
10 % Aromatic Diesel	52	29	15.1
Small Refiner Diesel	45	14	6.3
Alternative Formulations	48	57	27.4
Pool	49	100	

Relating all the categories of fuel to a corresponding "emissions-equivalent" 10% aromatic fuel enables WSPA to calculate a pooled cetane for a surrogate 10% aromatic fuel which includes all three categories of commercial diesel (Table 2). As indicated, the cetane calculated using this methodology is about 49 -- fully two cetane numbers below the 51 cetane midpoint of the proposed specification. This two number difference represents about 10% of the NOx benefit of the low aromatics diesel rule and about 15% of the particulate benefit.

In conclusion, WSPA believes the proposed certification fuel is not representative of the real commercial diesel pool that is cleaner burning. To develop a certification fuel specification representative of real commercial diesel, CARB staff should generate a "composite" set of specifications which represents all categories of diesel fuel currently produced in California. If CARB insists on using a surrogate 10% aromatic fuel as the basis for its specification, then CARB should extend their analysis using the emissions performance equivalency approach we have outlined to include the other categories of diesel fuel (e.g., alternative certified formulations) produced in the state. As this approach indicates, the cetane number midpoint of a 10% aromatic certification fuel should be 49 rather than 51. Using the methodologies WSPA has outlined will lead to certification fuel specifications which are more representative of in-use diesel and will result in emissions produced during the certification process which may be more representative of the in-use fleet. Such specifications would better serve the air quality needs of California.

Supports oral testimony given by Mr. Slodowske of Navistar. Discussion starts on page 54 of the transcript.

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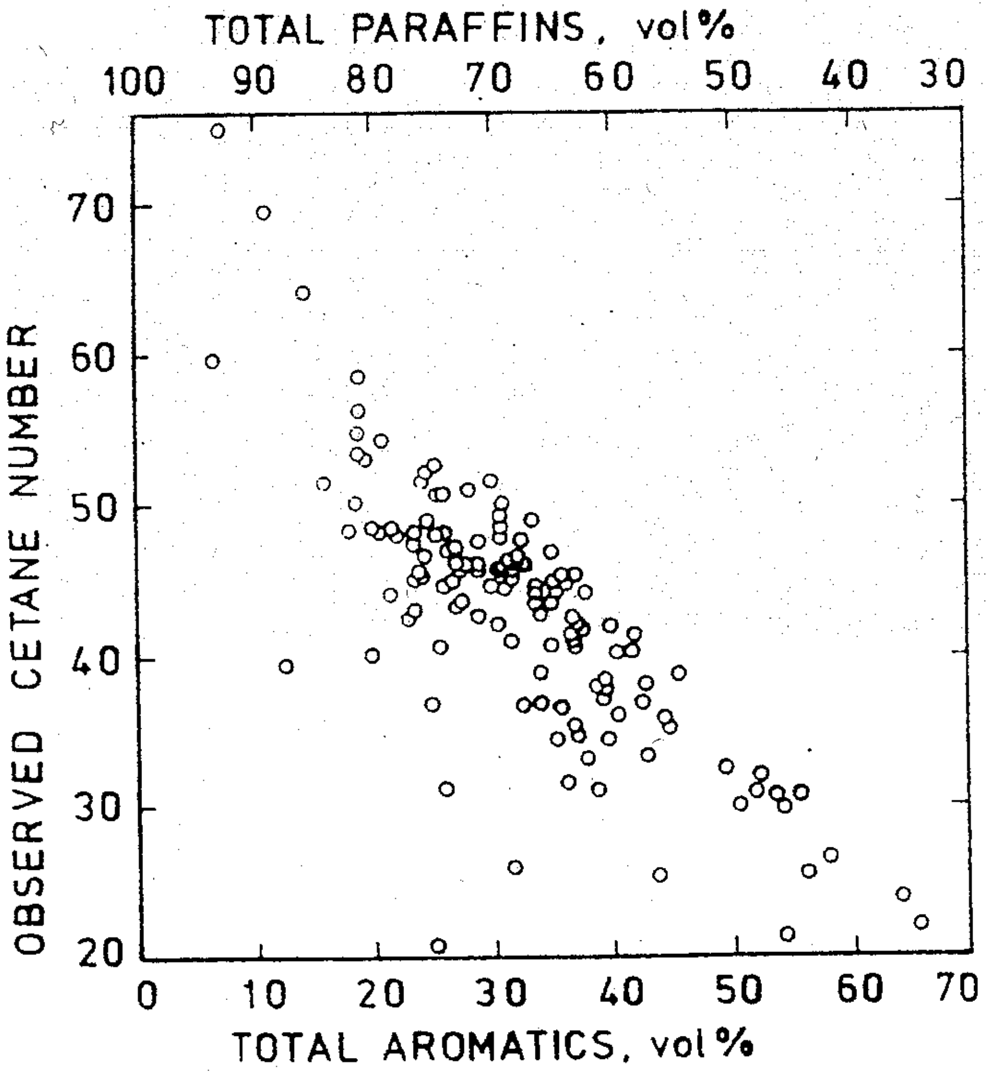

Figure 3. Relationship between aromatic content and cetane number (20).

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STATE OF CALIFORNIA
AIR RESOURCES BOARD

New Specifications for Diesel Engine Certification Fuel, Oxygen Specification for Natural Gas Certification Fuel, and Amendments to the Commercial Motor Vehicle Liquified Petroleum Gas Fuel Regulations.	)	**Hearing Date: Sept. 22, 1994**

STATEMENT OF THE ENGINE MANUFACTURERS ASSOCIATION

Good morning, my name is Glenn Keller and I serve as the Executive Director of the Engine Manufacturers Association. I am here today on behalf of the members of EMA who manufacture the engines which utilize the fuels covered by today's proposed certification fuel specifications. In particular, we will address the Board today on the proposed new specifications for diesel engine certification fuel.

When the ARB first adopted its low sulfur/low aromatics diesel fuel regulations specifying the quality of diesel fuel required for use in all motor vehicles effective October 1, 1993, they failed to establish a diesel certification fuel specification. EMA and its members were the first to express our concerns with regard to the regulation's allowance for certification fuels whose properties were too broadly defined. Since that time, we have worked with the ARB Staff to address these concerns by developing appropriate diesel certification fuel specifications that are representative of the California low sulfur and low aromatics diesel fuel formulations found in commerce.

The proposed specifications include a natural cetane number of 47 to 55, and an aromatic hydrocarbon content of 8 to 12 percent. The amendments would also provide that the specifications applicable to the diesel fuel used for in-use compliance testing are to be the same as the specifications applicable to the diesel fuel used in certification testing. EMA and its members support Staff's efforts to set the diesel engine certification fuel specification in accordance with industry's recommendations, and we agree with the proposal set before the Board for approval. In that spirit, we would like to inform the Board of why approving this set of diesel certification fuel specifications is so important to our industry.

Fuels specifications intended for use as certification test fuel has its properties defined among a constrained set of parameters to assure consistent results when used in engine emissions testing for certification application approval. Certification-grade fuel is also used during emission testing for the various regulatory enforcement programs which CARB may utilize to assure compliance with its regulations. Therefore, emission certification fuel specifications must be defined within a closed range to assure consistency and repeatability, so that the testing is a valid measure of the engine's emissions performance and not influenced by variables which could be introduced with the test fuel. It is important to note that there is a great deal of data which shows that a diesel engine's emissions can respond to relatively small incremental changes in certain properties of the test fuel.

Moreover, CARB has initiated three major rulemakings over the past several years for which the standards and their feasibility have been predicated on the use of low sulfur/low aromatics diesel fuel for certification. The standards promulgated in the 1995 Medium-Duty Vehicle Rule, the 1995 Utility and Lawn & Garden Equipment Rule, and the 1996 Urban Bus Rule are all linked to the diesel certification fuel specification being deliberated today. These aforementioned regulatory standards were all established with certain expectations as to how diesel certification fuel would be defined. The CARB Staff has developed a certification fuel specification that EMA's members who produce products which are governed by these rulemakings can utilize to comply with the regulatory obligation. Given the fact that some of these regulations will become effective in just over 90 days, it is too late in the certification process for CARB to make any additional changes to the diesel certification fuel specifications.

Of further importance to engine manufacturers and CARB Staff, is that the specifications be set so that there is an assured supply of diesel certification fuel available for a reasonable price for manufacturers and staff to perform emissions development exercises and compliance testing. It is our understanding that there are only two suppliers of diesel certification fuel that can consistently supply fuel with the same properties. One major supplier stated at a CARB fuels workshop that the lowest cetane value they can obtain by conventional means with existing resources for a 10% aromatic fuel is 52. Further, the reproducibility of cetane measurement is over ± 3 numbers in accordance with ASTM D 613. Therefore, the cetane range for specifying certification fuel must be set wide enough to address both the problems of cetane measurement reproducibility and fuel blending variability. As such, the maximum cetane number limit cannot be set lower than 55.

While EMA and its members requested that a maximum cetane number be set at 60, we worked closely with the Staff to understand their concerns regarding the establishment of an appropriate cetane range. We believe that CARB Staff has acted responsibly in setting the critical properties of certification fuel based upon their analysis of commercially available 10 percent aromatic motor vehicle diesel fuel properties surveyed throughout the state of California.

In conclusion, EMA and its members support CARB Staff's findings and agree with the range of certification fuel properties being proposed for adoption today. Engine manufacturers affected by the 1995 regulations which utilize this fuel have had no choice but to develop their product lines with the expectation that these certification fuel specifications will be adopted by the Board. If there is any revision to these specifications at this late date, it would have a major impact on engine manufacturers' ability to certify for 1995 and would potentially disrupt the marketplace.

If you have any questions, I will be pleased to answer them at this time.

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AAMA
American Automobile Manufacturers Association

7430 Second Avenue, Suite 300 • Detroit MI 48202
Tel. No. 313-872-4311 • Fax No. 313-872-5400

Andrew H. Card, Jr.
President and Chief Executive Officer

September 20, 1994

California Air Resources Board
2020 L Street
Sacramento, CA 95814

Attention: Pat Hutchins, Board Secretary

Re: Public Hearing to Consider New Specifications for Diesel Engine Certification Fuel, Proposed Amendments to the Oxygen Specification for Natural Gas Certification Fuel, and Proposed Amendments to the Commercial Motor Vehicle Liquefied Petroleum Gas Fuel Regulations

The American Automobile Manufacturers Association (AAMA) provides the following comments concerning the proposed amendments to the fuel regulations that will be addressed at the California Air Resources Board (CARB) hearing on September 22, 1994.

Diesel Engine Certification Fuel

AAMA supports the proposed certification diesel fuel proposal. AAMA commends CARB's efforts to establish a certification diesel fuel that is representative of commercial fuel, but is more tightly controlled. Specifications that are closely defined will reduce fuel composition variability, thereby providing a consistent standard fuel that can be used for testing.

Natural Gas Certification Fuel

AAMA supports the CARB proposed change to the oxygen content of natural gas certification fuel. However, we recommend a maximum oxygen content of 0.3 mole percent to limit the potential variability of test fuel. AAMA member companies originally petitioned the CARB to allow a lower oxygen content because fuel suppliers indicated they could not blend and supply the fuel with an oxygen content as high as required by the initial CARB specification. The proposed change solves this problem, but we believe it does not go far enough in limiting the variability problem.

Commercial Liquefied Petroleum Gas (LPG) Fuel

AAMA does not oppose the proposal for a two-year delay in the implementation of the 5 volume percent propene content requirement to January 1, 1997. However, AAMA requests that CARB make available for review and comment the proposal from the Western Propane Gas Association to conduct a testing program to evaluate emissions of propene and other ozone precursors from LPG fueled vehicles that is referenced in the Staff Report. AAMA also urges the CARB staff to establish a plan to ensure that the issue is resolved within the two-year deferral period.

Thank you for this opportunity to provide our comments on this proposal. If there are any questions concerning these comments, please contact Marcel Halberstadt at (313) 871-2303.

Sincerely,

Gerald A Esper

Gerald A. Esper
Director
Vehicle Environment Department

GAE/bjt

Chevron

Chevron U.S.A. Products Company
575 Market Street
San Francisco, CA 94105

Dixon B. Smith
General Manager
Strategic Planning and Business Evaluation
Phone 415- 894-3268
Fax 415 894-2769

September 21, 1994

Ms. Pat Hutchens
Board Secretary
California Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

Dear Ms. Hutchens,

Chevron appreciates the opportunity to comment on the proposal to adopt new specifications for diesel engine certification fuel (Item 94-9-1 for Public Hearing September 22, 1994).

One of CARB's major regulatory philosophies has been to require more stringent standards than Federal; this is certainly true of fuels both diesel and gasoline. CARB's extra stringency in fuels' emissions performance results in extra vehicle emissions performance when California fuels are used in vehicles certified to Federal standards--using higher-emitting Federal certification fuels--but operated in California. To the extent that California vehicles are allowed to be certified on cleaner-burning California fuels California will have lost its extra air quality "bang for the buck" from its cleaner-burning fuels.

Chevron believes that any emissions certification fuel should at least reflect the emissions performance of in-use fuel. To make a certification fuel cleaner-burning than in-use fuel further erodes the advantages of California's lower-emissions fuels. We do not believe that the methodology used by ARB staff to set the recommended certification fuel specification has or will produce a certification fuel reflective of the emissions performance of the current in-use diesel fuel pool. Basing the certification fuel specification solely on the characteristics of what true 10% aromatics fuel exists in the marketplace now ignores both the contribution to the in-use pool of alternatives certified to the large refiner standard and the contribution of small refiner fuel. Either one of these latter two categories of fuel will pull down the average emissions performance of the in-use pool.

According to your staff, the preponderance of diesel fuel currently in-use in California is large refiner certified alternative. Thus, any diesel engine certification fuel should be based on a certified alternative but with emissions performance (as characterized by aromatics content and cetane number) reflective of the entire pool including both true 10% fuel and small refiner fuel. The best basis for the determination of in-use fuel characteristics is, of course, actual fuel inspection data on all fuels. However, we understand that ARB staff does not have this data. In its absence, an approximation of some sort should be used.

Chevron believes there is a simple way to design a 10% aromatics certification fuel approximating the emissions of the in-use pool. The methodology assumes that all alternative formulations can be represented by a surrogate 10% aromatics fuel, specifically, the reference fuel that all large refiner certified alternatives must demonstrate emissions equivalency to, i.e., a 10% aromatics 48 cetane fuel. Similarly, all small refiner fuel can be represented by the small refiner alternative certification reference fuel, i.e., 20% aromatics and 47 cetane. Weighting these three contributions by their current (or in the case of small refiners, projected) marketshare as estimated by ARB staff (29% for true 10% aromatics fuel, 14% for small refiner fuel, and 57% for large refiner certified alternative) gives a cetane number for a 10% aromatics fuel of 49 instead of the range centerpoint of 51 proposed by ARB staff. Thus, a 10% aromatics fuel with emissions performance reflective of the in-use diesel pool would have a cetane level two numbers lower than what staff is proposing for the certification fuel. If the Board must choose a certification fuel now that would apply forever to all potential diesel engine certifications for the foreseeable future, this would be our recommendation.

However, it is arguable that today's in-use fuel pool will change significantly in the near future and that engine certification fuels should reflect future in-use fuels. We also recognize that engine manufacturers may have already committed significant resources to certifying engines for the 1995 model year using a fuel meeting staff's recommended specification and that, in any case, the contribution to the emissions inventory of the engines allowed to be certified on California diesel is relatively small.

While our preference is for the Board to adopt our recommended certification fuel cetane number, given these considerations we would understand if the Board adopted staff's recommendation. However, the Board should concurrently state its intention that the classes of engines now allowed to be certified on California diesel not be expanded unless and until a more thorough assessment of the in-use diesel pool were made and a new certification fuel adopted.

Sincerely,

Dixon Smith

STATE OF CALIFORNIA
AIR RESOURCES BOARD
RECEIVED 9/6/94
BY BOARD SECRETARY

xc: Board Members
JQS MHS
AS Legal
JB SSD

9/22/94

MESA
ENVIRONMENTAL

September 1, 1994

Board Secretary
Air Resources Board
P.O. Box 2815
Sacramento CA 95812

Subject: **Comments on Proposed Amendments to Title 13**

Representatives of CARB:

The following comments are offered in reference to the proposed amendments to Title 13 CCR.

"Oxygen Specification for Natural Gas Certification Fuel"

MESA supports the proposed modification to relax the oxygen requirement from 0.5% ±0.1 to 0.5% maximum for natural gas certification fuel. Based on data from a nation-wide natural gas composition survey, oxygen is not a common constituent in natural gas. In those areas where oxygen was found in natural gas, special circumstances, such as propane/air peakshaving or ethane/air dilution, existed. These cases were isolated both in geographical location and in time. California natural gas, in general, does not contain measurable amounts of oxygen, and therefore oxygen content should not be a requirement for the certification fuel, since it is *not* representative of in-use gas. Landfill gas is not a common fuel source for natural gas vehicles and should not be considered.

The emissions effect of low concentrations of oxygen in natural gas is insignificant. Oxygen has the effect of richening the stoichiometric fuel-air ratio, since some of the oxygen required for combustion is premixed with the fuel. In practice this simply means the fuel system must deliver more "fuel". If natural gas fuel blends with and without oxygen are compared on a *reactive* hydrogen/carbon ratio basis, the same amount of oxygen is required to completely oxidize the hydrocarbon molecules, regardless of whether the oxygen came premixed with the fuel or from the air that is subsequently mixed with the fuel. For emission certification testing reasons, it makes no sense to require that oxygen be premixed with the fuel.

The rich-flammability-limit of natural gas in air is approximately 14% fuel volume. This equates to 86% air or 18.1% oxygen for most common natural gas blends. Assuming the oxygen is properly blended with the natural gas, a 0.5% oxygen concentration should not pose any safety hazard.

3125 WEST BOLT STREET / 817 924-2353 / FORT WORTH, TEXAS 76110

Relaxing the oxygen content will reduce the cost of the certification test gas. This is good since certification cost is very high for the relatively small market that currently exists for natural gas vehicles. Government must work with industry to develop the alternative-fueled vehicle markets by not imposing unnecessarily restrictive standards. Only this way can the long term goal of cleaner air be realized through use of large numbers of natural gas vehicles.

"Commercial Specifications for LPG"

MESA supports the delay of the 5% propene specification until January 1, 1997. This will allow sufficient time for the producers and marketers to develop markets for the excess propene. Closed-loop adaptive fuel control systems will not have any problem maintaining low emissions with this small variation in composition.

Sincerely,

Steve King

Steven King. P.E.
Vice President, Engineering

Attachment: SAE #920593

SAE TECHNICAL
PAPER SERIES

920593

The Impact of Natural Gas Composition on Fuel Metering and Engine Operational Characteristics

Steven R. King
Southwest Research Institute

The Engineering Society
For Advancing Mobility
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90-0723PG

920593

THE IMPACT OF NATURAL GAS COMPOSITION ON FUEL METERING AND ENGINE OPERATIONAL CHARACTERISTICS

Steven R. King
Southwest Research Institute

ABSTRACT

The composition of end-use natural gas is known to vary significantly around the United States. Of primary interest for this analysis was the impact of natural gas fuel composition on fuel metering and engine operational characteristics. A fuel metering model was developed to analyze the impact of fuel composition on carbureted, fuel-injected (premixed), and direct-injected engine configurations. The change in physical properties of the fuel was found to have a profound effect on fuel metering characteristics. Fuel composition was found to affect different fuel metering configurations differently, but these variations were minor compared to the fuel property effects. Equivalence ratio variations of 12 percent lean and 6 percent rich were calculated from a median gas composition. Wobbe Index was identified as a key parameter for estimating the change in metered equivalence ratio between two fuels. Fuel composition also affects the lean-flammability-limit of the mixture which, when combined with fuel metering variations, can cause a lean-burn engine to misfire. Fuel temperature variations affect fuel metering and must also be considered. Results indicate that closed-loop mixture control is essential for stoichiometric engines and very beneficial for lean-burn engines. A closed-loop feedback system based on exhaust oxygen concentration is the preferred approach.

THE COMPOSITION OF end-use natural gas as supplied through the pipeline varies widely across the United States. While there are some geographical and seasonal tendencies, fuel composition appears to fluctuate at random to the end-user and is difficult to predict. A technical report by Liss and Thrasher (1)* contains information from a recent gas composition survey in the U.S.A. which defines and quantifies these fuel composition variations.

The natural gas supply industry provides a fuel composition consistent with common uses for natural gas. These applications include furnaces, burners, industrial processes, etc. The local distribution company (LDC) sells energy for these applications in terms of gas volume that implies an energy content per unit volume of gas, typically 1000 BTU/ft^3 (HHV) minimum for most areas of the country.

The major constituent of natural gas is methane (typically 85 to 95 percent). The balance consists of heavier hydrocarbons and inerts. As heavier hydrocarbons are substituted for methane, inerts must also be added to maintain a near constant fuel heating value per unit volume, since the heavier hydrocarbons have higher volumetric heating values than methane. Nitrogen and carbon dioxide are the most common diluents present in natural gas. In specific areas of the country high levels of propane and air are sometimes used to meet peak demand loads of the LDC. This is referred to as propane/air peak shaving.

Emissions legislation mandating use of alternative fuels at federal, state, and local levels has provided incentive for research and development of natural gas as an alternative vehicle fuel. As natural gas vehicle technology develops it is imperative that the impact of fuel composition variation be understood and controlled to provide safe and reliable natural gas vehicle operation.

Three key technology areas for successful implementation of advanced low emissions natural gas engines are combustion systems, exhaust catalysts, engine controls. All three areas are interrelated by gas fuel composition. Combustion systems must be optimized for natural gas, yet designed to tolerate the effect that varying fuel composition has on combustion properties, such as methane number (a measure of the fuel's resistance to auto-ignite) (2,3). Methane is

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*Numbers in parentheses designate references at end of paper.

stable and difficult to oxidize requiring new catalyst formulations to achieve low emissions. Control systems must adapt to varying fuel composition and accurately maintain the desired fuel-air mixture under all operating conditions. Technology advancements made for NGVs will also be applicable to stationary engines.

To understand why the effect of fuel composition is of concern, consider the operating characteristics of an internal combustion engine. Engine performance, efficiency, and emissions are dependent on many variables. These include design variables of compression ratio, volumetric efficiency, displacement, etc., and operational variables of equivalence ratio, spark timing, EGR, engine load, etc. Equivalence ratio is a fundamental engine operating variable which defines the base efficiency and engine-out emissions characteristics of the engine. (Equivalence ratio, ϕ, is the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio. A mixture with an equivalence ratio less than one is lean.) As such, it also defines the *type* of combustion system and the applicable method of emissions control.

Typical emissions trends as a function of equivalence ratio are shown in Fig. 1. It is essential to maintain the desired *equivalence ratio* of the engine under all operating conditions in order to minimize emissions, and maximize performance and efficiency.

Stoichiometric engines rely predominately on three-way catalytic aftertreatment for emissions control and require very precise mixture control to achieve simultaneous control of CO, HC, and NO_x emissions. It is generally understood and has been shown that the operating window for natural gas three-way catalysts is narrower than for gasoline catalysts and at a slightly richer set point (4,5).

Lean-burn (ϕ<0.75) natural gas engines operate with lower peak combustion temperatures than stoichiometric engines. This leads to lower heat loss (higher thermal efficiency) and reduced NO_x formation. Natural gas engines can run sufficiently lean to control NO_x to very low levels without exhaust aftertreatment. Often lean-burn engines operate very close to the lean-flammability-limit of the fuel-air mixture and small variations in equivalence ratio can either result in engine misfire or high NO_x emissions. As a result any variable which affects the metered equivalence ratio to the engine will affect engine performance and emissions, whether it be stoichiometric or lean-burn combustion.

Air-fuel ratio is often used to describe the degree to which a mixture is rich or lean. This terminology is incomplete when describing natural gas, since the stoichiometric air-fuel ratio varies with composition and without knowing the stoichiometric air-fuel ratio the degree to which a mixture is rich or lean cannot be determined. From a control system standpoint natural gas must be considered a flexible fuel with varying fuel properties. Since gas composition affects the physical properties of the fuel it follows that the quantity of fuel metered by the fuel system will also be affected, potentially changing the equivalence ratio to the engine.

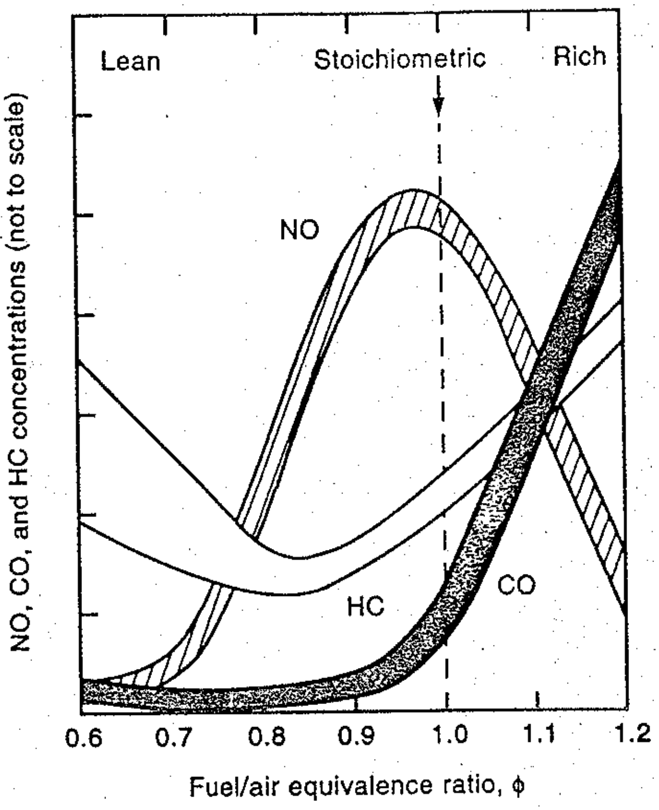


Fig. 1. Gaseous Emissions as a Function of Equivalence Ratio from a Spark-Ignited Engine

The objective of this analysis was to identify and quantify the impact of gas fuel composition on fuel metering and engine performance and emissions characteristics. This investigation was limited to the impact of the physical and chemical fuel properties which affect fuel metering and equivalence ratio. The effect of fuel composition on combustion properties (i.e., ignition delay, combustion duration, methane number, etc.) and how these affect engine performance and emissions was not examined.

METHODOLOGY

A four step approach was taken to evaluate the impact of natural gas fuel composition on fuel metering to the engine:

1) determine the variation in fuel composition in the United States and identify the key fuel

properties affected by this variation,
2) identify the types of fuel metering systems on natural gas engines and the metering characteristics of each,
3) determine the governing relationships between the fuel and air flow for the different types of fuel systems and engines, and
4) evaluate the effect of fuel composition on metered equivalence ratio and the resultant effect on engine performance and emissions.

GAS COMPOSITION VARIATION AND TEST GASES

The variability of natural gas as provided by the LDC was determined through available literature, personal contacts, and engine development experience. Sources for this information include a recently completed gas composition survey conducted by Gas Research Institute (GRI) (1), gas transportation and distribution companies, and experience with gas composition variation at the Southwest Research Institute engine research facilities and its impact on engine design and development procedures.

Results of the gas survey indicate that significant gas composition variation does exist at the LDC and is not predictable. Fuels which provided a representative cross-section of end-use natural gas blends were selected for analysis in this study. Of particular concern was the use of propane/air peak shaving and ethane/air dilution in certain areas of the U.S.A. Also investigated were atypical gas blends identified by the national gas survey which could potentially be obtained and used in an NGV.

Twelve test gases were selected for evaluation. The test gases include five gases which represent the 50, 10, 90 percentile, minimum, and maximum Wobbe Index, gases A through E, respectively; a high-energy gas with high propane and butane content, gas F; two propane/air peak shaving gases, gases G and H; a high ethane gas representative of some LNG, gas I; and pure methane, ethane, and propane, gases J, K, and L, respectively.

A partial list of fuel properties which are affected by composition is shown in Table 1. Fuel properties which affect metering characteristics and knock resistance are of primary importance to the engine and vehicle manufacturer. Knock resistance of the fuel was not addressed in this study. The test fuels, their composition, and their properties are shown in Table 2. Fuel properties were calculated using standard analytical procedures.

Combustion experiments conducted by SwRI have shown that within the limited range of LDC gas compositions found in the U.S.A., the effect of gas composition on engine power, efficiency, and emissions is small (3) at a constant equivalence ratio. The principal means by which gas composition affects engine power and emissions is through the resulting change in metered equivalence ratio to the engine.

Table 1. Fuel Properties Affected by Gas Composition

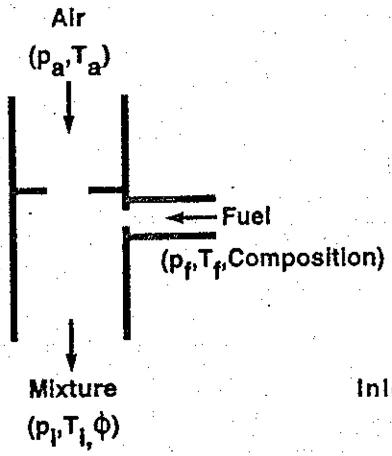
Fuel Property	Symbol
Hydrogen/Carbon Ratio	H/C (reactive, actual)
Molecular Weight	m_f
Gas Constant	R
Specific Heats	C_p, C_v
Density, Specific Gravity	ρ, SG
Heating Value	HHV, LHV
Wobbe Index	WI
Stoichiometric Fuel-Air Ratio	F_s
BTU/ft^3 of Stoichiometric Mix	Q_m
Octane Number	MON, RON
Flammability Limits	LFL, RFL

ENGINE TYPES AND FUEL METERING CHARACTERISTICS

Fuel composition affects the fuel demand of the engine and the metered orifice flow through the fuel system. The fuel demand, in terms of mass flow, is defined by the stoichiometric fuel-air ratio and the desired equivalence ratio set point, e.g., ϕ=1.005 for a stoichiometric engine and ϕ=0.68 for some lean-burn engines.

Three distinct and different methods for fuel control and introduction on natural gas engines were identified. The first is carburetion where air flow across a restriction creates a pressure drop which draws a proportional volume of fuel into the air stream. The second is fuel injection (FI) where fuel is introduced into the air stream prior to admission into the cylinder and can either be metered as choked (sonic) or unchoked flow. The third type of fuel metering is direct injection (DI) into the cylinder. The governing relationships for each fuel metering type are different.

Carburetion is by far the most common method of fuel metering used on natural gas engines today. Carburetion can take on various forms, such as a venturi in combination with a demand (zero pressure) fuel regulator, a variable venturi mixing valve, etc., but all operate using Bernoulli's principal. For carbureted engines, the volumetric air flow creates a pressure drop at the throat of a restriction which draws a



Equivalence: $$\phi = \frac{(\dot{M}_f/\dot{M}_a)}{F_s} \qquad \text{Eq. (1)}$$

Fuel Flow: $$\dot{M}_f = Ap_f \sqrt{\frac{g_o m k}{RT_f}} \sqrt{\left(\frac{2}{k-1}\right)\left(r_p^{\left(\frac{2}{k}\right)} - r_p^{\left(\frac{k+1}{k}\right)}\right)} \qquad \text{Eq. (2)}$$

Air Flow: $$\dot{M}_a = \text{Depends on Type of Fuel Metering} \qquad \text{Eq. (3)}$$

Air Flow: $$\dot{M}_a = f\left(\rho_a, e_v, A_p, S\right) \qquad \text{Eq. (4)}$$

Inlet Air Density: $$\rho_a = \frac{29\, p_I}{RT_I}\left(\frac{1}{1 + F_I\left(\frac{29}{m_f}\right)}\right) \qquad \text{Eq. (5)}$$

Power: $$\text{Power} = f\left(\dot{M}_a, F_I, Q_c, \eta\right) \qquad \text{Eq. (6)}$$

For Two Fuels; 1 and 2: $$\frac{\phi_2}{\phi_1} = \left(\frac{\dot{M}_2}{\dot{M}_1}\right)_f \left(\frac{\dot{M}_1}{\dot{M}_2}\right)_a \left(\frac{F_1}{F_2}\right)_s \qquad \text{Eq. (7)}$$

Fig. 2. Governing Equations for Fuel Metering Model

desired equivalence ratio with the 50 percentile gas composition (gas A). Fuel properties were then varied to determine the effect of the gas composition on the metered equivalence ratio to the engine. The solutions were arrived at through iterative solving of the appropriate group of governing equations.

For the carbureted engine the air flow relationship used the same form as the fuel flow, with the orifice area (venturi) appropriately sized. The pressure at the throat of the carburetor venturi was used as the downstream pressure for the fuel flow orifice. In this manner the fuel flow was dependent on the air flow. For the fuel-injected engine, the fuel injector orifice area and supply pressure were designed for choked operation and the proper fuel flow with gas A. Air was assumed to fill the volume not filled by fuel during the fuel injection event, again given a constant volumetric efficiency. The direct-injected engine received a fixed amount of air flow based on no displacement of air in the intake manifold by fuel. The in-cylinder fuel injection event for the DI engine was assumed choked.

Power output is proportional to the mass air flow, equivalence ratio, and the fuel heating value. With these parameters known and dependent on fuel metering, the change in power output of the engine could be determined. Similarly, given well established emissions trends as shown in Fig. 1, the resultant engine-out emissions were estimated.

ANALYSIS AND RESULTS

FUEL METERING - Fuel metering analysis results are shown in Table 3. Results are presented in terms of percent change from the 50 percentile gas blend (gas A). Stated another way, the numbers shown indicate the percent change in *metered equivalence ratio* which would result if the engine was switched from gas A to the gas blend in question.

For the 10 to 90 percentile fuel blends (based on Wobbe Index) a total variation in equivalence ratio of 3.3 percent, 3.6 percent, and 3.1 percent resulted with the DI, FI, and carbureted engines, respectively. This appears to be a relatively small variation in equivalence ratio at first, but consider the narrow operating window for a three-way natural gas catalyst on a stoichiometric engine. A 0.5 percent variation, rich or lean, in equivalence ratio would result in significantly reduced catalyst efficiency and high catalyst-out exhaust emissions. For a lean-burn engine this small metering variation could result in high unburned hydrocarbon emissions due to a lean mixture, or an increase in NO_x emissions due to a rich mixture.

The largest lean deviation from the median gas

Table 2. Natural Gas Fuel Blends and Properties

Constituent (mole percent)	Gas A	Gas B	Gas C	Gas D	Gas E	Gas F	Gas G	Gas H	Gas I	Gas J	Gas K	Gas L
Methane	94.2	88.7	95.3	75.8	90.0	84.2	65.1	46.5	89.0	100.0	0.0	0.0
Ethane	2.8	4.7	2.6	11.2	4.9	8.6	2.2	1.6	11.0	0.0	100.0	0.0
Propane	0.6	1.3	0.5	0.9	2.2	3.7	16.4	28.7	0.0	0.0	0.0	100.0
Butane	0.1	0.4	0.2	0.1	1.1	2.1	0.3	0.2	0.0	0.0	0.0	0.0
Pentane	0.1	0.1	0.1	0.0	0.4	0.0	0.1	0.1	0.0	0.0	0.0	0.0
Hexane	0.0	0.1	0.1	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	0.7	0.7	0.8	2.8	0.7	0.6	0.5	0.4	0.0	0.0	0.0	0.0
Nitrogen	1.5	4.0	0.4	6.9	0.3	0.8	12.3	18.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	2.3	0.0	0.0	3.0	4.5	0.0	0.0	0.0	0.0
Gas Properties												
H/C Ratio	3.88	3.80	3.87	3.64	3.69	3.61	3.38	3.11	3.80	4.00	3.00	2.67
m_f	17.11	18.04	17.02	19.88	18.63	19.44	23.28	27.47	17.59	16.04	30.07	44.10
$(A/F)_{st}$	16.41	15.67	16.65	13.48	16.56	16.39	13.07	12.07	17.02	17.24	16.09	15.68
HHV (BTU/ft^3)	1024	1031	1033	989	1124	1161	1123	1230	1092	1008	1767	2514
Specific Gravity	0.593	0.625	0.589	0.689	0.645	0.673	0.806	0.951	0.609	0.556	1.041	1.527
Wobbe Index	1330	1304	1345	1192	1400	1415	1251	1261	1399	1353	1731	2035
(Q_m) (BTU/ft^3 mix)	95.7	95.8	95.8	96.4	96.5	96.8	97.6	98.8	96.3	95.6	99.8	101.1
ρ_a/ρ_i at F_s (air=1)	0.906	0.907	0.907	0.902	0.914	0.917	0.913	0.920	0.912	0.905	0.943	0.960

proportional volume of fuel into the air stream. The air and fuel flows are unchoked (subsonic). In this system the fuel flow is *dependent* on the air flow and the total volume flow rate to the engine is constant for a given speed and load since volumetric efficiency is constant.

Natural gas engines which operate with a premixed FI are currently under development by many companies. In a fuel-injected engine the fuel is metered based on predetermined engine operating conditions, such as engine speed, intake manifold pressure, and throttle position, and can be controlled mechanically or electronically. Fuel flow is therefore dependent on a known calibration of the engine and is *independent* of air flow. The fuel-air ratio can vary; however, the total volume flow of mixture must remain constant, since the volumetric efficiency of an engine is constant for a fixed speed and load, as with the carbureted engine. It follows then that the air flow is *dependent* on the fuel flow, and as the fuel flow varies at fixed operating conditions so must the air flow. This is true for both choked (sonic) and unchoked fuel flow conditions.

For the direct-injected engine the fuel flow is *independent* of the air flow. The fuel flow is also necessarily choked since high fuel pressure is needed to inject the fuel in the small time interval available for the injection event.

In the direct-injected engine the air flow is also *independent* of fuel flow, since the cylinder inducts and traps only air prior to the injection event. For this study it is assumed that the fuel is injected after the intake valve is closed.

GOVERNING RELATIONSHIPS FOR FUEL AND AIR METERING

The purpose of this study was to determine the impact of fuel composition on fuel metering and engine operational characteristics. To accomplish this objective calculations were performed and results presented in terms of percent change in equivalence ratio relative to a median gas composition. In addition to the fuel metering effects, this technique allowed the emissions characteristics of the engine to be quite accurately estimated.

Consider the simplified fuel-air mixing device shown in Fig. 2. The air is supplied at a constant pressure (p_a) and temperature (T_a), and the fuel at a constant pressure (p_f), temperature (T_f), and known composition. The inlet pressure (p_i) is less than p_a and p_f resulting in flow of air and fuel into the inlet system. The air orifice (venturi) and the fuel orifice are fixed and sized to provide the desired fuel-air mixture ratio.

A computer model was developed to simulate carbureted, fuel-injected, and direct-injected fuel metering configurations based on the described fuel-air mixing device. The governing relationships for air and fuel metering are shown in Fig. 2 (6). Definitions and descriptions of symbols are shown in Appendix A. Air and fuel were considered to be ideal, compressible fluids. Input variables to the model include fuel properties, fuel pressure and temperature, air pressure and temperature, intake manifold pressure, volumetric efficiency, thermal efficiency, swept volume, and piston speed. The model was calibrated to provide the

Table 3. Fuel Metering Results for Representative Gas Compositions

Effect	Gas A	Gas B	Gas C	Gas D	Gas E	Gas F	Gas G	Gas H	Gas I	Gas J	Gas K	Gas L
% Change in ϕ Direct Injection	--	-2.14	1.14	-11.7	4.56	5.44	-8.25	-8.74	4.73	1.97	25.4	45.7
% Change in ϕ FI Premix	--	-2.42	1.17	-12.4	4.05	4.67	-9.68	-10.8	4.54	2.34	22.0	39.8
% Change in ϕ Carburetion	--	-1.97	1.16	-11.5	5.16	6.32	-7.25	-7.07	5.10	1.73	29.4	52.3
% Change in Wobbe Index	--	-1.95	1.13	-10.4	5.19	6.39	-5.94	-5.19	5.19	1.73	30.2	53.0

mixture was 12.4 percent for the FI engine using gas D. The largest rich deviation was 6.3 percent for the carbureted engine using gas F. Gas D is representative of gas composition found in Denver and gas F was pipeline gas supplied by the LDC to the engine laboratory at SwRI. Gases K and L, which are pure ethane and propane, were excluded from this comparison since they are not representative of end-use gas blends. They are included in the table for reference purposes only.

WOBBE INDEX - Table 3 shows a close relationship between the change in Wobbe Index and the change in metered equivalence ratio. Fig. 3 graphically shows this relationship. It can be shown that for two gaseous fuels; 1 and 2, of pure hydrocarbon blends (no inerts) where Δp, A_o, and $\dot{M}_a$ are constant

$$\frac{\phi_1}{\phi_2} = \frac{WI_1}{WI_2} \qquad \text{Eq. (8)}$$

Eq. (8) shows that the change in metered equivalence ratio between two pure hydrocarbon fuels is equal to the change in Wobbe Index between the fuels. Klimstra reported similar results for carbureted natural gas engines (7). The derivation of the relationship between the metered equivalence ratio and the Wobbe Index is shown in Appendix B. For illustration purposes the derivation was simplified using incompressible fluid and ideal flow equations. This relationship assumes the product of Q_cF_s is constant which is approximately true for common hydrocarbon fuels. Deviation from the linear relationship is caused by the presence of inerts in the natural gas fuel blends. This deviation is most pronounced for gases G and H which are peakshaving gases with high levels of propane and air. In actuality the fuel Δp will remain constant only for unchoked fuel flow conditions, since r_p for sonic fuel flow is dependent on composition, and $\dot{M}_a$ is not constant except for the direct-injected engine configuration.

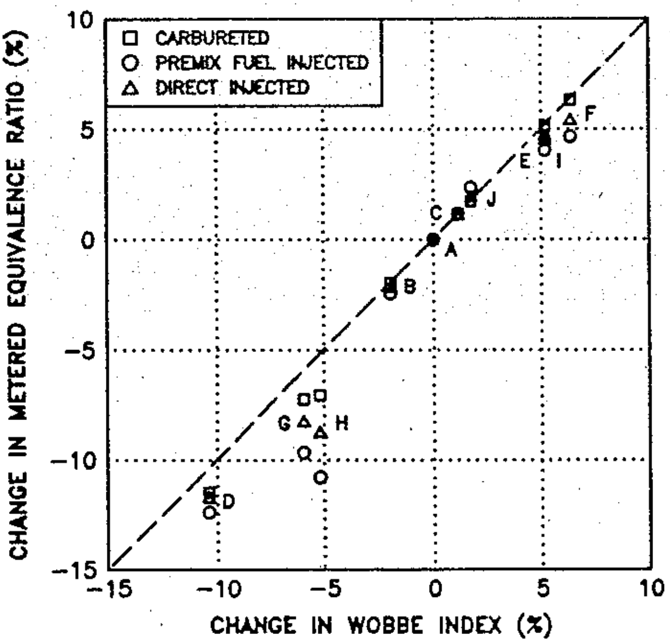


Fig. 3. Relationship Between Wobbe Index and Metered Equivalence Ratio

Fig. 4 shows the stoichiometric air requirement for various gaseous hydrocarbon fuels and select natural gas blends studied in this investigation. From this graph it is evident that for common hydrocarbon fuels there exists a relationship between the theoretical amount of air required for complete combustion and the volumetric heating value. Given this relationship, the combustion energy per unit volume of air is nearly constant for common hydrocarbon fuels.

POWER - Power output of an engine is directly proportional to the mass air flow to the engine, heat energy released per unit mass of air, and fuel-air cycle efficiency, Fig. 2, Eq. (6), and is therefore affected by

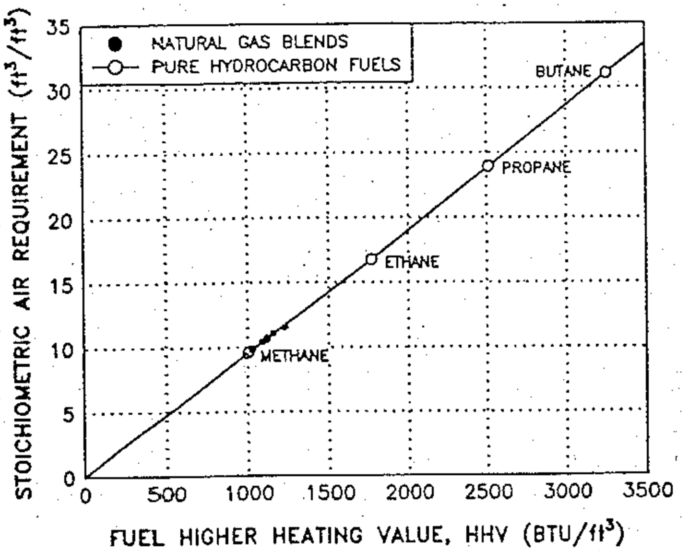


Fig. 4. Air Requirement for Various Gaseous Fuels at Stoichiometry

fuel composition. Mass air flow is proportional to air density Eq. (4). Inlet mixtures obey Dalton's law of partial pressures, thus inlet *air density* varies according to the relationship shown in Eq. (5). A fuel with a low molecular weight will occupy a larger percentage of the inlet mixture volume than a fuel with a high molecular weight at a constant fuel-air ratio.

Fig. 5 shows the effect of molecular weight on air capacity of an engine relative to methane at constant equivalence ratio. The air capacity of the natural gas fuel blends investigated in this study are shown in Table 2. The combined effect from a change in metered equivalence ratio, molecular weight, and stoichiometric fuel-air ratio can result in a dramatic power increase, or decrease, depending on the initial equivalence ratio of the engine. A change in fuel-air ratio has a directly proportional impact on the power and is by far the dominating factor affecting power. The change in the mixture volume occupied by the fuel has a smaller secondary effect.

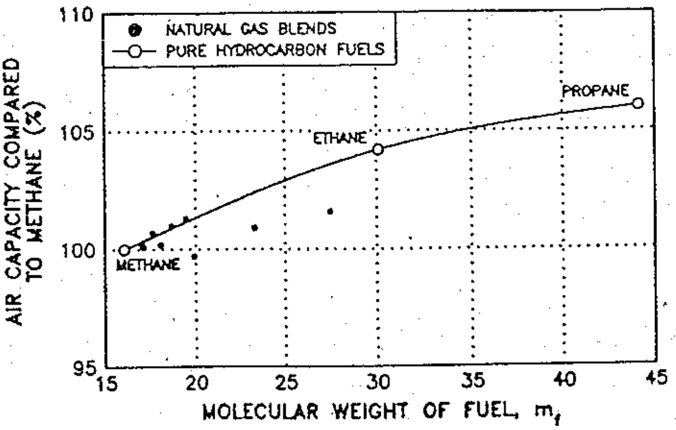


Fig. 5. Effect of Fuel Molecular Weight on Air Capacity for a Stoichiometric Mixture

Thermodynamic fuel-air cycle efficiency, η, is increased as a mixture is leaned. The change in theoretical fuel-air cycle efficiency can be significant and must be considered for large changes in equivalence ratio. For example, a change in equivalence ratio from 0.8 to 1.0 for a 10:1 compression ratio engine would result in a 4.8 percent drop in fuel-air cycle efficiency. Appendix C shows the relationship between efficiency and equivalence ratio for a constant volume fuel-air cycle.

EMISSIONS - Exhaust emissions from a spark-ignited internal combustion engine were previously shown to be dependent on equivalence ratio (Fig. 1). Since a change in fuel composition has been shown to change the equivalence ratio it follows that the emissions will also change. To illustrate the magnitude of these emissions changes consider the data shown in Table 4. Gases A, B, C, D, and E were selected for this analysis and are shown along with the resulting equivalence ratio and brake specific emissions for a

Table 4. Effect of Fuel Composition on Emissions of a Lean-Burn Natural Gas Engine

	Gas A	Gas B	Gas C	Gas D	Gas E
Wobbe Index	1330	1304	1345	1192	1400
Equivalence Ratio, FI	0.680	0.664	0.688	0.596	0.708
Change in Equivalence Ratio (%)	--	-2.42	1.17	-12.4	4.05
NO_x (g/hp-hr)	3.0	2.1	3.6	0.4	5.2
THC (g/hp-hr)	1.3	1.6	1.1	11.8	0.9
CO (g/hp-hr)	1.5	1.6	1.4	2.9	1.3

typical lean-burn natural gas engine. Brake specific emissions were obtained from Fig. 6 and are emissions trends from a representative open chamber lean-burn natural gas engine. While all emissions are affected to some degree, of particular interest are the NO_x emissions from gas E and the hydrocarbon emissions from gas D. As the equivalence ratio increased from 0.680 to 0.708 with gas E, NO_x emissions increased from 3.0 to 5.2 g/hp-hr, a 73 percent increase. Similarly, the equivalence ratio of 0.596 resulting from gas D is near the lean-flammability-limit for most combustion systems and produced an 800 percent increase in unburned hydrocarbon emissions.

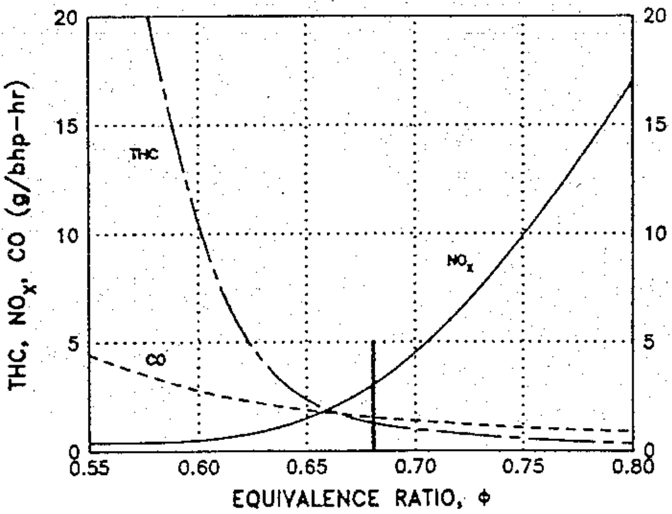


Fig. 6. Lean-Burn Gas Engine Emissions (Constant Speed, Full-Load)

For a stoichiometric engine that relies on a three-way catalyst for emissions control the metering effect is even more pronounced than for lean-burn engines. The change in equivalence ratio affects not only engine-out emissions, but moves the mixture outside the high-efficiency operating window of the catalyst significantly reducing oxidation/reduction performance.

ENGINE OPERATIONAL CHARACTERISTICS- Fuel metering inaccuracies can have a dramatic, and sometimes catastrophic effect on lean-burn engine operation. Today's lean-burn engines are turbocharged to achieve high power and thermal efficiency, approaching that of a diesel. To achieve such good performance the engines are operated very lean, as lean as ϕ=0.60, with boost pressures up to 25 psi. Under these operating conditions a lean-burn engine is very sensitive to mixture strength and spark timing.

An increase in equivalence ratio in a turbocharged lean-burn engine has a twofold effect. First, it provides additional heat energy to the engine so power is increased for a constant boost level. Second, the added heat energy increases the available exhaust energy which tends to increase boost pressure. Provided the turbocharger system has sufficient control capability, boost pressure can be maintained. In some instances the wastegate control may have insufficient flow capacity to bypass the excess exhaust energy and the boost increases above safe limits. In this situation the increased boost means additional mass air flow to the engine accompanied by still more fuel. This is an unstable condition which can build upon itself until the air flow is restricted, the fuel flow is restricted, or an engine failure occurs.

Rich mixtures are more prone to detonate than lean mixtures and the engines are typically designed with little margin from knock to provide optimum performance. Unfortunately, the fuel compositions which cause rich fuel metering conditions also have increased amounts of heavy hydrocarbons which lower the octane of the fuel making detonation even more likely to occur.

Stoichiometric engines do not experience the same excess power and detonation problems as described for lean-burn engines. Most are not turbocharged and richening or leaning the fuel mixture from stoichiometry will result in loss of power. Stoichiometric fuel-air mixtures are more prone to detonate than rich or lean mixtures due to higher flame speeds and higher combustion temperatures, so detonation is not a problem when metering inaccuracies are introduced.

RELATED FUEL METERING AND COMPOSITION ISSUES

LEAN-FLAMMABILITY-LIMIT - Fuel composition affects the lean-flammability-limit (LFL) of a fuel-air mixture. The LFL can be determined for standard atmospheric conditions using Le Chatelier's procedure (8). An increase in hydrocarbon emissions at very lean equivalence ratios is indicative of the fact that the LFL is being approached and flame quenching is occurring. The LFL of gases A through E were calculated and are shown in Table 5. Note the LFL equivalence ratio and the metered equivalence ratio for the same gases as determined previously. For gases A, B, C, and E there exists a significant margin from the LFL after the change to the new fuel. However, for gas D the metered equivalence ratio is below the LFL resulting in unstable combustion, engine misfire, and extremely high unburned hydrocarbon emissions.

EQUIVALENCE RATIO CONTROL - The combination of the change in fuel metering and the change in LFL with fuel composition illustrates the importance of accurate fuel control for natural gas engines. A fuel composition sensor could provide

Table 5. Lean-Flammability Limits of Gaseous Fuels

	Gas A	Gas B	Gas C	Gas D	Gas E
LFL of Fuel by Volume* (%)	5.25	5.31	5.22	6.11	4.74
LFL of Fuel by Mass (%)	3.18	3.38	3.14	4.29	3.11
LFL Air-Fuel Ratio	30.5	28.5	30.8	22.3	31.0
LFL ϕ	0.539	0.549	0.540	0.604	0.530
Change in LFL ϕ (%)	--	1.9	0.2	12.1	-1.7
Metered ϕ, FI	0.680	0.664	0.688	0.596	0.708
Margin from LFL (%)	31	25	32	0	38

*From Le Chatelier's Formula.

feed-forward gas data to better predict the metering characteristics of the fuel system, however, feedback control would still be required to "trim" the fuel system for accurate fuel metering. At the time of this writing, there. were no commercially available natural gas sensors suitable for service on a vehicle.

The preferred method to provide adaptability to varying fuel composition on lean-burn engines is through feedback with a universal exhaust gas oxygen (UEGO) sensor. Test results from an oxygen sensor evaluation (9) show that the UEGO sensor provides the needed performance (accuracy, response, sensitivity, and repeatability) to function as a feedback sensor for lean-burn natural gas engines.

Fig. 7 shows the effect of fuel composition on theoretical oxygen concentration in the exhaust. The variation in hydrogen/carbon ratio of common end-use gas blends is small (3.11 to 3.88). This results in less than a 0.05 variation in the free exhaust oxygen concentration at a fixed equivalence ratio, thus making oxygen a suitable parameter for feedback control. Currently the availability of this type sensor is limited and the cost is high, but market demand should bring the cost to acceptable levels as the need develops. For stoichiometric engines, zirconia and titania oxide oxygen sensors provide acceptable switching characteristics for adequate closed-loop control.

Lean-burn engines often vary the operating equivalence ratio to shape their torque curve. With varying equivalence ratios it is necessary to account for the change in inlet air volume displaced by the fuel to achieve accurate fuel-air mixture control. Electronic control systems should employ use of the equations in Fig. 2 for this purpose.

FUEL TEMPERATURE EFFECTS - The effect of inlet air temperature on carbureted gasoline engine performance is well understood. The temperature of the gasoline as it is metered through the carburetor has a negligible effect on the fuel metering accuracy since the density change is small. With natural gas the situation is quite different and fuel temperature must be considered when operating a carbureted natural gas engine with varying ambient conditions.

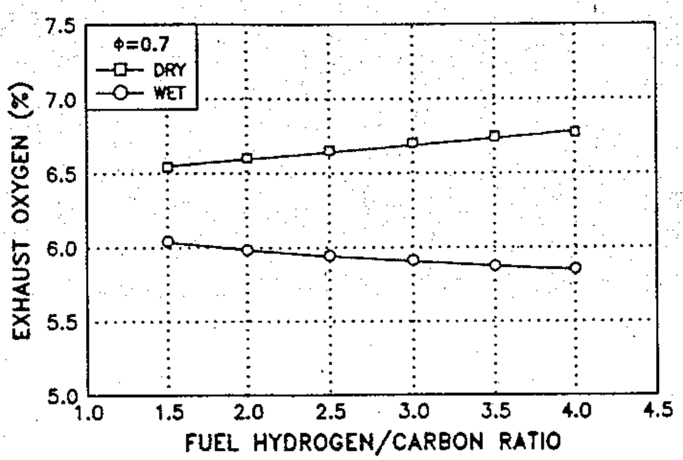


Fig. 7. Effect of Fuel Composition on Exhaust Oxygen Concentration at Constant Equivalence Ratio

The fuel metering model was used to analyze the effect of fuel and air temperature on metering characteristics. Fig. 8 shows the relationship between inlet air and fuel supply temperatures, and how these temperatures affect the metered equivalence ratio to the engine. Provided the fuel and air temperature are equal the temperature can be varied and it will not affect the equivalence ratio. However, significant variations can occur if the fuel and air temperature are allowed to deviate from one another. An example of such a circumstance would be the application of a

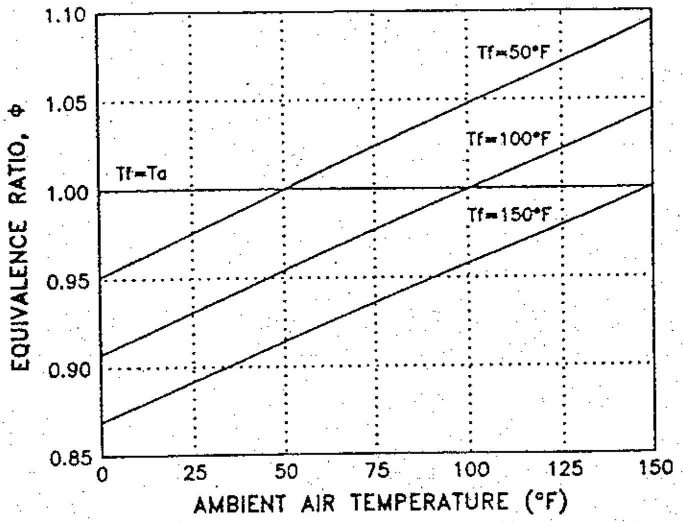


Fig. 8. Effect of Air and Fuel Temperature on Carbureted Equivalence Ratio

turbocharged non-aftercooled engine in a compressed natural gas vehicle. Under high load conditions at high boost levels the intake air temperature can be quite high (250° - 300°F). At the same time the fuel temperature can be below ambient due to expansion cooling of the compressed gas through the regulators. The result is hot inlet air and cold fuel, and large variations in equivalence ratio (over 10 percent) are possible. It is anticipated that electronically-controlled engines will have temperature and pressure compensation to eliminate metering inaccuracies resulting from variations in air and fuel supply conditions.

CONCLUSIONS

Based on results from this fuel metering investigation the following conclusions can be made:

1. The composition of end-use natural gas available for use in natural gas vehicles varies significantly in the U.S.A. This composition variation is not predictable. The impact of this variation must be understood and controlled to provide safe and reliable NGV operation.

2. A fuel metering model was developed to simulate fuel metering characteristics of a natural gas-fueled engine. Fuel properties of representative end-use gas blends were used to evaluate the impact of fuel composition on engine operating characteristics. Three fuel system configurations were evaluated: carburetion, fuel injection, and direct injection. Variations in metering performance do exist between the metering types. Results indicate that equivalence ratio variations of 12 percent lean and 6 percent rich from a median gas composition are possible with current pipeline quality gas blends.

3. The Wobbe Index was identified as a parameter which can be used to approximate the metering performance of two fuels. The change in metered equivalence ratio between two fuels can be closely approximated by the corresponding change in Wobbe Index between the two fuels.

4. Fuel composition affects the lean-flammability-limit of the fuel-air mixture. When combined with the fuel metering variations, the change in LFL can result in combustion instability and misfire in a lean-burn engine.

5. The oxygen concentration in the exhaust is a function of the equivalence ratio and is the key to accurate fuel control for stoichiometric and lean-burn natural gas engines. Fuel composition has a negligible effect on the oxygen concentration in the exhaust at a fixed equivalence ratio. The UEGO sensor provides the desired feedback characteristics for closed-loop adaptive control of a lean-burn engine.

6. Fuel temperature variations can cause significant fuel metering variations on carbureted natural gas engines. Equivalence ratio variations of more than 10 percent are possible with fuel temperature swings of 100°F. The solution is to maintain the fuel and air supply temperatures equal, or at least fixed relative to one another.

ACKNOWLEDGMENTS

The author would like to acknowledge Charles Wood and David Meyers of SwRI, and William Liss of GRI, for their support during the course of this investigation.

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APPENDIX A

SYMBOLS AND DESCRIPTIONS

Symbol	Description	Dimension
A	area	L^2
C_p	specific heat at constant pressure	$QM^{-1}\theta^{-1}$
C_v	specific heat at constant volume	$QM^{-1}\theta^{-1}$
e_v	volumetric efficiency	1
F_i	inlet fuel-air ratio	1
F_s	stoichiometric fuel-air ratio	1
g_o	force-mass-acceleration coefficient	$MLt^{-2}F^{-1}$
H/C	hydrogen-carbon ratio of fuel	1
HHV	higher heating value of fuel at STP	QL^{-3}
k	specific heat ratio, C_p/C_v	1
K	coefficient or constant	1
LFL	lean-flammability-limit	1
LHV	lower heating value of fuel at STP	QL^{-3}
m	molecular weight	1
m_f	molecular weight of fuel	1
$\dot{M}_a$	mass air flow rate	Mt^{-1}
$\dot{M}_f$	mass fuel flow rate	Mt^{-1}
MON	motor octane number	1
p_a	absolute air pressure	FL^{-2}
p_f	absolute fuel pressure	FL^{-2}
p_i	absolute inlet pressure	FL^{-2}
Δp	pressure differential	FL^{-2}
$\dot{q}$	volume flow rate	L^3t^{-1}
Q	quantity of heat	Q
Q_c	heat of combustion per unit mass	QM^{-1}
Q_v	heat of combustion per unit volume	QL^{-3}
Q_m	heat combustion of stoichiometric mixture per unit volume at STP	QL^{-3}
r_p	absolute pressure ratio	1
R	universal gas constant	$FL\theta^{-1}M^{-1}$
RFL	rich-flammability-limit	1
RON	research octane number	1
S	piston speed	Lt^{-1}
SG	specific gravity	1
STP	standard temperature and pressure	1
T_a	absolute air temperature	T
T_f	absolute fuel temperature	T
T_i	absolute inlet temperature	T
WI	Wobbe Index	Q
η	efficiency	1
ρ	density	ML^{-3}
ϕ	equivalence ratio	1

APPENDIX B

RELATIONSHIP BETWEEN WOBBE INDEX AND METERED EQUIVALENCE RATIO

For a gaseous fuel metered through an orifice the volume flow rate (incompressible, ideal flow) is:

$$\dot{q}_f = A_o \sqrt{\frac{2\Delta p}{\rho_f}} \qquad \text{Eq. (B1)}$$

The energy flow rate provided by this fuel is:

$$\dot{q}_f \, Q_v = A_o \, Q_v \sqrt{\frac{2\Delta p}{\rho_f}} \qquad \text{Eq. (B2)}$$

By definition:

$$WI = \frac{Q_v}{\sqrt{SG_f}} = Q_v \left(\frac{\sqrt{\rho_{a,STP}}}{\sqrt{\rho_f}} \right) \qquad \text{Eq. (B3)}$$

Substituting for Q_v in Eq. B2 gives:

$$\dot{q}_f \, Q_v = A_o \sqrt{2\Delta p} \, (WI) \left(\frac{1}{\sqrt{\rho_{a,STP}}} \right) \qquad \text{Eq. (B4)}$$

The fuel-air ratio is:

$$F_I = \frac{\dot{M}_f}{\dot{M}_a} = \frac{\dot{q}_f \, \rho_f}{\dot{M}_a} \qquad \text{Eq. (B5)}$$

The equivalence ratio is:

$$\phi = \frac{F_f}{F_s} = \frac{\dot{q}_f\,\rho_f}{\dot{M}_a}\left(\frac{1}{F_s}\right) \qquad \text{Eq. (B6)}$$

Substituting for $\dot{q}_f$ from Eq. B4:

$$\phi = \frac{A_o\sqrt{2\Delta P}\,(Wl)}{\sqrt{\rho_{a,STP}}\,Q_v}\left(\frac{\rho_f}{\dot{M}_a}\right)\frac{1}{F_s} \qquad \text{Eq. (B7)}$$

since

$$Q_v = Q_c\,\rho_f \qquad \text{Eq. (B8)}$$

then

$$\phi = \frac{A_o\sqrt{2\Delta p}}{\sqrt{\rho_{a,STP}}\,\dot{M}_a}\left(\frac{Wl}{Q_c\,F_s}\right) \qquad \text{Eq. (B9)}$$

For two fuels; 1 and 2, where Δp, A_o, and $\dot{M}_a$ are constant:

$$\frac{\phi_1}{\phi_2} = \frac{Wl_1}{Wl_2}\,\frac{(Q_c\,F_s)_2}{(Q_c\,F_s)_1} \qquad \text{Eq. (B10)}$$

(Q_cF_s) is nearly constant for common hydrocarbon fuels of interest, therefore

$$\frac{\phi_1}{\phi_2} = \frac{Wl_1}{Wl_2} \qquad \text{Eq. (B11)}$$

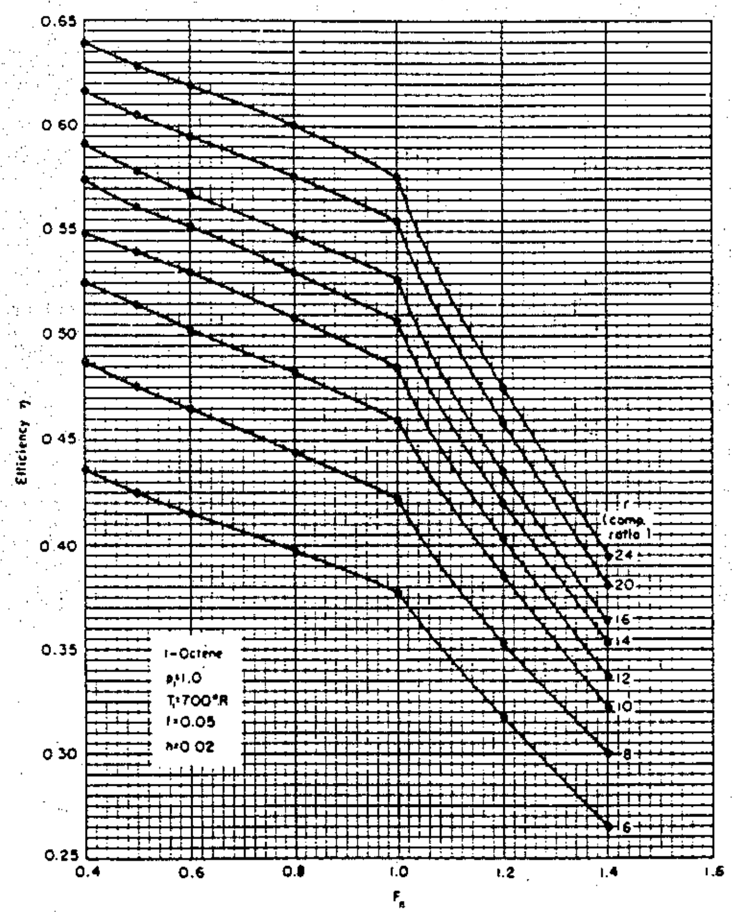
and

$$\frac{\Delta\phi}{\phi} = \frac{\Delta Wl}{Wl} \qquad \text{Eq. (B12)}$$

APPENDIX C

EFFICIENCY VERSUS ϕ FOR CONSTANT VOLUME FUEL-AIR CYCLE

Source: Reference (6)



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MESA
ENVIRONMENTAL

September 1, 1994

Board Secretary
Air Resources Board
P.O. Box 2815
Sacramento CA 95812

Subject: **Comments on Proposed Amendments to Title 13**

Representatives of CARB:

The following comments are offered in reference to the proposed amendments to Title 13 CCR.

"Oxygen Specification for Natural Gas Certification Fuel"

MESA supports the proposed modification to relax the oxygen requirement from 0.5% ±0.1 to 0.5% maximum for natural gas certification fuel. Based on data from a nation-wide natural gas composition survey, oxygen is not a common constituent in natural gas. In those areas where oxygen was found in natural gas, special circumstances, such as propane/air peakshaving or ethane/air dilution, existed. These cases were isolated both in geographical location and in time. California natural gas, in general, does not contain measurable amounts of oxygen, and therefore oxygen content should not be a requirement for the certification fuel, since it is *not* representative of in-use gas. Landfill gas is not a common fuel source for natural gas vehicles and should not be considered.

The emissions effect of low concentrations of oxygen in natural gas is insignificant. Oxygen has the effect of richening the stoichiometric fuel-air ratio, since some of the oxygen required for combustion is premixed with the fuel. In practice this simply means the fuel system must deliver more "fuel". If natural gas fuel blends with and without oxygen are compared on a *reactive* hydrogen/carbon ratio basis, the same amount of oxygen is required to completely oxidize the hydrocarbon molecules, regardless of whether the oxygen came premixed with the fuel or from the air that is subsequently mixed with the fuel. For emission certification testing reasons, it makes no sense to require that oxygen be premixed with the fuel.

The rich-flammability-limit of natural gas in air is approximately 14% fuel volume. This equates to 86% air or 18.1% oxygen for most common natural gas blends. Assuming the oxygen is properly blended with the natural gas, a 0.5% oxygen concentration should not pose any safety hazard.

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Relaxing the oxygen content will reduce the cost of the certification test gas. This is good since certification cost is very high for the relatively small market that currently exists for natural gas vehicles. Government must work with industry to develop the alternative-fueled vehicle markets by not imposing unnecessarily restrictive standards. Only this way can the long term goal of cleaner air be realized through use of large numbers of natural gas vehicles.

"Commercial Specifications for LPG"

MESA supports the delay of the 5% propene specification until January 1, 1997. This will allow sufficient time for the producers and marketers to develop markets for the excess propene. Closed-loop adaptive fuel control systems will not have any problem maintaining low emissions with this small variation in composition.

Sincerely,

Steve King

Steven King. P.E.
Vice President, Engineering

Attachment: SAE #920593

SAE TECHNICAL
PAPER SERIES

920593

The Impact of Natural Gas Composition on Fuel Metering and Engine Operational Characteristics

Steven R. King
Southwest Research Institute

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920593

THE IMPACT OF NATURAL GAS COMPOSITION ON FUEL METERING AND ENGINE OPERATIONAL CHARACTERISTICS

Steven R. King
Southwest Research Institute

ABSTRACT

The composition of end-use natural gas is known to vary significantly around the United States. Of primary interest for this analysis was the impact of natural gas fuel composition on fuel metering and engine operational characteristics. A fuel metering model was developed to analyze the impact of fuel composition on carbureted, fuel-injected (premixed), and direct-injected engine configurations. The change in physical properties of the fuel was found to have a profound effect on fuel metering characteristics. Fuel composition was found to affect different fuel metering configurations differently, but these variations were minor compared to the fuel property effects. Equivalence ratio variations of 12 percent lean and 6 percent rich were calculated from a median gas composition. Wobbe Index was identified as a key parameter for estimating the change in metered equivalence ratio between two fuels. Fuel composition also affects the lean-flammability-limit of the mixture which, when combined with fuel metering variations, can cause a lean-burn engine to misfire. Fuel temperature variations affect fuel metering and must also be considered. Results indicate that closed-loop mixture control is essential for stoichiometric engines and very beneficial for lean-burn engines. A closed-loop feedback system based on exhaust oxygen concentration is the preferred approach.

THE COMPOSITION OF end-use natural gas as supplied through the pipeline varies widely across the United States. While there are some geographical and seasonal tendencies, fuel composition appears to fluctuate at random to the end-user and is difficult to predict. A technical report by Liss and Thrasher (1)* contains information from a recent gas composition survey in the U.S.A. which defines and quantifies these fuel composition variations.

The natural gas supply industry provides a fuel composition consistent with common uses for natural gas. These applications include furnaces, burners, industrial processes, etc. The local distribution company (LDC) sells energy for these applications in terms of gas volume that implies an energy content per unit volume of gas, typically 1000 BTU/ft^3 (HHV) minimum for most areas of the country.

The major constituent of natural gas is methane (typically 85 to 95 percent). The balance consists of heavier hydrocarbons and inerts. As heavier hydrocarbons are substituted for methane, inerts must also be added to maintain a near constant fuel heating value per unit volume, since the heavier hydrocarbons have higher volumetric heating values than methane. Nitrogen and carbon dioxide are the most common diluents present in natural gas. In specific areas of the country high levels of propane and air are sometimes used to meet peak demand loads of the LDC. This is referred to as propane/air peak shaving.

Emissions legislation mandating use of alternative fuels at federal, state, and local levels has provided incentive for research and development of natural gas as an alternative vehicle fuel. As natural gas vehicle technology develops it is imperative that the impact of fuel composition variation be understood and controlled to provide safe and reliable natural gas vehicle operation.

Three key technology areas for successful implementation of advanced low emissions natural gas engines are combustion systems, exhaust catalysts, engine controls. All three areas are interrelated by gas fuel composition. Combustion systems must be optimized for natural gas, yet designed to tolerate the effect that varying fuel composition has on combustion properties, such as methane number (a measure of the fuel's resistance to auto-ignite) (2,3). Methane is

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*Numbers in parentheses designate references at end of paper.

stable and difficult to oxidize requiring new catalyst formulations to achieve low emissions. Control systems must adapt to varying fuel composition and accurately maintain the desired fuel-air mixture under all operating conditions. Technology advancements made for NGVs will also be applicable to stationary engines.

To understand why the effect of fuel composition is of concern, consider the operating characteristics of an internal combustion engine. Engine performance, efficiency, and emissions are dependent on many variables. These include design variables of compression ratio, volumetric efficiency, displacement, etc., and operational variables of equivalence ratio, spark timing, EGR, engine load, etc. Equivalence ratio is a fundamental engine operating variable which defines the base efficiency and engine-out emissions characteristics of the engine. (Equivalence ratio, ϕ, is the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio. A mixture with an equivalence ratio less than one is lean.) As such, it also defines the *type* of combustion system and the applicable method of emissions control.

Typical emissions trends as a function of equivalence ratio are shown in Fig. 1. It is essential to maintain the desired *equivalence ratio* of the engine under all operating conditions in order to minimize emissions, and maximize performance and efficiency.

Stoichiometric engines rely predominately on three-way catalytic aftertreatment for emissions control and require very precise mixture control to achieve simultaneous control of CO, HC, and NO_x emissions. It is generally understood and has been shown that the operating window for natural gas three-way catalysts is narrower than for gasoline catalysts and at a slightly richer set point (4,5).

Lean-burn ($\phi<0.75$) natural gas engines operate with lower peak combustion temperatures than stoichiometric engines. This leads to lower heat loss (higher thermal efficiency) and reduced NO_x formation. Natural gas engines can run sufficiently lean to control NO_x to very low levels without exhaust aftertreatment. Often lean-burn engines operate very close to the lean-flammability-limit of the fuel-air mixture and small variations in equivalence ratio can either result in engine misfire or high NO_x emissions. As a result any variable which affects the metered equivalence ratio to the engine will affect engine performance and emissions, whether it be stoichiometric or lean-burn combustion.

Air-fuel ratio is often used to describe the degree to which a mixture is rich or lean. This terminology is incomplete when describing natural gas, since the stoichiometric air-fuel ratio varies with composition and without knowing the stoichiometric air-fuel ratio the degree to which a mixture is rich or lean cannot be determined. From a control system standpoint natural gas must be considered a flexible fuel with varying fuel properties. Since gas composition affects the physical properties of the fuel it follows that the quantity of fuel metered by the fuel system will also be affected, potentially changing the equivalence ratio to the engine.

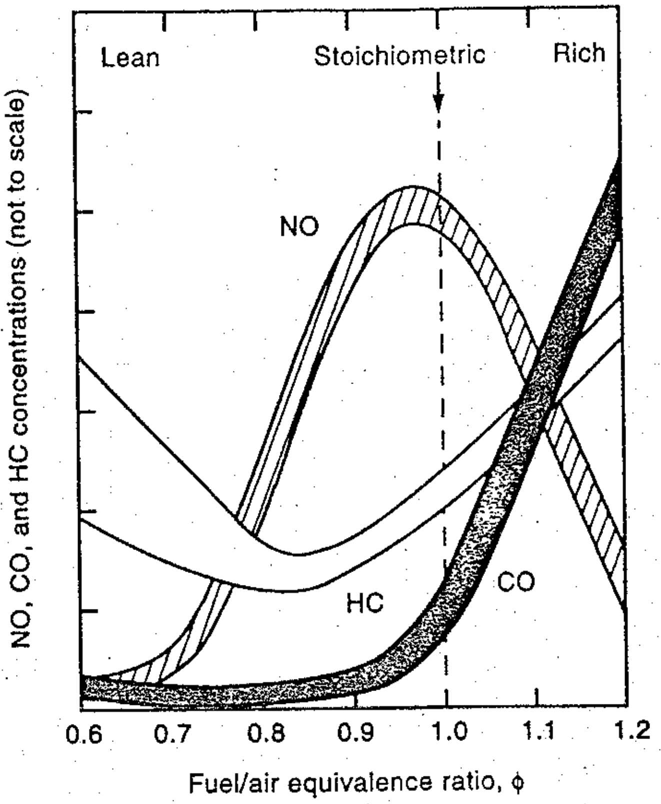


Fig. 1. Gaseous Emissions as a Function of Equivalence Ratio from a Spark-Ignited Engine

The objective of this analysis was to identify and quantify the impact of gas fuel composition on fuel metering and engine performance and emissions characteristics. This investigation was limited to the impact of the physical and chemical fuel properties which affect fuel metering and equivalence ratio. The effect of fuel composition on combustion properties (i.e., ignition delay, combustion duration, methane number, etc.) and how these affect engine performance and emissions was not examined.

METHODOLOGY

A four step approach was taken to evaluate the impact of natural gas fuel composition on fuel metering to the engine:

1) determine the variation in fuel composition in the United States and identify the key fuel

properties affected by this variation,

2) identify the types of fuel metering systems on natural gas engines and the metering characteristics of each,
3) determine the governing relationships between the fuel and air flow for the different types of fuel systems and engines, and
4) evaluate the effect of fuel composition on metered equivalence ratio and the resultant effect on engine performance and emissions.

GAS COMPOSITION VARIATION AND TEST GASES

The variability of natural gas as provided by the LDC was determined through available literature, personal contacts, and engine development experience. Sources for this information include a recently completed gas composition survey conducted by Gas Research Institute (GRI) (1), gas transportation and distribution companies, and experience with gas composition variation at the Southwest Research Institute engine research facilities and its impact on engine design and development procedures.

Results of the gas survey indicate that significant gas composition variation does exist at the LDC and is not predictable. Fuels which provided a representative cross-section of end-use natural gas blends were selected for analysis in this study. Of particular concern was the use of propane/air peak shaving and ethane/air dilution in certain areas of the U.S.A. Also investigated were atypical gas blends identified by the national gas survey which could potentially be obtained and used in an NGV.

Twelve test gases were selected for evaluation. The test gases include five gases which represent the 50, 10, 90 percentile, minimum, and maximum Wobbe Index, gases A through E, respectively; a high-energy gas with high propane and butane content, gas F; two propane/air peak shaving gases, gases G and H; a high ethane gas representative of some LNG, gas I; and pure methane, ethane, and propane, gases J, K, and L, respectively.

A partial list of fuel properties which are affected by composition is shown in Table 1. Fuel properties which affect metering characteristics and knock resistance are of primary importance to the engine and vehicle manufacturer. Knock resistance of the fuel was not addressed in this study. The test fuels, their composition, and their properties are shown in Table 2. Fuel properties were calculated using standard analytical procedures.

Combustion experiments conducted by SwRI have shown that within the limited range of LDC gas compositions found in the U.S.A., the effect of gas composition on engine power, efficiency, and emissions is small (3) at a constant equivalence ratio. The principal means by which gas composition affects engine power and emissions is through the resulting change in metered equivalence ratio to the engine.

Table 1. Fuel Properties Affected by Gas Composition

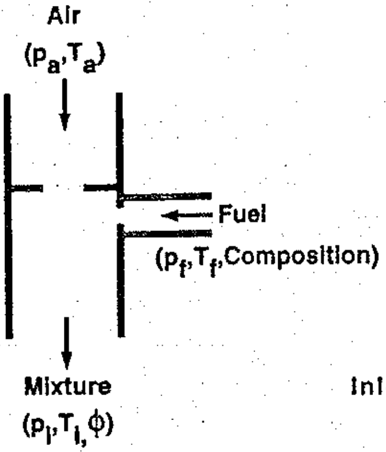
Fuel Property	Symbol
Hydrogen/Carbon Ratio	H/C (reactive, actual)
Molecular Weight	m_f
Gas Constant	R
Specific Heats	C_p, C_v
Density, Specific Gravity	ρ, SG
Heating Value	HHV, LHV
Wobbe Index	WI
Stoichiometric Fuel-Air Ratio	F_s
BTU/ft^3 of Stoichiometric Mix	Q_m
Octane Number	MON, RON
Flammability Limits	LFL, RFL

ENGINE TYPES AND FUEL METERING CHARACTERISTICS

Fuel composition affects the fuel demand of the engine and the metered orifice flow through the fuel system. The fuel demand, in terms of mass flow, is defined by the stoichiometric fuel-air ratio and the desired equivalence ratio set point, e.g., ϕ=1.005 for a stoichiometric engine and ϕ=0.68 for some lean-burn engines.

Three distinct and different methods for fuel control and introduction on natural gas engines were identified. The first is carburetion where air flow across a restriction creates a pressure drop which draws a proportional volume of fuel into the air stream. The second is fuel injection (FI) where fuel is introduced into the air stream prior to admission into the cylinder and can either be metered as choked (sonic) or unchoked flow. The third type of fuel metering is direct injection (DI) into the cylinder. The governing relationships for each fuel metering type are different.

Carburetion is by far the most common method of fuel metering used on natural gas engines today. Carburetion can take on various forms, such as a venturi in combination with a demand (zero pressure) fuel regulator, a variable venturi mixing valve, etc., but all operate using Bernoulli's principal. For carbureted engines, the volumetric air flow creates a pressure drop at the throat of a restriction which draws a



Equivalence: $$\phi = \frac{(\dot{M}_f/\dot{M}_a)}{F_s}$$ Eq. (1)

Fuel Flow: $$\dot{M}_f = Ap_f\sqrt{\frac{g_o m k}{RT_f}}\sqrt{\left(\frac{2}{k-1}\right)\left(r_p^{\left(\frac{2}{k}\right)} - r_p^{\left(\frac{k+1}{k}\right)}\right)}$$ Eq. (2)

Air Flow: $\dot{M}_a$ = Depends on Type of Fuel Metering Eq. (3)

Air Flow: $$\dot{M}_a = f\left(\rho_a, e_v, A_p, S\right)$$ Eq. (4)

Inlet Air Density: $$\rho_a = \frac{29\ p_i}{RT_i}\left(\frac{1}{1 + F_i\left(\frac{29}{m_f}\right)}\right)$$ Eq. (5)

Power: $$\text{Power} = f\left(\dot{M}_a, F_i, Q_c, \eta\right)$$ Eq. (6)

For Two Fuels; 1 and 2: $$\frac{\phi_2}{\phi_1} = \left(\frac{\dot{M}_2}{\dot{M}_1}\right)_f\left(\frac{\dot{M}_1}{\dot{M}_2}\right)_a\left(\frac{F_1}{F_2}\right)_s$$ Eq. (7)

Fig. 2. Governing Equations for Fuel Metering Model

desired equivalence ratio with the 50 percentile gas composition (gas A). Fuel properties were then varied to determine the effect of the gas composition on the metered equivalence ratio to the engine. The solutions were arrived at through iterative solving of the appropriate group of governing equations.

For the carbureted engine the air flow relationship used the same form as the fuel flow, with the orifice area (venturi) appropriately sized. The pressure at the throat of the carburetor venturi was used as the downstream pressure for the fuel flow orifice. In this manner the fuel flow was dependent on the air flow. For the fuel-injected engine, the fuel injector orifice area and supply pressure were designed for choked operation and the proper fuel flow with gas A. Air was assumed to fill the volume not filled by fuel during the fuel injection event, again given a constant volumetric efficiency. The direct-injected engine received a fixed amount of air flow based on no displacement of air in the intake manifold by fuel. The in-cylinder fuel injection event for the DI engine was assumed choked.

Power output is proportional to the mass air flow, equivalence ratio, and the fuel heating value. With these parameters known and dependent on fuel metering, the change in power output of the engine could be determined. Similarly, given well established emissions trends as shown in Fig. 1, the resultant engine-out emissions were estimated.

ANALYSIS AND RESULTS

FUEL METERING - Fuel metering analysis results are shown in Table 3. Results are presented in terms of percent change from the 50 percentile gas blend (gas A). Stated another way, the numbers shown indicate the percent change in *metered equivalence ratio* which would result if the engine was switched from gas A to the gas blend in question.

For the 10 to 90 percentile fuel blends (based on Wobbe Index) a total variation in equivalence ratio of 3.3 percent, 3.6 percent, and 3.1 percent resulted with the DI, FI, and carbureted engines, respectively. This appears to be a relatively small variation in equivalence ratio at first, but consider the narrow operating window for a three-way natural gas catalyst on a stoichiometric engine. A 0.5 percent variation, rich or lean, in equivalence ratio would result in significantly reduced catalyst efficiency and high catalyst-out exhaust emissions. For a lean-burn engine this small metering variation could result in high unburned hydrocarbon emissions due to a lean mixture, or an increase in NO_x emissions due to a rich mixture.

The largest lean deviation from the median gas

Table 2. Natural Gas Fuel Blends and Properties

Constituent (mole percent)	**Gas A**	**Gas B**	**Gas C**	**Gas D**	**Gas E**	**Gas F**	**Gas G**	**Gas H**	**Gas I**	**Gas J**	**Gas K**	**Gas L**
Methane	94.2	88.7	95.3	75.8	90.0	84.2	65.1	46.5	89.0	100.0	0.0	0.0
Ethane	2.8	4.7	2.6	11.2	4.9	8.6	2.2	1.6	11.0	0.0	100.0	0.0
Propane	0.6	1.3	0.5	0.9	2.2	3.7	16.4	28.7	0.0	0.0	0.0	100.0
Butane	0.1	0.4	0.2	0.1	1.1	2.1	0.3	0.2	0.0	0.0	0.0	0.0
Pentane	0.1	0.1	0.1	0.0	0.4	0.0	0.1	0.1	0.0	0.0	0.0	0.0
Hexane	0.0	0.1	0.1	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	0.7	0.7	0.8	2.8	0.7	0.6	0.5	0.4	0.0	0.0	0.0	0.0
Nitrogen	1.5	4.0	0.4	6.9	0.3	0.8	12.3	18.0	0.0	0.0	0.0	0.0
Oxygen	0.0	0.0	0.0	2.3	0.0	0.0	3.0	4.5	0.0	0.0	0.0	0.0
Gas Properties												
H/C Ratio	3.88	3.80	3.87	3.64	3.69	3.61	3.38	3.11	3.80	4.00	3.00	2.67
m_f	17.11	18.04	17.02	19.88	18.63	19.44	23.28	27.47	17.59	16.04	30.07	44.10
$(A/F)_{st}$	16.41	15.67	16.65	13.48	16.56	16.39	13.07	12.07	17.02	17.24	16.09	15.68
HHV (BTU/ft^3)	1024	1031	1033	989	1124	1161	1123	1230	1092	1008	1767	2514
Specific Gravity	0.593	0.625	0.589	0.689	0.645	0.673	0.806	0.951	0.609	0.556	1.041	1.527
Wobbe Index	1330	1304	1345	1192	1400	1415	1251	1261	1399	1353	1731	2035
(Q_m) (BTU/ft^3 mix)	95.7	95.8	95.8	96.4	96.5	96.8	97.6	98.8	96.3	95.6	99.8	101.1
ρ_a/ρ_i at F_s (air=1)	0.906	0.907	0.907	0.902	0.914	0.917	0.913	0.920	0.912	0.905	0.943	0.960

proportional volume of fuel into the air stream. The air and fuel flows are unchoked (subsonic). In this system the fuel flow is *dependent* on the air flow and the total volume flow rate to the engine is constant for a given speed and load since volumetric efficiency is constant.

Natural gas engines which operate with a premixed FI are currently under development by many companies. In a fuel-injected engine the fuel is metered based on predetermined engine operating conditions, such as engine speed, intake manifold pressure, and throttle position, and can be controlled mechanically or electronically. Fuel flow is therefore dependent on a known calibration of the engine and is *independent* of air flow. The fuel-air ratio can vary; however, the total volume flow of mixture must remain constant, since the volumetric efficiency of an engine is constant for a fixed speed and load, as with the carbureted engine. It follows then that the air flow is *dependent* on the fuel flow, and as the fuel flow varies at fixed operating conditions so must the air flow. This is true for both choked (sonic) and unchoked fuel flow conditions.

For the direct-injected engine the fuel flow is *independent* of the air flow. The fuel flow is also necessarily choked since high fuel pressure is needed to inject the fuel in the small time interval available for the injection event.

In the direct-injected engine the air flow is also *independent* of fuel flow, since the cylinder inducts and traps only air prior to the injection event. For this study it is assumed that the fuel is injected after the intake valve is closed.

GOVERNING RELATIONSHIPS FOR FUEL AND AIR METERING

The purpose of this study was to determine the impact of fuel composition on fuel metering and engine operational characteristics. To accomplish this objective calculations were performed and results presented in terms of percent change in equivalence ratio relative to a median gas composition. In addition to the fuel metering effects, this technique allowed the emissions characteristics of the engine to be quite accurately estimated.

Consider the simplified fuel-air mixing device shown in Fig. 2. The air is supplied at a constant pressure (p_a) and temperature (T_a), and the fuel at a constant pressure (p_f), temperature (T_f), and known composition. The inlet pressure (p_i) is less than p_a and p_f resulting in flow of air and fuel into the inlet system. The air orifice (venturi) and the fuel orifice are fixed and sized to provide the desired fuel-air mixture ratio.

A computer model was developed to simulate carbureted, fuel-injected, and direct-injected fuel metering configurations based on the described fuel-air mixing device. The governing relationships for air and fuel metering are shown in Fig. 2 (6). Definitions and descriptions of symbols are shown in Appendix A. Air and fuel were considered to be ideal, compressible fluids. Input variables to the model include fuel properties, fuel pressure and temperature, air pressure and temperature, intake manifold pressure, volumetric efficiency, thermal efficiency, swept volume, and piston speed. The model was calibrated to provide the

Table 3. Fuel Metering Results for Representative Gas Compositions

Effect	Gas A	Gas B	Gas C	Gas D	Gas E	Gas F	Gas G	Gas H	Gas I	Gas J	Gas K	Gas L
% Change in ϕ Direct Injection	--	-2.14	1.14	-11.7	4.56	5.44	-8.25	-8.74	4.73	1.97	25.4	45.7
% Change in ϕ FI Premix	--	-2.42	1.17	-12.4	4.05	4.67	-9.68	-10.8	4.54	2.34	22.0	39.8
% Change in ϕ Carburetion	--	-1.97	1.16	-11.5	5.16	6.32	-7.25	-7.07	5.10	1.73	29.4	52.3
% Change in Wobbe Index	--	-1.95	1.13	-10.4	5.19	6.39	-5.94	-5.19	5.19	1.73	30.2	53.0

mixture was 12.4 percent for the FI engine using gas D. The largest rich deviation was 6.3 percent for the carbureted engine using gas F. Gas D is representative of gas composition found in Denver and gas F was pipeline gas supplied by the LDC to the engine laboratory at SwRI. Gases K and L, which are pure ethane and propane, were excluded from this comparison since they are not representative of end-use gas blends. They are included in the table for reference purposes only.

WOBBE INDEX - Table 3 shows a close relationship between the change in Wobbe Index and the change in metered equivalence ratio. Fig. 3 graphically shows this relationship. It can be shown that for two gaseous fuels; 1 and 2, of pure hydrocarbon blends (no inerts) where Δp, A_o, and $\dot{M}_a$ are constant

$$\frac{\phi_1}{\phi_2} = \frac{WI_1}{WI_2} \qquad \text{Eq. (8)}$$

Eq. (8) shows that the change in metered equivalence ratio between two pure hydrocarbon fuels is equal to the change in Wobbe Index between the fuels. Klimstra reported similar results for carbureted natural gas engines (7). The derivation of the relationship between the metered equivalence ratio and the Wobbe Index is shown in Appendix B. For illustration purposes the derivation was simplified using incompressible fluid and ideal flow equations. This relationship assumes the product of Q_cF_s is constant which is approximately true for common hydrocarbon fuels. Deviation from the linear relationship is caused by the presence of inerts in the natural gas fuel blends. This deviation is most pronounced for gases G and H which are peakshaving gases with high levels of propane and air. In actuality the fuel Δp will remain constant only for unchoked fuel flow conditions, since r_p for sonic fuel flow is dependent on composition, and $\dot{M}_a$ is not constant except for the direct-injected engine configuration.

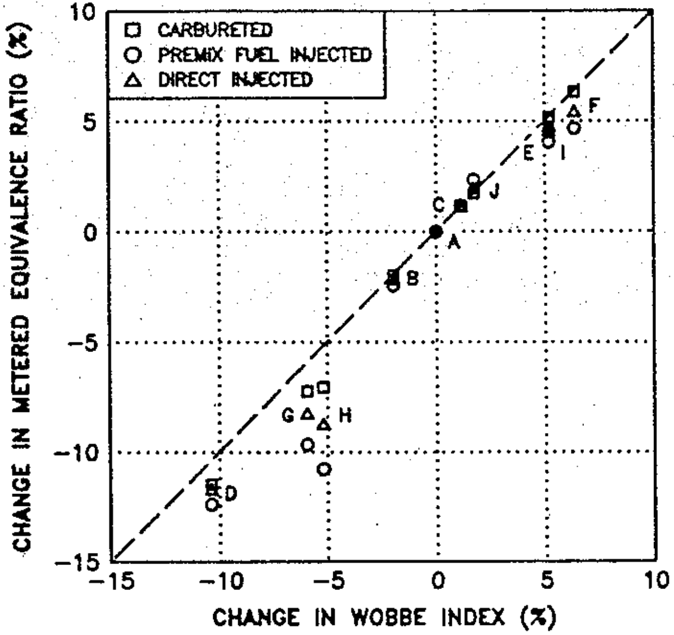


Fig. 3. Relationship Between Wobbe Index and Metered Equivalence Ratio

Fig. 4 shows the stoichiometric air requirement for various gaseous hydrocarbon fuels and select natural gas blends studied in this investigation. From this graph it is evident that for common hydrocarbon fuels there exists a relationship between the theoretical amount of air required for complete combustion and the volumetric heating value. Given this relationship, the combustion energy per unit volume of air is nearly constant for common hydrocarbon fuels.

POWER - Power output of an engine is directly proportional to the mass air flow to the engine, heat energy released per unit mass of air, and fuel-air cycle efficiency, Fig. 2, Eq. (6), and is therefore affected by

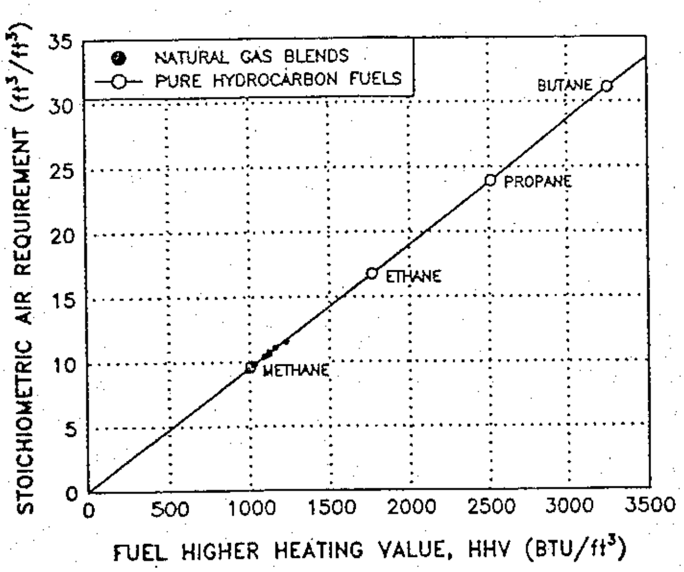


Fig. 4. Air Requirement for Various Gaseous Fuels at Stoichiometry

fuel composition. Mass air flow is proportional to air density Eq. (4). Inlet mixtures obey Dalton's law of partial pressures, thus inlet *air density* varies according to the relationship shown in Eq. (5). A fuel with a low molecular weight will occupy a larger percentage of the inlet mixture volume than a fuel with a high molecular weight at a constant fuel-air ratio.

Fig. 5 shows the effect of molecular weight on air capacity of an engine relative to methane at constant equivalence ratio. The air capacity of the natural gas fuel blends investigated in this study are shown in Table 2. The combined effect from a change in metered equivalence ratio, molecular weight, and stoichiometric fuel-air ratio can result in a dramatic power increase, or decrease, depending on the initial equivalence ratio of the engine. A change in fuel-air ratio has a directly proportional impact on the power and is by far the dominating factor affecting power. The change in the mixture volume occupied by the fuel has a smaller secondary effect.

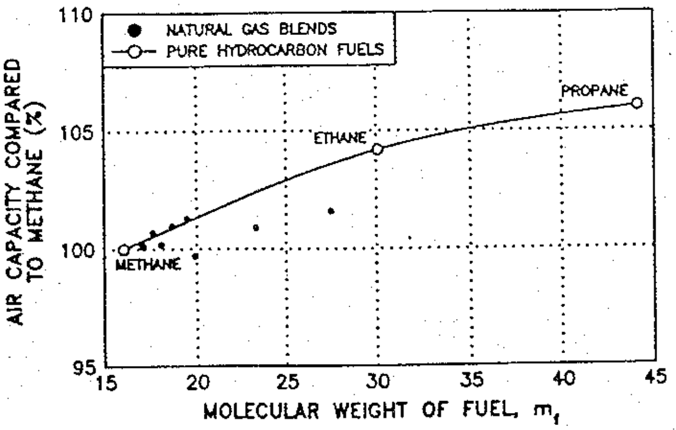


Fig. 5. Effect of Fuel Molecular Weight on Air Capacity for a Stoichiometric Mixture

Thermodynamic fuel-air cycle efficiency, η, is increased as a mixture is leaned. The change in theoretical fuel-air cycle efficiency can be significant and must be considered for large changes in equivalence ratio. For example, a change in equivalence ratio from 0.8 to 1.0 for a 10:1 compression ratio engine would result in a 4.8 percent drop in fuel-air cycle efficiency. Appendix C shows the relationship between efficiency and equivalence ratio for a constant volume fuel-air cycle.

EMISSIONS - Exhaust emissions from a spark-ignited internal combustion engine were previously shown to be dependent on equivalence ratio (Fig. 1). Since a change in fuel composition has been shown to change the equivalence ratio it follows that the emissions will also change. To illustrate the magnitude of these emissions changes consider the data shown in Table 4. Gases A, B, C, D, and E were selected for this analysis and are shown along with the resulting equivalence ratio and brake specific emissions for a

Table 4. Effect of Fuel Composition on Emissions of a Lean-Burn Natural Gas Engine

	Gas A	Gas B	Gas C	Gas D	Gas E
Wobbe Index	1330	1304	1345	1192	1400
Equivalence Ratio, FI	0.680	0.664	0.688	0.596	0.708
Change in Equivalence Ratio (%)	--	-2.42	1.17	-12.4	4.05
NO_x (g/hp-hr)	3.0	2.1	3.6	0.4	5.2
THC (g/hp-hr)	1.3	1.6	1.1	11.8	0.9
CO (g/hp-hr)	1.5	1.6	1.4	2.9	1.3

typical lean-burn natural gas engine. Brake specific emissions were obtained from Fig. 6 and are emissions trends from a representative open chamber lean-burn natural gas engine. While all emissions are affected to some degree, of particular interest are the NO_x emissions from gas E and the hydrocarbon emissions from gas D. As the equivalence ratio increased from 0.680 to 0.708 with gas E, NO_x emissions increased from 3.0 to 5.2 g/hp-hr, a 73 percent increase. Similarly, the equivalence ratio of 0.596 resulting from gas D is near the lean-flammability-limit for most combustion systems and produced an 800 percent increase in unburned hydrocarbon emissions.

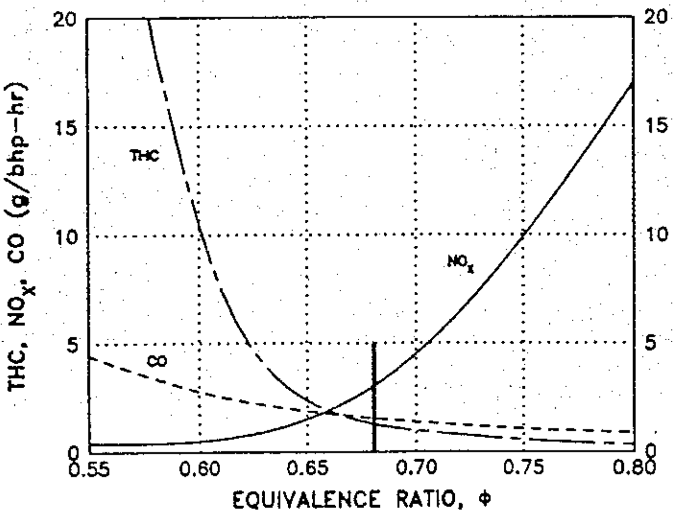


Fig. 6. Lean-Burn Gas Engine Emissions (Constant Speed, Full-Load)

For a stoichiometric engine that relies on a three-way catalyst for emissions control the metering effect is even more pronounced than for lean-burn engines. The change in equivalence ratio affects not only engine-out emissions, but moves the mixture outside the high-efficiency operating window of the catalyst significantly reducing oxidation/reduction performance.

ENGINE OPERATIONAL CHARACTERISTICS- Fuel metering inaccuracies can have a dramatic, and sometimes catastrophic effect on lean-burn engine operation. Today's lean-burn engines are turbocharged to achieve high power and thermal efficiency, approaching that of a diesel. To achieve such good performance the engines are operated very lean, as lean as ϕ=0.60, with boost pressures up to 25 psi. Under these operating conditions a lean-burn engine is very sensitive to mixture strength and spark timing.

An increase in equivalence ratio in a turbocharged lean-burn engine has a twofold effect. First, it provides additional heat energy to the engine so power is increased for a constant boost level. Second, the added heat energy increases the available exhaust energy which tends to increase boost pressure. Provided the turbocharger system has sufficient control capability, boost pressure can be maintained. In some instances the wastegate control may have insufficient flow capacity to bypass the excess exhaust energy and the boost increases above safe limits. In this situation the increased boost means additional mass air flow to the engine accompanied by still more fuel. This is an unstable condition which can build upon itself until the air flow is restricted, the fuel flow is restricted, or an engine failure occurs.

Rich mixtures are more prone to detonate than lean mixtures and the engines are typically designed with little margin from knock to provide optimum performance. Unfortunately, the fuel compositions which cause rich fuel metering conditions also have increased amounts of heavy hydrocarbons which lower the octane of the fuel making detonation even more likely to occur.

Stoichiometric engines do not experience the same excess power and detonation problems as described for lean-burn engines. Most are not turbocharged and richening or leaning the fuel mixture from stoichiometry will result in loss of power. Stoichiometric fuel-air mixtures are more prone to detonate than rich or lean mixtures due to higher flame speeds and higher combustion temperatures, so detonation is not a problem when metering inaccuracies are introduced.

RELATED FUEL METERING AND COMPOSITION ISSUES

LEAN-FLAMMABILITY-LIMIT - Fuel composition affects the lean-flammability-limit (LFL) of a fuel-air mixture. The LFL can be determined for standard atmospheric conditions using Le Chatelier's procedure (8). An increase in hydrocarbon emissions at very lean equivalence ratios is indicative of the fact that the LFL is being approached and flame quenching is occurring. The LFL of gases A through E were calculated and are shown in Table 5. Note the LFL equivalence ratio and the metered equivalence ratio for the same gases as determined previously. For gases A, B, C, and E there exists a significant margin from the LFL after the change to the new fuel. However, for gas D the metered equivalence ratio is below the LFL resulting in unstable combustion, engine misfire, and extremely high unburned hydrocarbon emissions.

EQUIVALENCE RATIO CONTROL - The combination of the change in fuel metering and the change in LFL with fuel composition illustrates the importance of accurate fuel control for natural gas engines. A fuel composition sensor could provide

Table 5. Lean-Flammability Limits of Gaseous Fuels

	Gas A	Gas B	Gas C	Gas D	Gas E
LFL of Fuel by Volume* (%)	5.25	5.31	5.22	6.11	4.74
LFL of Fuel by Mass (%)	3.18	3.38	3.14	4.29	3.11
LFL Air-Fuel Ratio	30.5	28.5	30.8	22.3	31.0
LFL ϕ	0.539	0.549	0.540	0.604	0.530
Change in LFL ϕ (%)	--	1.9	0.2	12.1	-1.7
Metered ϕ, FI	0.680	0.664	0.688	0.596	0.708
Margin from LFL (%)	31	25	32	0	38

*From Le Chatelier's Formula.

feed-forward gas data to better predict the metering characteristics of the fuel system, however, feedback control would still be required to "trim" the fuel system for accurate fuel metering. At the time of this writing, there were no commercially available natural gas sensors suitable for service on a vehicle.

The preferred method to provide adaptability to varying fuel composition on lean-burn engines is through feedback with a universal exhaust gas oxygen (UEGO) sensor. Test results from an oxygen sensor evaluation (9) show that the UEGO sensor provides the needed performance (accuracy, response, sensitivity, and repeatability) to function as a feedback sensor for lean-burn natural gas engines.

Fig. 7 shows the effect of fuel composition on theoretical oxygen concentration in the exhaust. The variation in hydrogen/carbon ratio of common end-use gas blends is small (3.11 to 3.88). This results in less than a 0.05 variation in the free exhaust oxygen concentration at a fixed equivalence ratio, thus making oxygen a suitable parameter for feedback control. Currently the availability of this type sensor is limited and the cost is high, but market demand should bring the cost to acceptable levels as the need develops. For stoichiometric engines, zirconia and titania oxide oxygen sensors provide acceptable switching characteristics for adequate closed-loop control.

Lean-burn engines often vary the operating equivalence ratio to shape their torque curve. With varying equivalence ratios it is necessary to account for the change in inlet air volume displaced by the fuel to achieve accurate fuel-air mixture control. Electronic control systems should employ use of the equations in Fig. 2 for this purpose.

FUEL TEMPERATURE EFFECTS - The effect of inlet air temperature on carbureted gasoline engine performance is well understood. The temperature of the gasoline as it is metered through the carburetor has a negligible effect on the fuel metering accuracy since the density change is small. With natural gas the situation is quite different and fuel temperature must be considered when operating a carbureted natural gas engine with varying ambient conditions.

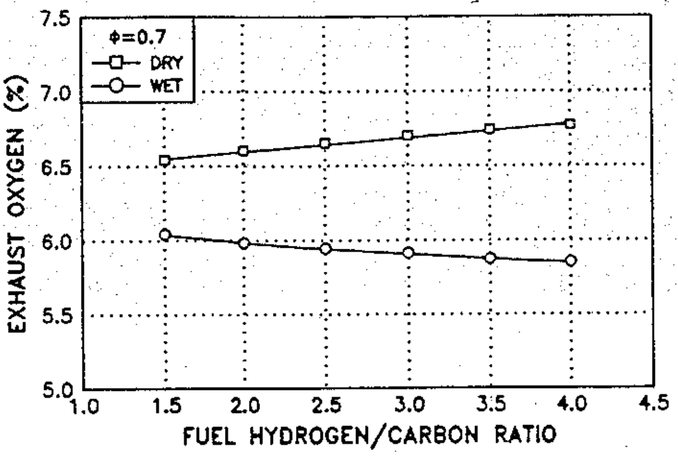


Fig. 7. Effect of Fuel Composition on Exhaust Oxygen Concentration at Constant Equivalence Ratio

The fuel metering model was used to analyze the effect of fuel and air temperature on metering characteristics. Fig. 8 shows the relationship between inlet air and fuel supply temperatures, and how these temperatures affect the metered equivalence ratio to the engine. Provided the fuel and air temperature are equal the temperature can be varied and it will not affect the equivalence ratio. However, significant variations can occur if the fuel and air temperature are allowed to deviate from one another. An example of such a circumstance would be the application of a

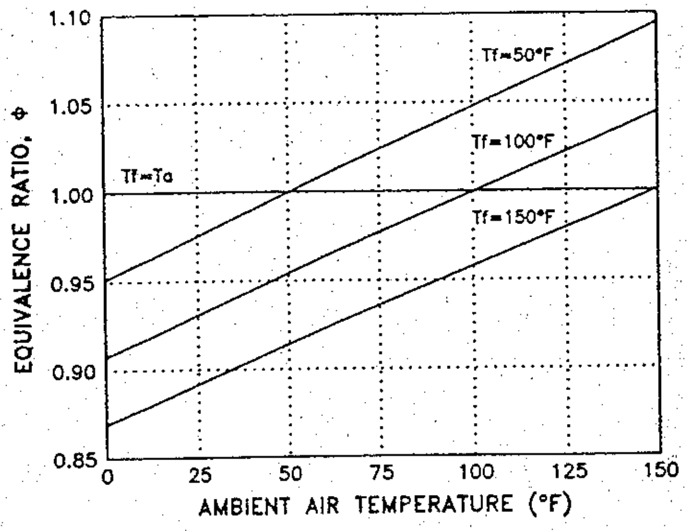


Fig. 8. Effect of Air and Fuel Temperature on Carbureted Equivalence Ratio

turbocharged non-aftercooled engine in a compressed natural gas vehicle. Under high load conditions at high boost levels the intake air temperature can be quite high (250° - 300°F). At the same time the fuel temperature can be below ambient due to expansion cooling of the compressed gas through the regulators. The result is hot inlet air and cold fuel, and large variations in equivalence ratio (over 10 percent) are possible. It is anticipated that electronically-controlled engines will have temperature and pressure compensation to eliminate metering inaccuracies resulting from variations in air and fuel supply conditions.

CONCLUSIONS

Based on results from this fuel metering investigation the following conclusions can be made:

1. The composition of end-use natural gas available for use in natural gas vehicles varies significantly in the U.S.A. This composition variation is not predictable. The impact of this variation must be understood and controlled to provide safe and reliable NGV operation.

2. A fuel metering model was developed to simulate fuel metering characteristics of a natural gas-fueled engine. Fuel properties of representative end-use gas blends were used to evaluate the impact of fuel composition on engine operating characteristics. Three fuel system configurations were evaluated: carburetion, fuel injection, and direct injection. Variations in metering performance do exist between the metering types. Results indicate that equivalence ratio variations of 12 percent lean and 6 percent rich from a median gas composition are possible with current pipeline quality gas blends.

3. The Wobbe Index was identified as a parameter which can be used to approximate the metering performance of two fuels. The change in metered equivalence ratio between two fuels can be closely approximated by the corresponding change in Wobbe Index between the two fuels.

4. Fuel composition affects the lean-flammability-limit of the fuel-air mixture. When combined with the fuel metering variations, the change in LFL can result in combustion instability and misfire in a lean-burn engine.

5. The oxygen concentration in the exhaust is a function of the equivalence ratio and is the key to accurate fuel control for stoichiometric and lean-burn natural gas engines. Fuel composition has a negligible effect on the oxygen concentration in the exhaust at a fixed equivalence ratio. The UEGO sensor provides the desired feedback characteristics for closed-loop adaptive control of a lean-burn engine.

6. Fuel temperature variations can cause significant fuel metering variations on carbureted natural gas engines. Equivalence ratio variations of more than 10 percent are possible with fuel temperature swings of 100°F. The solution is to maintain the fuel and air supply temperatures equal, or at least fixed relative to one another.

ACKNOWLEDGMENTS

The author would like to acknowledge Charles Wood and David Meyers of SwRI, and William Liss of GRI, for their support during the course of this investigation.

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APPENDIX A

SYMBOLS AND DESCRIPTIONS

Symbol	Description	Dimension
A	area	L^2
C_p	specific heat at constant pressure	$QM^{-1}\theta^{-1}$
C_v	specific heat at constant volume	$QM^{-1}\theta^{-1}$
e_v	volumetric efficiency	1
F_i	inlet fuel-air ratio	1
F_s	stoichiometric fuel-air ratio	1
g_o	force-mass-acceleration coefficient	$MLt^{-2}F^{-1}$
H/C	hydrogen-carbon ratio of fuel	1
HHV	higher heating value of fuel at STP	QL^{-3}
k	specific heat ratio, C_p/C_v	1
K	coefficient or constant	1
LFL	lean-flammability-limit	1
LHV	lower heating value of fuel at STP	QL^{-3}
m	molecular weight	1
m_f	molecular weight of fuel	1
$\dot{M}_a$	mass air flow rate	Mt^{-1}
$\dot{M}_f$	mass fuel flow rate	Mt^{-1}
MON	motor octane number	1
p_a	absolute air pressure	FL^{-2}
p_f	absolute fuel pressure	FL^{-2}
p_i	absolute inlet pressure	FL^{-2}
Δp	pressure differential	FL^{-2}
$\dot{q}$	volume flow rate	L^3t^{-1}
Q	quantity of heat	Q
Q_c	heat of combustion per unit mass	QM^{-1}
Q_v	heat of combustion per unit volume	QL^{-3}
Q_m	heat combustion of stoichiometric mixture per unit volume at STP	QL^{-3}
r_p	absolute pressure ratio	1
R	universal gas constant	$FL\theta^{-1}M^{-1}$
RFL	rich-flammability-limit	1
RON	research octane number	1
S	piston speed	Lt^{-1}
SG	specific gravity	1
STP	standard temperature and pressure	1
T_a	absolute air temperature	T
T_f	absolute fuel temperature	T
T_i	absolute inlet temperature	T
WI	Wobbe Index	Q
η	efficiency	1
ρ	density	ML^{-3}
ϕ	equivalence ratio	1

APPENDIX B

RELATIONSHIP BETWEEN WOBBE INDEX AND METERED EQUIVALENCE RATIO

For a gaseous fuel metered through an orifice the volume flow rate (incompressible, ideal flow) is:

$$\dot{q}_f = A_o \sqrt{\frac{2\Delta p}{\rho_f}} \qquad \text{Eq. (B1)}$$

The energy flow rate provided by this fuel is:

$$\dot{q}_f\, Q_v = A_o\, Q_v \sqrt{\frac{2\Delta p}{\rho_f}} \qquad \text{Eq. (B2)}$$

By definition:

$$WI = \frac{Q_v}{\sqrt{SG_f}} = Q_v \left(\frac{\sqrt{\rho_{a,STP}}}{\sqrt{\rho_f}}\right) \qquad \text{Eq. (B3)}$$

Substituting for Q_v in Eq. B2 gives:

$$\dot{q}_f\, Q_v = A_o \sqrt{2\Delta p}\, (WI) \left(\frac{1}{\sqrt{\rho_{a,STP}}}\right) \qquad \text{Eq. (B4)}$$

The fuel-air ratio is:

$$F_i = \frac{\dot{M}_f}{\dot{M}_a} = \frac{\dot{q}_f\, \rho_f}{\dot{M}_a} \qquad \text{Eq. (B5)}$$

The equivalence ratio is:

$$\phi = \frac{F_l}{F_s} = \frac{\dot{q}_f\,\rho_f}{\dot{M}_a}\left(\frac{1}{F_s}\right) \qquad \text{Eq. (B6)}$$

Substituting for $\dot{q}_f$ from Eq. B4:

$$\phi = \frac{A_o\sqrt{2\Delta P}\,(Wl)}{\sqrt{\rho_{a,STP}}\,Q_v}\left(\frac{\rho_f}{\dot{M}_a}\right)\frac{1}{F_s} \qquad \text{Eq. (B7)}$$

since

$$Q_v = Q_c\,\rho_f \qquad \text{Eq. (B8)}$$

then

$$\phi = \frac{A_o\sqrt{2\Delta p}}{\sqrt{\rho_{a,STP}}\,\dot{M}_a}\left(\frac{Wl}{Q_c\,F_s}\right) \qquad \text{Eq. (B9)}$$

For two fuels; 1 and 2, where Δp, A_o, and $\dot{M}_a$ are constant:

$$\frac{\phi_1}{\phi_2} = \frac{Wl_1}{Wl_2}\,\frac{(Q_c\,F_s)_2}{(Q_c\,F_s)_1} \qquad \text{Eq. (B10)}$$

(Q_cF_s) is nearly constant for common hydrocarbon fuels of interest, therefore

$$\frac{\phi_1}{\phi_2} = \frac{Wl_1}{Wl_2} \qquad \text{Eq. (B11)}$$

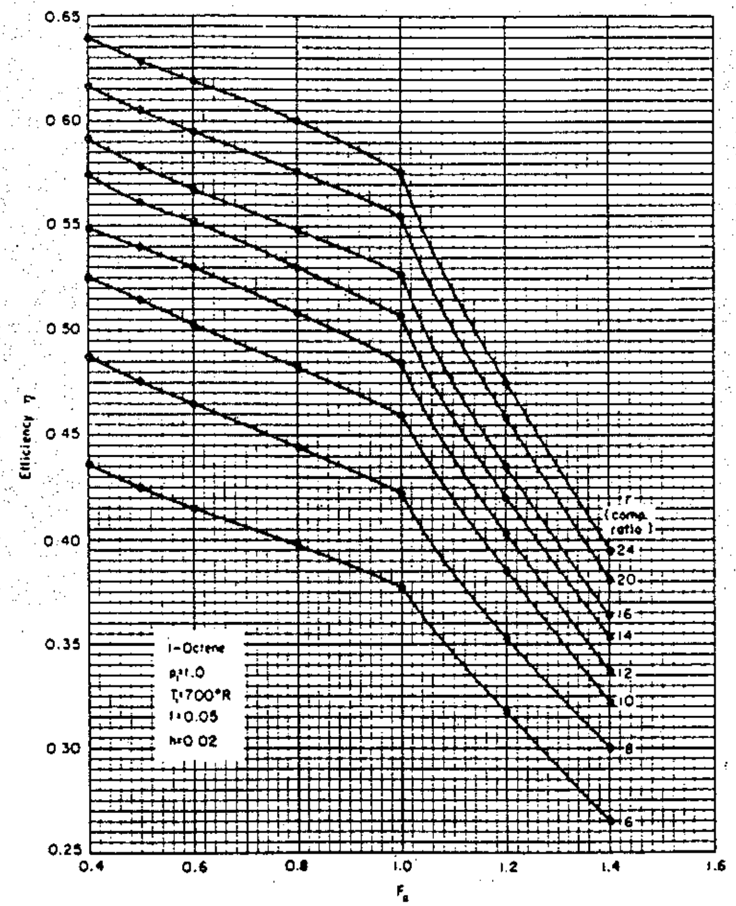
and

$$\frac{\Delta\phi}{\phi} = \frac{\Delta Wl}{Wl} \qquad \text{Eq. (B12)}$$

APPENDIX C

EFFICIENCY VERSUS ϕ FOR CONSTANT VOLUME FUEL-AIR CYCLE

Source: Reference (6)



California
Natural Gas Vehicle
Coalition

September 16, 1994

Mr Dean Simeroth
Branch Chief
California Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

Dear Mr. Simeroth:

Re: Amendment to Oxygen Content Range for CNG Certification Fuel

The California NGV Coalition wishes to be on record as supporting ARB's proposed amendment to the subject certification specification for CNG, scheduled for approval by the Board on September 22, 1994. As staff's work has revealed, this amendment will make the process of blending CNG "cert" fuel safer and -- we hope -- less costly, without adversely impacting the validity of the certification test itself.

The Coalition represents a membership of California CNG suppliers including PG&E, SoCalGas, SDG&E and the City of Long Beach Gas Department.

Very truly yours,

Gregory E Vlasek

Gregory E. Vlasek
Executive Director

cc: Brian Stokes, PG&E
Jennifer Sansone, SDG&E
Andrew Hirsch, SoCalGas
Paul Smock, Long Beach Gas

925 L Street, Suite 1485 • Sacramento, CA 95814
(916) 448-5036 • (916) 448-5732 Fax