THE EFFICIENT USE OF NATURAL GAS IN TRANSPORTATION

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INTRODUCTION

Concerns over air quality and greenhouse gas emissions have prompted discussion as well as action on alternative fuels and energy efficiency. Natural gas and natural gas derived fuels and fuel additives are prime alternative fuel candidates for the transportation sector. The Clean Fuel Vehicle provisions of the Clean Air Act of 1990 (CAA) set the stage for "clean alternative fuels" from natural gas, such as compressed natural gas (CNG), liquified natural gas (LNG), methanol, and liquified petroleum gas (LPG). Methyl tertiary butyl ether (MTBE) is a popular gasoline additive used to lower Reid Vapor Pressure (RVP) to comply with the oxygenate requirements of the CAA. Currently, most MTBE capacity has been met by captive refinery plants using existing isobutylene streams and butanes from fluid catalytic cracking units in petroleum refineries (Unzelman 1991). However, there is growing evidence that additional capacity will be met by natural gas-derived butanes, as suggested by construction of new MTBE facilities at major gas fields (New Fuels Report 1990). Alkylate is another low RVP, high octane blending component which can be derived from natural gas-derived butanes.

It has been argued by C. Marchetti of the International Institute of Applied Systems Analysis and D. Santini of Argonne that natural gas will be the next dominant world fuel (Santini et al. 1989). During most of the 1980s rates of gas discoveries exceeded those of crude oil, as noted by Santini et al. (1989). If this prediction turns out to be true, natural gas will be the feedstock for much of transportation. This paper examines what the natural gas-based fuel might become.

APPROACH

In this study, we reexamine and add to past work on energy efficiency and greenhouse gas emissions of natural gas fuels for transportation (DeLuchi 1991, Santini et al. 1989, Ho and Renner 1990, Unnasch et al. 1989). We add to past work by looking at MTBE (from natural gas and butane component of natural gas), alkylate (from natural gas butanes), and gasoline from natural gas. We also reexamine CNG, LPG, LNG, and methanol based on our analysis of vehicle efficiency potential. We compare the results against nonoxygenated gasoline.

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We obtained from the literature estimates of extraction, refining, and distribution efficiency for CNG, LNG, LPG, methanol, and baseline gasoline. We obtained an average efficiency of the natural gas-to-gasoline pathway for the Shell Middle Distillate Synthesis (SMDS) process (van der Burgt et al. 1989). From discussions with and information from refinery equipment manufacturers, we constructed a hypothetical natural gas-to-MTBE pathway (Wilcher 1991). Similarly, we constructed a hypothetical natural gas butane-to-alkylate pathway (Wilcher 1991). For the MTBE and alkylate pathways, we considered the path of a "parcel" of original natural gas taken from extraction at the well to blending with crude oil-derived gasoline and finally to combustion in a vehicle. The combustion of both MTBE and alkylate would occur at that efficiency obtained by the vehicle burning the mixture of gasoline and the natural gas-derived component. For pathways that do not utilize the entire natural gas stream, such as the LPG (using propane and butane only) and alkylate pathway (using butane only), we assume the balance of the natural gas components (mainly methane) would more than likely be converted at higher efficiencies compared to internal combustion engined vehicles if used in industrial/commercial/residential space heating or industrial cogeneration applications. Therefore, we did not investigate the pathway of these other components.

We considered passenger cars only. Two vehicle cases were considered: (1) constant performance acceleration vehicles; and (2) constant range vehicles (defined below). Finally, we compare the overall ("feedstock to tailpipe") efficiency of each natural gas fuel with baseline gasoline.

For each pathway, we estimated emissions and the warming effects of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), three major greenhouse gases. We used the preliminary warming indices for CH_4 and N_20 at the 20 year and 100 year time horizons developed in 1990 by the Intergovernmental Panel on Climate Change (IPCC) (Renner and Santini 1991). For CH_4, we used a 20-year warming index of 63, and a 100-year warming index of 21. For N_2O, we used a 20-year warming index of 270, and a 100-year warming index of 290. We did not consider warming effects beyond 100 years. Renner and Santini (1991) observed that a very large percentage of the cumulative warming effects due to CH_4 emissions occur in the first few decades. Renner and Santini also estimated that the discounting of economic damage over time implies the warming effects beyond a century has very little influence on average warming effects.

There are some differences between this analysis and the others mentioned above that are worth noting. Unnasch et al. 1989 argues that natural gas fuels could be produced from natural gas currently being flared, and this would greatly reduce greenhouse gas emissions. His study shows CNG and methanol from currently wasted gas is superior in reducing greenhouse gas emissions over crude oil-derived gasoline. Santini et al. (1989) supports Unnasch's findings in part by suggesting that for the short-term, using currently vented and flared natural gas for reinjection or transportation far outweighs global warming reduction opportunities available through substitution of one natural-gas-based fuel for another. However, they estimate that the elimination of flaring and venting could only substitute for a small percentage of potential alternative fuel energy needs. As reported by Ho and Renner (1990), worldwide gas being flared has been reduced by 70% since 1978, and what remains is unlikely to be a major feedstock source due to geographic and economic hurdles. Because this analysis focuses on longer term (year 2010 and beyond) applications for natural gas based fuels, we assumed venting and flaring of natural gas and crude oil production occurs as calculated by Ho and Renner (1990). However, for comparison, we also show the impact of eliminating all venting and flaring for each pathway.

We did not consider emissions attributable to vehicle manufacture. Differences in these emissions are negligible when considering the fuels investigated here.

We did not look at the effects of additional criteria pollutants (NO_X, CO, and nonmethane hydrocarbons). For example, we did not examine NO_x emissions resulting from high compression ratios. We assumed that each dedicated vehicle was designed to meet the same emission standards for criteria pollutants so these emissions would not cause differences among the fuels examined. We did not consider the potential benefits of lower sulfur and nitrogen from natural gas derived gasoline (van der Burgt et al. 1989). Nor did we consider the economics and fuel distribution logistics. Consideration of geographical distribution of natural gas and crude oil resources and associated economics could significantly alter the conclusions reached in this study. Fuel shipping distances can have an important effect, especially when remote feedstock locations compete with domestic supplies.

Fuel Process

Generalized MTBE, alkylate, and natural gas-derived gasoline process flows are illustrated in Figure 1. Table 1 shows the energy efficiency for feedstock to fuel, vehicle efficiency, and overall (fuel and vehicle) efficiency. Energy efficiency of transforming feedstock to fuel (feedstock production and transport, preparation, conversion/refining, and fuel transport and distribution) is shown in the top section of Table 1. Process details and assumptions for CNG, LPG, methanol, and gasoline extraction and production are described in detail in Ho and Renner (1990) and DeLuchi (1991). For simplicity, we used the average of the Ho and Renner conversion/refining estimates for advanced and base technologies.

We assume MTBE is made from natural gas butanes and natural-gas-derived methanol. First, field butanes with an assumed composition of 70% n-butane and 30% isobutane is isomerized to yield 95% isobutane. An energy efficiency of 86% (product energy divided by the sum of feedstock energy and process energy) was calculated by the authors based on generic process efficiencies and yields obtained from UOP for their Butamer process (Wilcher 1991). The isobutane is dehydrogenated to isobutylene assuming generic process efficiencies and yields of the UOP Oleflex process (Hydrocarbon Processing 1991). The energy efficiency of natural gas to methanol via steam reforming to produce synthesis gas (syngas) and subsequent methanol synthesis is assumed to be 70% based on the average conversion/refining data presented in Ho and Renner (1990). The energy efficiency of the MTBE plant, utilizing the isobutylene and methanol feedstocks, was estimated to be 93%, based on generic process efficiencies and yields of the UOP Ethermax process (Wilcher 1991). Approximately 80% (vol) isobutylene and 34% (vol) methanol yields 100% (vol) MTBE, which results in a calculated process energy efficiency of 76% (excluding natural gas production and transport, and fuel product transport and distribution efficiencies). We assume the MTBE is mixed with baseline gasoline and combusted with the same efficiency as the baseline gasoline (minor improvements would actually be expected). Within practical limits, it is not necessary to know the ratio of MTBE (or other natural gas derived additives such as butane alkylate) to gasoline since we are following a "parcel" of natural gas which "sees" the thermal efficiency achieved by the engine when burning the reformulated gasoline.

We assume natural gas butanes are isomerized and are fed into a hydrofluoric acid (HF) alkylation plant having an energy efficiency of 86% to make alkylate. We assume the HF alkylation plant has the same efficiency as when it is receiving raffinate from the MTBE plant described by Wilcher (1991). An overall energy efficiency of 78% (excluding natural gas production and transport, and fuel product transport and distribution efficiencies) for alkylate production is estimated.

For natural gas to gasoline, an efficiency of 63% was used, typical for the SMDS process (van der Burgt 1989). Efficiency is highly dependent on the mix of gasoil, kerosene, and naphtha desired. Additional process study is required to determine the effects of product slate on energy efficiency.

To estimate greenhouse gas emissions, the average of base and advanced technology data presented by Ho and Renner (1990) was used for baseline gasoline, CNG, LPG, and methanol. For the LNG pathway, it was assumed that CO_2, CH_4 and N_2O emissions when in the form of CNG were identical to the CNG pathway. The LNG pathway emissions were increased by using the ratio of CNG conversion efficiency to that of LNG.

For MTBE, alkylate, and gasoline from natural gas, we assume feedstock CO_2, CH_4, and N_2O emission rates (per million btu of fuel) are those given by Ho and Renner (1990) for domestic natural gas production and transport. CO_2 and N_2O emissions for the preparation and conversion stage were adjusted according to the energy efficiency ratio between the baseline gasoline and the natural gas process. Transportation emissions for the natural gas products are those used for baseline gasoline. As mentioned, the portion attributable to venting and flaring estimates are presented separately.

Vehicle

We assume each vehicle alternative is optimized to run on one fuel, i.e., there are no efficiency penalties typical of flexible-fueled vehicle operation. The baseline vehicle is assumed to be the hypothetical, maximum technology model year 2001 Ford Taurus as described by the Office of Technology Assessment (U.S. Congress 1991), weighing 2810 lbs and achieving a fuel consumption of 35.3 miles per gallon. Engine-only performance estimates for all fuels are shown in Table 2. Vehicle assumptions and efficiency estimates are shown in the lower section of Table 1. Compression ratios were estimated by multiplying the baseline vehicle compression ratio by the ratio between dedicated CNG and methanol fueled engine compression ratios and conventional engine compression ratios presented in Santini et al. (1989). The compression ratio for LPG was obtained in the same manner using data from the National Propane Gas Association (undated). It was assumed that the compression ratio is not changed for engines running on reformulated fuels (MTBE and alkylate) and gasoline from natural gas. Actually, a slight increase in compression ratio is expected with higher octane alternatives, but our assumption does not materially affect the results. Air standard thermal efficiencies were then calculated, and adjusted for changes in volumetric efficiency for the gaseous fuels. For fuel containing MTBE and alkylate, we assumed a 2% increase in thermal efficiency based on mileage improvement data (DeLuchi 1991). We assumed that gasoline from natural gas is the same as that of the nonoxygenated, baseline gasoline. Efficiency of the methanol engine was adjusted because the high latent heat of vaporization cools the intake charge which increases volumetric efficiency. Finally, adjustments were made to account for the differences in mean effective pressure.

For the constant performance case, we assumed: (1) constant acceleration (i.e., all vehicles have the same power-to-vehicle-weight ratio); (2) constant fuel volume; and (3) the same platform design (no increase or decrease in passenger space and cargo volume). We assume the engine displacement (measured as the swept volume by the piston) is adjusted to keep the power-to-vehicle weight constant. The results include an adjustment for the weight of the tank, fuel, and engine. This case assumes acceleration characteristics are important and that consumers will not trade down for poorer performing vehicles, especially if they cost more. Positioning the Impact electric vehicle as a performance commuter car by General Motors, for example, accounts for particular attributes of electric vehicles (Amann 1990). Instead of designing for long-range travel (batteries replacing cargo volume), GM engineers focused on developing a lightweight vehicle with a relatively low vehicle weight-to-power ratio of 19.3. Due to large tank weights and volume, CNG vehicles arc similarly penalized if designed for conventional range. Like the Impact, CNG vehicles could meet consumer expectations for acceleration while meeting typical daily commuting ranges and cargo volumes if designed accordingly. The social cost of frequent refueling (time and convenience considerations) and refueling emissions were not assessed.

The constant range case assumes range is more important than acceleration characteristics and cargo volume or passenger space. For this case, we assumed (1) all vehicles are capable of traveling 350 miles between refueling; (2) engine displacement is constant; and (3) the same platform design (i.e., to allow for larger tanks, passenger space and/or cargo volume will decrease). We assume the engine displacement is kept constant. The results include an adjustment for the weight of the tank and fuel.

Greenhouse gas emissions attributable to the vehicle were estimated using Ho and Renner (1990) assumptions. We adjusted CO_2 g/mi emissions in proportion to vehicle energy efficiency. We assumed CH_4 emissions for CNG and LNG vehicles are controlled to a 1.5 g/mi level. We assumed vehicles running on the other fuels emit 0.08 g/mi of CH_4. We assumed all vehicles emit 0.1 g/mi of N_2O.

RESULTS AND DISCUSSION

Fuel Processing Energy Efficiency

The top portion of Table 1 summarizes fuel processing energy efficiency. Based on our assumptions, production of gasoline is more efficient than natural gas fuel production for transportation, which is the conclusion also reached by Ho and Renner (1990). Because additional processing is needed, oxygenation and alkylation of the baseline gasoline should decrease energy efficiency. Our estimates support this hypothesis. Our estimates also suggest that conversion and refining of alkylate is slightly more efficient than MTBE conversion and refining, assuming natural gas is used as a feedstock. Although we calculate higher efficiencies for the MTBE plant over the HF alkylation plant, the syngas step required to produce methanol feedstock for MTBE reduces overall energy efficiency below that of the overall alkylation process. The volume of feedstock requiring isomerization greatly affects the calculation of efficiency of alkylate production. For example, for high iso- to n-butane ratios typically found in petroleum refinery catalytic cracking units, alkylate production efficiencies of up to 86% (for a volume ratio of 3:1) are predicted, compared to 78% theoretically obtained from natural gas feedstock containing 30% (vol) iso- and 70% (vol) n-butane.

Overall energy efficiency of LPG is estimated to be higher than that of CNG because of higher fuel transport and distribution efficiency. Overall energy efficiency of CNG is estimated to be higher than that of LNG primarily because less energy is required for compression. Methanol's overall energy efficiency is lower than LPG, CNG, and LNG because the syngas process is relatively energy intensive, even after accounting for the highly exothermic methanol synthesis step. The gasoline from natural gas process is estimated to have the lowest conversion/refining energy efficiency (and hence the lowest overall energy efficiency) because, like methanol, syngas is produced in an intermediate step, and implied by our assumptions, less heat is liberated by the Fischer-Tropsch reaction than in the methanol synthesis reaction. Further analysis is required to determine actual component efficiencies of the natural gas-to-gasoline pathway.

Vehicle Efficiency

Table 1 summarizes the results of the constant performance and constant range vehicle cases. Both cases yield the same relative ranking in terms of vehicle energy efficiency relative to baseline gasoline except for CNG. Similar to the findings of other researchers, CNG vehicles face the greatest penalty when compared on a constant range basis (DeLuchi 1991, Ho and Renner 1990, Santini et al. 1989). Our results suggest that CNG vehicle performance (acceleration) and utility (passenger space and cargo volume) is comparable to a gasoline-fueled vehicle if the range between refueling is shortened to about 85 miles. The engine displacement could be downsized by 2%, while vehicle weight could be reduced slightly. Energy efficiency would be 6% higher. For short-range commuting of under 20 miles-per-round-trip, refueling would occur about once per workweek. Assuming the CNG vehicle is designed for a 350 mile range, vehicle weight increases by about 190 pounds, and no improvement is seen in energy efficiency compared to a conventional vehicle. The LNG vehicle is also penalized if compared on a constant range basis, but still maintains improved performance over the baseline gasoline vehicle.

The methanol-fueled vehicle is estimated to have the highest energy efficiency, 14% higher than the baseline vehicle for the constant acceleration case, and 12% higher for the constant range case. For the same acceleration as a gasoline-fueled vehicle, the methanol engine can be downsized by 8% (or about 0.16 liter [L]). Since methanol contains less energy per gallon than gasoline, the range of the methanol vehicle is estimated to be about 62% of the gasoline vehicle. Efficiency of the LPG vehicle is slightly greater than CNG and LNG for the constant performance case, but is much better than these fuels for the constant range case since LPG has a greater energy density than CNG or LNG.

Process and Vehicle Efficiency

The lower portion of Table 1 shows the combined process and vehicle efficiency of each natural gas fuel relative to gasoline for the constant performance and constant range vehicle cases. Results suggest that the LPG pathway is superior over the others for both cases, with an overall efficiency improvement of 5% over the baseline gasoline pathway. The highest overall efficiency is calculated for LPG because of its high fuel transport and distribution efficiencies relative to CNG and LNG. Fuel transport and distribution energy is based on the relative energy content of each fuel, and LPG has greater energy density than either. Compression energy is accounted for under distribution energy in the table. Compression energy requirements for LPG is lower than CNG or change of state (gas to liquid) requirements and state maintenance requirements for LNG.

CNG processing energy efficiency is lower than baseline gasoline processing energy efficiency offsetting by an equal amount the gain in efficiency from designing the CNG vehicle for constant performance and short range. The constant range design assumption for CNG vehicles severely penalizes efficiency, also noted in other studies (Santini et al. 1989). For LNG, we assumed domestic sources, and therefore do not include LNG boil-off during shipment and regassification.

The overall energy efficiency of the alkylate pathway is estimated to be approximately the same as the MTBE pathway energy efficiency. The overall energy efficiency of the baseline gasoline pathway is greater than for either additive. For MTBE, this is expected because the steam reforming process used to produce the methanol feedstock is relatively energy intensive. For alkylate, the combined isomerization, dehydrogenation, and alkylation conversion of butanes in natural gas are less efficient than baseline gasoline production from crude oil.

Methanol is combusted in the vehicle with high efficiency compared to the baseline gasoline vehicle. However, our results suggest that the overall efficiency is lower than all pathways except for gasoline from natural gas because of the syngas step.

Based on our assumptions, the least energy efficient pathway for domestic natural gas is the production of gasoline. Overall energy efficiency is 32% below that of baseline gasoline, primarily as a result of the low efficiency assumed for the conversion/refining step.

Greenhouse Gas Emissions, Expressed in CO_2 Equivalents, Constant Performance Case

Figures 2 and 3 summarize the greenhouse gas emission estimates using the 20 year IPCC warming indices for CH_4 and N_2O, assuming the constant performance vehicle case. The IPCC warming indices present the estimated warming effect of a unit of mass of CH_4 or N_2O relative to that from a unit of mass of CO_2, integrated over the time period of interest. Applying the warming factor to CH_4 or N_2O converts it to "CO_2 equivalent" units. Figures 4 and 5 show the same results using the 100 year warming indices. (CH_4 and N_2O emission rates discussed below are expressed in term of CO_2 equivalent.) The CH_4 increment shown is the amount estimated from venting and flaring from natural gas and crude oil production. The results for the constant range vehicle case (not shown here) show that the greatest increase in emissions would be for CNG and could change CNG's position in the 100-year case. No change in relative ranking of greenhouse gas emissions from other fuels are predicted for the constant range case. Results from using the 20 year indices for the constant performance vehicle case are discussed immediately below, followed by comparative discussion of the results using 100 year indices.

CNG and LNG are estimated to produce the most greenhouse gas emissions when 20 year indices are used, primarily because of the high CH_4 emissions (Figure 2). Including CH_4 emissions associated with venting and flaring at natural gas fields, emissions are about 26% higher than baseline gasoline, which, aside from LPG, produces the least amount of greenhouse gas emissions per mile. Assuming all methane is utilized at the natural gas field (eliminating the "CH_4 increment" illustrated in the figure), greenhouse gas emissions are still 12% higher than baseline gasoline because of the high assumed tailpipe CH_4 emissions. Figure 3 shows that CNG and LNG estimates are greatly affected by the assumed CH_4 and N_2O emissions and venting/flaring increment. Although we estimate that the overall CNG energy efficiency is greater than overall LNG energy efficiency, emissions are approximately the same for both fuels because we assume most emissions are actually a result of fuel transportation and not from processing. We assume LNG has the same fuel transportation efficiency as CNG (DeLuchi 1991), both being moved within the domestic natural gas transmission system. We assume conversion to LNG close to final distribution/sales, consistent with our domestic production assumption.

Our findings show LPG emits the lowest level of greenhouse gas emissions because of high vehicle efficiency combined and low emissions of CH_4 from fuel processing and tailpipe emission assumptions. LPG emissions are about 3% lower than baseline gasoline emissions including the CH_4 increment, and about 22% lower when compared against CNG or LNG. Excluding the CH_4 increment, LPG emits 13% less greenhouse gas emissions than baseline gasoline. Greenhouse gas emissions from alkylate are higher than baseline gasoline. Alkylate greenhouse gas emissions are comparable to MTBE greenhouse gas emissions. Methanol produces lower greenhouse gas emissions than alkylate and MTBE because methanol vehicle efficiency is high. However, methanol fuel production emissions (on a CO_2 gram-per-btu fuel basis) are almost 10% higher. Greenhouse gas emissions from gasoline produced from natural gas are lower than CNG or LNG because gasoline tailpipe CH_4 emissions are assumed to be very low. However, greenhouse gas emissions from natural gas-based gasoline are higher than alkylate or MTBE greenhouse gas emissions because of higher CO_2 emissions.

The 100 year indices assume a lower warming potential for CH_4 emissions. As shown in Figures 4 and 5, LPG produces less greenhouse gas emissions than baseline gasoline, and CNG and LNG perhaps slightly less. If CH_4 emissions from venting and flaring are excluded, methanol also produces less greenhouse gases. The efficiency of the methanol vehicle counteracts the relatively low efficiency of the syngas process, resulting a small (2%) net decrease in greenhouse gas emissions, excluding venting and flaring emissions. Greenhouse gas emissions from MTBE and alkylate are about the same, and higher than baseline gasoline because of lower fuel processing efficiency. Natural gas-based gasoline produces the most greenhouse gases because of low fuel processing efficiency.

CONCLUSIONS

Our findings suggest that over the long-term (a century), dedicated use of LPG, CNG, LNG and methanol in transportation can lower overall greenhouse gas emissions compared with the use of gasolines with MTBE or alkylate. A CNG vehicle designed for shorter range but with adequate acceleration would improve overall energy efficiency and decrease greenhouse gas emissions over a vehicle designed to compete with gasoline on a range basis. In the short-term (20 years), CNG and LNG are estimated to cause more warming, especially if we assume venting and flaring will occur. If CNG and LNG are to realize greenhouse gas reductions both in the short- and long-term, very strict regulation of emissions from the tailpipe would be necessary. Use of LPG is the most energy efficient pathway, according to our estimates. However, since LPG is a relatively small component of natural gas compared with methane, there may be supply constraints by the year 2010. The efficiency of the baseline gasoline pathway is high. On a short term basis, baseline gasoline pathway greenhouse gas emissions are low. While the use of oxygenates such as MTBE may reduce tailpipe emissions, no clear benefits exist from an energy efficiency and greenhouse gas perspective over the use of alkylate as a high octane, low RVP additive. Methanol is the most desirable from a vehicle efficiency perspective. However, the syngas to methanol production step significantly reduces overall energy efficiency. Improvements in the syngas step will benefit efficiencies of producing methanol, MTBE (methanol feedstock) and natural gas-derived gasoline. Production of gasoline from natural gas is the least energy efficient pathway, according to our estimates, and results in the highest greenhouse gas emissions over the long-term. Our findings are greatly affected by assumptions of the global warming effect of CH_4, emissions rates of CH_4 from the tailpipe and from venting associated with gas extraction, and vehicle efficiency. Our findings are also affected by fuel transportation energy assumptions. Fuel conversion/refining efficiency assumptions affects results to a lesser degree.

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Table 1. Feedstock-to-fuel efficiency, vehicle parameters and efficiency, and fuel cycle efficiency of natural gas fuel pathways.

FEEDSTOCK-TO-FUEL EFFICIENCY	CNG a	LNG b	LPG a	MEoH a	MTBE c	GASOLINE FROM NG e	ALKYLATE c	BASE a
Feedstock Production	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.97
Feedstock Transport	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98
Preparation	0.97	0.85	0.89	0.97	0.97	0.97	0.97	0.91
Conversion/Refining	1.00	1.00	1.00	0.70	0.76 d	0.63 f	0.78 d	1.00
Fuel Transport	0.95	0.95	0.97	0.95	0.98	0.98	0.98	0.98
Fuel Distribution	0.89	0.89	0.99	0.98	0.99	0.99	0.99	0.99
Feedstock-to-fuel efficiency	0.78	0.68	0.82	0.60	0.68	0.57	0.70	0.83
VEHICLE PARAMETERS								
CONSTANT PERFORMANCE VEHICLE g	CNG	LNG	LPG	MEoH	MTBE	GASOLINE FROM NG	ALKYLATE c	BASE
Engine displacement, fraction of baseline	0.98	0.97	0.94	0.92	1.00	1.00	1.00	1.00
Fuel+tank weight increment over baseline	-25	-45	11	0	0	0	0	0
Range (mi)	85	111	289	213	350	350	350	350
Vehicle weight (lbs)	2783	2761	2814	2799	2810	2810	2810	2810
Vehicle efficiency (Btu/mi) h	3102	3083	3079	2890	3233	3281	3233	3281
Vehicle efficiency relative to baseline	1.06	1.06	1.07	1.14	1.01	1.00	1.01	1.00
CONSTANT RANGE VEHICLE i								
Engine displacement, fraction of baseline	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Fuel+tank weight increment over baseline	189	50	37	55	0	0	0	0
Range (mi)	350	350	350	350	350	350	350	350
Vehicle weight (lbs)	2999	2860	2847	2865	2810	2810	2810	2810
Vehicle efficiency (Btu/mi) h	3302	3172	3102	2937	3233	3281	3233	3281
Vehicle efficiency relative to baseline	1.00	1.03	1.06	1.12	1.01	1.00	1.01	1.00
FUEL CYCLE EFFICIENCY (FUEL AND VEHICLE) RELATIVE TO BASELINE CONSTANT PERFORMANCE VEHICLE	1.00	0.88	1.05	0.83	0.83	0.68	0.86	1.00
FUEL CYCLE EFFICIENCY (FUEL AND VEHICLE) RELATIVE TO BASELINE CONSTANT RANGE VEHICLE	0.95	0.86	1.05	0.82	0.83	0.68	0.86	1.00

NOTES:

a Average of base and advanced technology from Ho and Renner (1990).

b Ho and Renner (1990) values for CNG used except for preparation (liquefaction) efficiency. Liquefaction efficiency of 83.19% estimated by DeLuchi (1991) was used.

c Ho and Renner (1990) feedstock data for natural gas; Fuel transport data for baseline gasoline; Conversion and refining efficiency based on process information by Wilcher (1991).

d Assumes butanes obtained from natural gas field.

e Efficiency of gasoline/diesel fuel mix from natural gas. Gasoline fuel transport and distribution efficiency is assumed.

f Average efficiency of Shell two stage synthesis process., from van der Burgt et al. (1989).

g Constant power-to-vehicle weight ratio and platform size (constant passenger space volume and tank volume). Engine is downsized to keep power constant.

h Assumes a 0.23% increase in fuel consumption per 1% increase in power to vehicle weight ratio (Santini et al. 1989). Assumes a 0.64% increase in fuel consumption per 1% increase in vehicle weight (U.S. Department of Energy 1992).

i Constant range. Constant platform size, but tank volume varies at expense of cargo space. Constant engine displacement (power-to-vehicle weight varies).

Table 2. Engine Assumptions

Parameter	CNG	LNG	LPG	MEoH	MTBE	GASOLINE FROM N.G.	ALKY.	BASE b
Compression ratio a	14.55	14.55	15.02	12.50	10.00	10.00	10.00	10.00
Unadjusted thermal efficiency	1.07	1.07	1.08	1.09	1.02	1.00	1.02	1.00
Power ratio, volumetric efficiency	0.90	0.90	0.94	1.00	1.00	1.00	1.00	1.00
Power ratio, heat of vaporization	1.00	1.00	1.00	1.04	1.00	1.00	1.00	1.00
Power ratio, mean pressure effects	1.04	1.04	1.04	1.03	1.00	1.00	1.00	1.00
Power ratio, net change from baseline	1.01	1.01	1.07	1.09	1.02	1.00	1.02	1.00

NOTES
a Data obtained from Santini et al. (1989), Amann (1990), DeLuchi (1991), and Ho and Renner (1990).
b Baseline vehicle is a hypothetical Ford Taurus as described by U.S. Congress (1991).

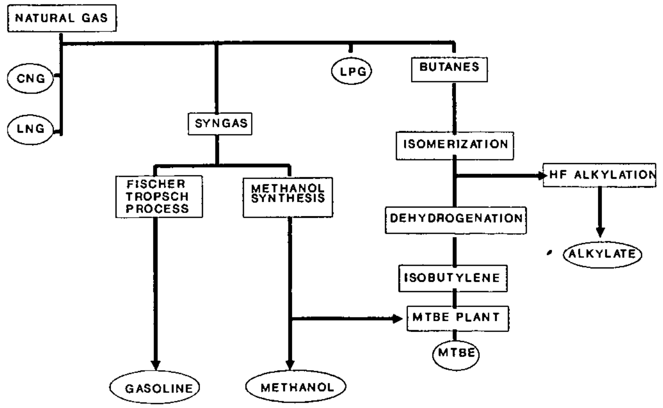

Figure 1. Schematic of natural gas fuel production pathways.

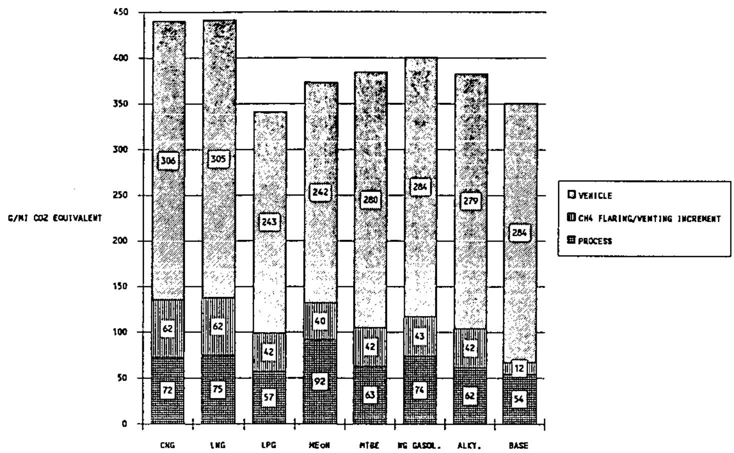

Figure 2. 20-year CO_2 equivalent emissions for constant performance case: vehicle, methane flaring/venting, and process contributions. (Venting/flaring increment assumes CH_4 is emitted during extraction of natural gas feedstock. N_2O emissions from venting/flaring assumed negligible.)

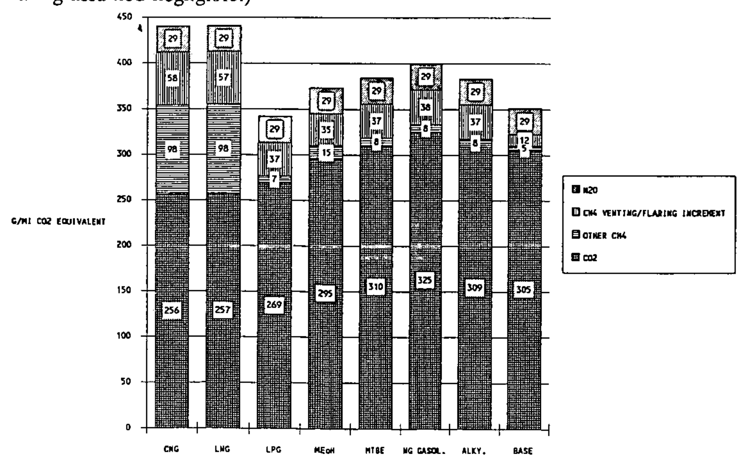

Figure 3. 20-year CO_2 equivalent emissions from natural gas fuel pathways: contributions from different greenhouse gases, constant performance case. (Venting/flaring increment assumes CH_4 is emitted during extraction of natural gas. N_2O emissions from venting/flaring assumed negligible. Other CH_4 is emitted from process conversion/refining and/or from the vehicle tailpipe.)

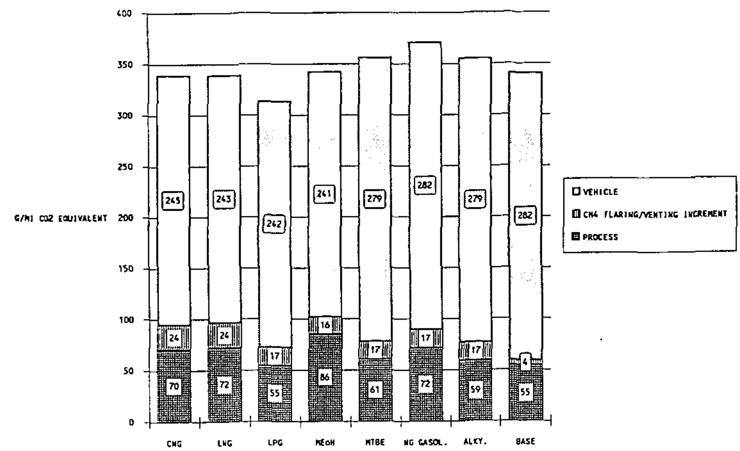

Figure 4. 100-year CO_2 equivalent emissions for constant performance case: vehicle, methane flaring/venting, and process contributions. (Venting/flaring increment assumes CH_4 gas is emitted during extraction of natural gas. N_2O emissions from venting/flaring assumed negligible.)

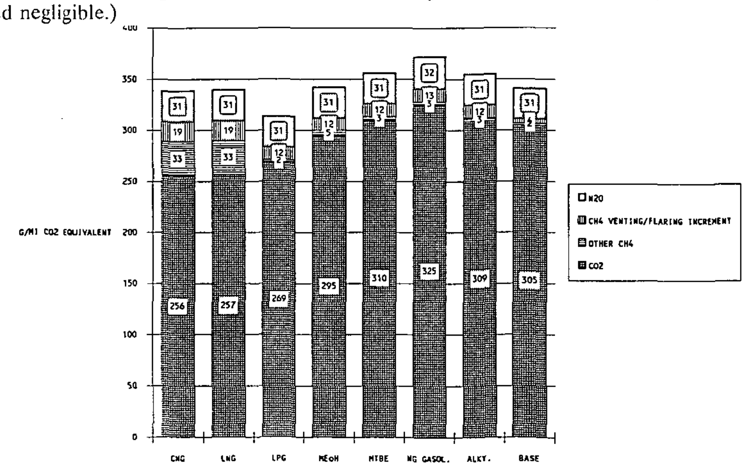

Figure 5. 100-year CO_2 equivalent emissions from natural gas fuel pathways: contributions from different greenhouse gases, constant performance case. (Venting/flaring increment assumes CH_4 is emitted during extraction of natural gas feedstock. N_2O emissions from venting/flaring assumed negligible. Other CH_4 is emitted from process conversion/refining and/or from the vehicle tailpipe.)