The Real Air Quality Benefits of Gaseous-Fueled Vehicles

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ABSTRACT

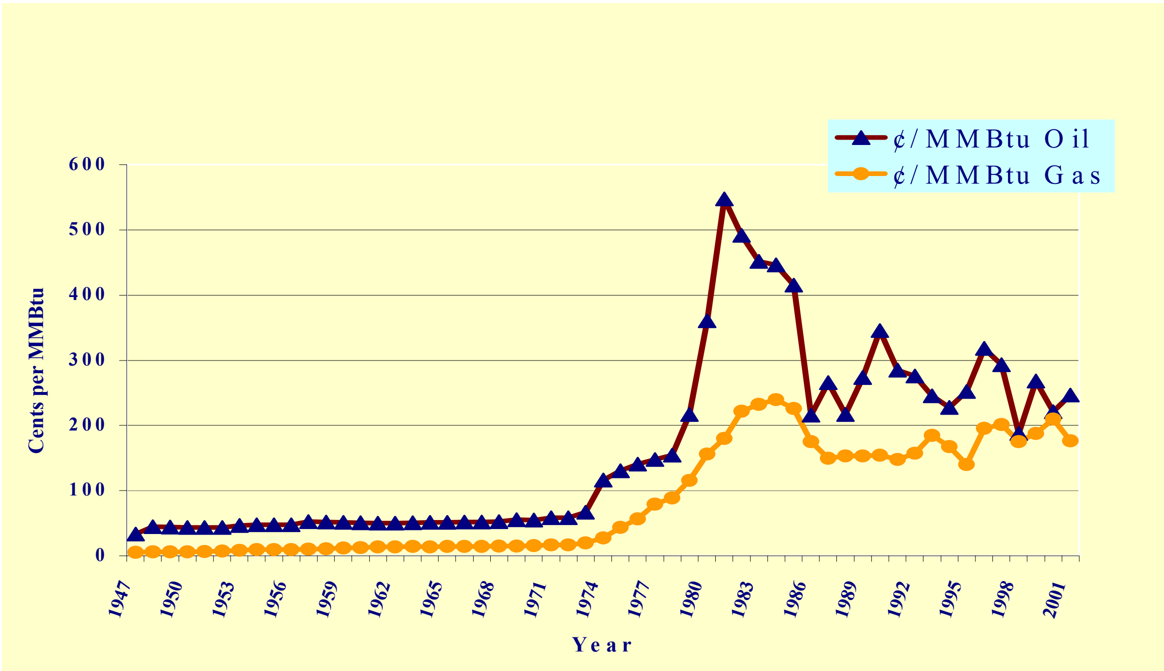
This paper provides a justification for prominent inclusion of currently available gaseous-fueled vehicles (i.e., vehicles powered by propane, sometimes called liquefied petroleum gas [LPG], or natural gas—chiefly, methane—stored onboard the vehicle in gaseous or liquid state but combusted as a gas) in the mix of strategies to (a) reduce public exposure to toxic and fine particulate emissions in the urbanized areas of the developing world and (b) achieve local and regional improvements in ozone air quality. It also presents estimates of associated emission reduction credits into the future. Important considerations discussed are the location of fine particle and toxic emissions in congested urban areas, and the location and timing of ozone precursor emissions, with emphasis on how gaseous-fueled vehicles' role in the relationship among and magnitude of these variables differs from that of their conventionally-fueled counterparts. Efforts to enhance the measurement and quantification of gaseous-fuel benefits are also described.

INTRODUCTION

Unexpectedly large reductions of key emission precursors to Tropospheric ozone have been achieved by selecting specific light and heavy duty gaseous-fueled (propane and natural gas) vehicle offerings from original equipment manufacturers (OEMs) in lieu of their gasoline- and, in some instances, diesel-fueled counterparts. Even greater benefits accrue when such vehicles supplant gasoline- and diesel-powered units in developing countries experiencing generally elevated human toxic and particulate air pollutant exposure. "Upstream" emissions of reactive organic gases from fuel storage and distribution within the airshed of interest are also reduced by use of gaseous fuel.

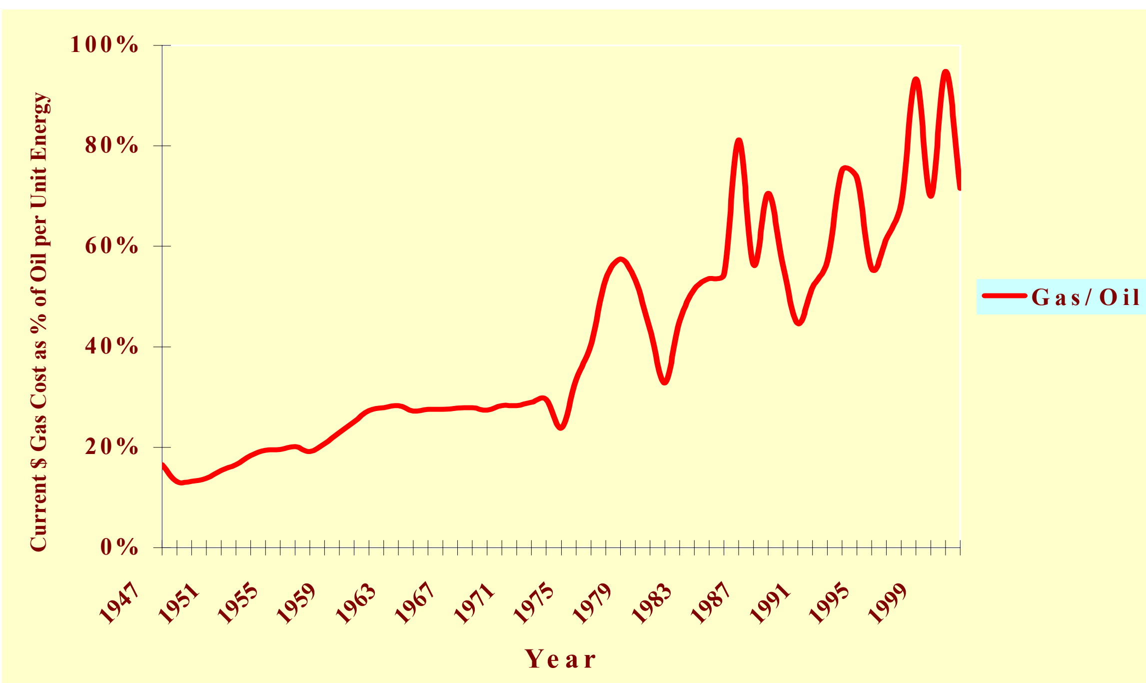
Of course, ozone precursor reduction benefits are not necessarily to be won at a lower fuel cost. In recent years, as Figure 1a shows, the (current dollar) USA retail price of natural gas has trended toward parity with that of gasoline on a joule for joule (Btu for Btu) basis, in contrast to its behavior through the mod-1970s. Yet, as illustrated by Figure 1b, there has been considerable volatility in this trend, especially since the onset of domestic natural gas price deregulation. (This is not a general result, however, as, depending on its own reserves and import arrangements, each country's gas to oil price ratio may not reflect USA relationships.) Moreover, questions remain about (a) the oxide of nitrogen (NOx) emissions of gaseous fuels, because their (on average) leaner combustion conditions can result excess loading of oxygen in the exhaust stream precluding reduction catalysts from functioning optimally, and (b) leakage of CH_4 to the atmosphere--likely to increase with the addition of multiple natural gas dispensing points--which poses a known and potent greenhouse gas threat.[1] Nevertheless, as shown in Figure 2, natural gas is a relatively plentiful fossil fuel, even discounting potential recovery from landfills, with reserves likely to
outlast those of petroleum even at increased consumption rates. (This fact, among others, has

Figure 1a. Current Dollar Wellhead Prices of Crude Oil and Natural Gas, 1947-2000



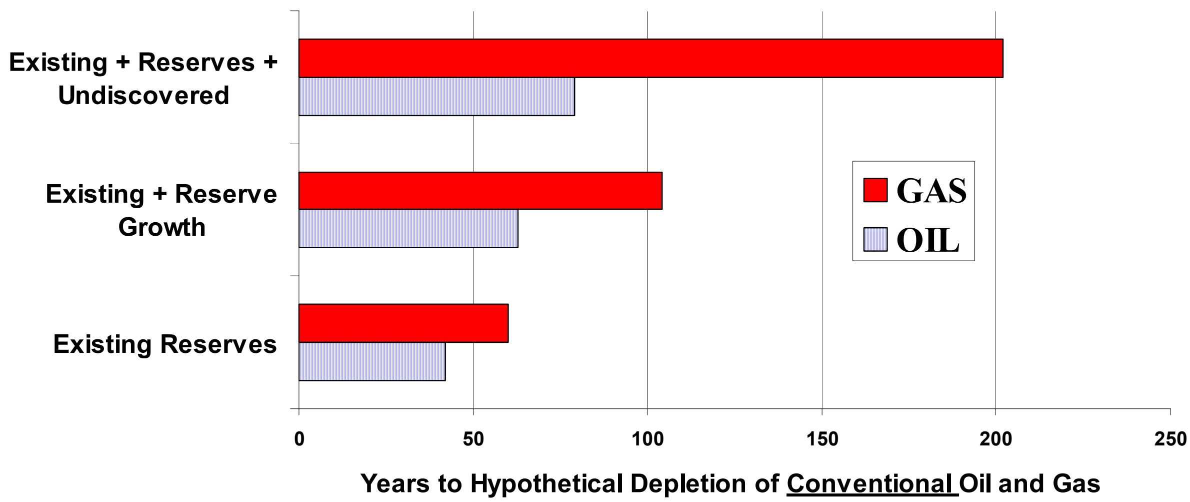
Data Source: American Petroleum Institute, *Basic Petroleum Data Book: Petroleum Industry Statistics* **XXI**:2, (August 2001), Section VI, Table 6

Figure 1b. Five-Decade Trend in USA Mean Wellhead Energy Unit Price of Natural Gas Relative to Oil



Data Source: Prepared by D. Santini using Figure 1a data plus Tables 9.1 and 9.11 of Energy Information Administration's *Monthly Energy Review* (February 2002), induced some major energy companies to plan seriously for relatively near-future conditions in which hydrogen produced from natural gas and used in propulsion fuel cells displaces a substantial percentage of the petroleum fuel now used in transportation.[2]) The predominant share of natural gas reserves, either in the ground or "flared" during petroleum extraction, resides in emerging countries in deep need of international markets and investments for their products. Thus, policies to promote replacement of petroleum energy consumption in transportation by gaseous fuels, especially natural gas, continue to warrant serious consideration.

Figure 2. Comparative Expected Depletion of Oil and Gas at Current Usage Rates



Source: (1) American Petroleum Institute, *Basic Petroleum Data Book: Petroleum Industry Statistics* **XXI**:2, (August 2001): Sec. II, Table 1, Sec. IV Table 1, and Sec. XIII Tables 1 and 4; and (2) Rogner, H.H., "An Assessment of World Hydrocarbon Resources," *Annual Review of Energy and the Environment* (R.H. Socolow, ed.), Washington, DC (1997), p. 249.

GASEOUS FUELS AND URBAN AIR QUALITY IN THE THIRD WORLD: A NATURAL SYNERGISM

Pollutant Exposure and Human Activity Patterns

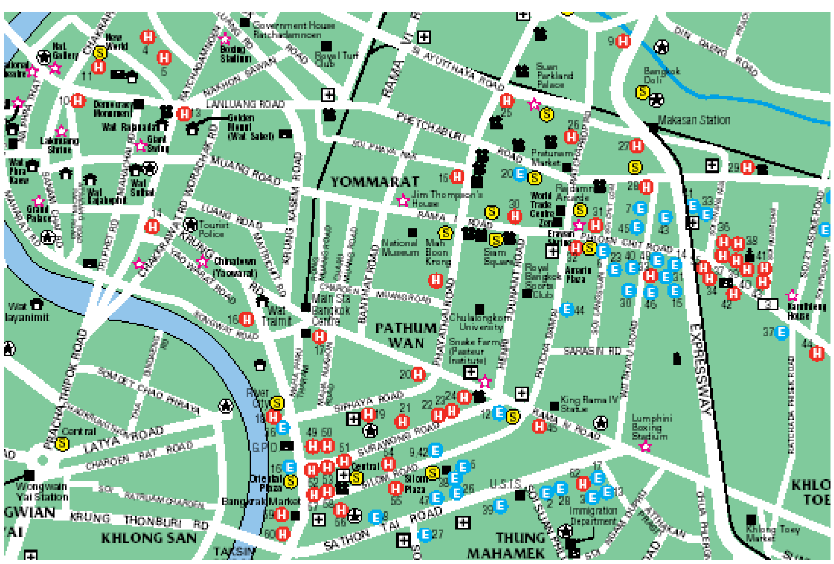
In a large part of the developing world, and especially in the Tropics and the Southern Hemisphere, people in cities and towns spend much of their waking hours out of doors. Often, the morphology of the places they inhabit is not conducive to effective dispersion of the air contaminants released by area and mobile source combustion. Moreover, local urban microclimates such as those in relatively arid regimes can experience frequent air mass inversions that further trap, beneath low mixing lids, the pollution already filling the narrow and numerous streets and alleyways. There poses a clear and imminent health hazard to residents of many of these communities, especially to their younger members.

Figures 3a through 3c are satellite images and maps showing the density of street patterns in central portions of, respectively, a Latin American and two Asian metropolitan areas. These networks, either because of their heritage from the pre-industrial era or development that did not anticipate the impact of the personal automobile, have not been specifically configured for the efficient passage of motor vehicle traffic. Further, higher-design arterial systems that are often superimposed on them are too limited in capacity to provide consistent relief from chronic vehicular congestion, much of which is accounted for by highly polluting two-stroke engines and other mobile combustion sources uncontrolled by catalysts. The cities shown, and many like them, are located in warm to temperate climates in which the resident populace spends much time in the ambient (outdoor) air. Thus, the vehicle-related outdoor pollutant exposures characteristic in North America only (or primarily) of urban cores during the weekday—and for lower average periods of time—can in developing countries be prevalent where inhabitants perform much of their breathing.

Figure 3a. Example Commercial and Residential Densities in Latin America

Figure 3b. Example Commercial and Residential Densities in Asia

Figure 3c. Example Street Configuration in Asia



These conditions can represent an undesirable and possibly even dangerous convergence of bad air and high population-weighted exposures that calls for near-term solutions in order to protect the health of sensitive and young residents. A place to start might be displacement of some of the principal, and often very dirty, propulsion fuels.

Quality of Motor Fuels and Combustion Technologies in the Developing World

Historically, fossil fuels in their most impure and health-threatening forms have been utilized routinely in countries of the developing world. This was the result either of the undesirability of such fuels in richer nations (and their consequent relative cheapness in spot markets), or the fact that it was locally produced or manufactured from indigenous feedstock. In parts of the Middle East, a high sulfur-content (up to 60,000 ppm by weight) version of the fuel oil called mazout was routinely burned in electricity generating plants located close to highly populated residential areas. Only within the last five years has tetraethyl lead been removed from the gasolines available in major, densely populated cities such as Cairo, Bangkok, and Manila (the last as of 12/23/00). However, continued extensive use of high-sulfur diesel propulsion fuels by those cities' vehicles poses heath insult problems from both ambient fine particles and toxic inhalation. Also, additives supplanting lead in gasoline in order to replace lost octane can bring their own problems, especially if the chosen replacements are aromatics (with their toxic properties) or butane. The latter replacement effectively volatilizes and mobilizes stored gasoline, thus increasing ozone precursor loading. This phenomenon negatively affected air quality in many world cities in the late 1980s and early 1990s after lead was phased out of gasoline without sufficient attention to its replacement additive. Transitional problems related to replacement of petroleum fuel additives during the process of petroleum fuel "detoxification" remain an important issue in the developing world, as indicated by the prominence of related topics in the International Urban Forums sponsored at A&WMA annual meetings in recent years.[3] Vigorous introduction of gaseous fuels in transportation can circumvent many of these problems.

It is, of course, important to avoid an ambitious strategic promulgation of gaseous fuel fleets that fails to recognize embedded institutional obstacles, a failing that brought "commuter chaos" to New Delhi during the spring of 2001.[4,5] Uncoordinated planning followed by unrealistic, unilateral mandates can result not only in dismal failure to achieve policy ends, but may well also engender a more negative public attitude toward gaseous transportation fuels.

Ironically, even in the wake of the New Delhi disaster as demand for natural gas far outpaced availability, the resultant air quality improvement appeared to be as promised. In this context it is important to remember that there are ancillary air quality benefits of a transition to gaseous transportation fuels not deriving directly from cleaner vehicular combustion. In particular, the elimination or substantial reduction of evaporative hydrocarbon emissions associated with storage and distribution of petroleum products can suppress both ozone formation and air toxic (e.g., benzene) concentrations.

Bringing New Transport Fuels to Market—Where High Promise Exists

The economic interests of a developing nation are well served when it is endowed with a base of natural resources in worldwide demand; this enables the nation to develop these resources either for export or to utilize domestically in place of costlier imported substitutes. In the case of fossil fuels, many nations have discovered that their own reserves of natural gas can be utilized in domestic applications formerly the exclusive province of imported petroleum products. This in turn can free up their domestically produced petroleum for sale in the international marketplace, where sweet and/or high-hydrogen crude stocks are in great demand.

OZONE PRECURSOR MITIGATION BENEFITS

Characteristics of Precursor Reductions

This section discusses differences in criteria pollutant emissions of late model year gaseous-fueled vehicles relative to their petroleum-fueled counterparts (the relevant comparison fuel being gasoline or diesel) that illustrate how gaseous fuels have the potential to improve urban air quality to a greater than proportional degree.

Table 1 shows U.S. federal certification emission test results for a selection of recent model year light- and heavy-duty gaseous-powered vehicles relative to the same make and model petroleum (gasoline- and diesel-) fueled counterparts. (Heavy-duty vehicles-trucks and buses--are compared exclusively to diesel units because gasoline fueling is not relevant in higher gross weight classes.) Figure 4 compares these test results on a percentage basis. Beyond the raw differences in NMHC, NOx, and PM, it is important to note two more detailed observations: (1) virtually all of the light-duty NMHC savings vs. gasoline are achieved in the cold start mode (Bag 1 of the Federal Test Procedure) and (2) savings vs. diesel are especially impressive for both NOx and fine PM (measured by mass, not count per unit volume). It is implied by (1) that, at least for the near term, the higher the proportion of morning starts near the core of an urban area on natural gas fuel, the greater the reduction in early NMHC loading so critical for midday formation of ozone downwind. This may be more true of cities not subject to the U.S.' stringency of vehicle emission controls and where the fleet is older, on average. (It should also be borne in mind that the intent of the illustration in Table 1 is to compare the relative cold transient performance of gasoline and gaseous-fuel counterparts, not the performance of Bag 1 compared to the full FTP within vehicle type. Bag 1 data represent only a subset of the full FTP cycle.) It is implied by (2) that gaseous-fueled transit buses can be immediate and effective agents in the mitigation of PM health insult to transit-dependent urban dwellers, and that "NOx-limited" ozone non-attainment regions can seek partial remedy of air quality violations by near-term retirement or retrofit of diesel buses in favor of natural gas and propane. This also may be more true of cities not subject to the U.S.' stringency of vehicle emission controls and where the fleet is older, on average.

In highlighting in Table 1 the net benefit of gaseous-fueled vehicles during the cold transient (start-up) phase of operation, this review points to an aspect of ambient ozone mitigation often overlooked: reducing the sources and causes of high atmospheric loading of reactive hydrocarbons before mid-day insolation triggers significant ozone formation. In VOC-limited ozone-forming conditions, prevalent across most of North America, exhaust hydrocarbon and carbon monoxide emissions from later-model gasoline-fueled vehicles peak during the morning commute hours (6 - 8:30 a.m.). These become available to oxidation photochemistry downwind during the late morning and early afternoon hours, generally removed from the densely developed urban cores where they were originally released and where ozone titration by NO can have a mitigating effect locally.

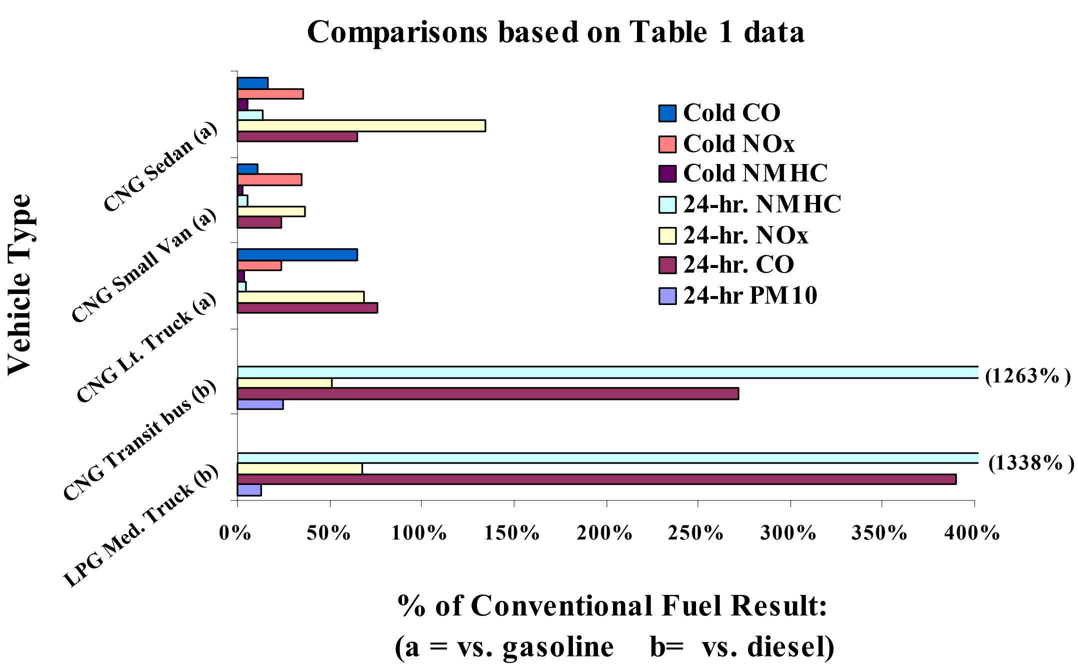
Similarly, regional ozone control strategies have emphasized the importance of synoptic scale NOx reductions and local reductions in VOC. Current strategies, such as those generally adopted **Table 1.** Recent certification test comparisons (g/km or *g/kWh*): gaseous-fueled vehicles and their conventional make and model counterparts

POLLUTANT / Vehicle/Fuel	NMHC-Bag 1	NMHC-Full FTP	NOx-Bag 1	NOx-Full FTP	CO- Bag 1	CO-Full FTP	PM2.5-Full FTP
Sedan/gasoline	**0.196**	**0.072**	**0.103**	**0.023**	**3.525**	**0.925**	**NR**
Sedan/CNG	**0.011**	**0.010**	**0.037**	**0.031**	**0.571**	**0.600**	**NR**
Small van/gasol.	**0.366**	**0.078**	**0.426**	**0.143**	**3.921**	**0.845**	**NR**
Small van/CNG	**0.011**	**0.004**	**0.147**	**0.053**	**0.427**	**0.203**	**NR**
Lt. truck/gasol.	**0.193**	**0.042**	**0.068**	**0.016**	**2.465**	**0.581**	**NR**
Lt. truck/CNG	**0.007**	**0.002**	**0.016**	**0.011**	**1.593**	**0.444**	**NR**
Med. truck/diesel	**N/A**	***0.08***[a]	**N/A**	***4.54***	**N/A**	***1.82***	***0.100***
Med. truck/LPG	**N/A**	***1.07***[a]	**N/A**	***3.08***	**N/A**	***7.10***	***0.013***
Transit bus/dies.	**N/A**	***0.08***[a]	**N/A**	***5.20***	**N/A**	***0.92***	***0.131***
Transit bus/CNG	**N/A**	***1.01***[a]	**N/A**	***2.66***	**N/A**	***2.50***	***0.032***

NR = Not Regulated currently or under Federal Tier 2 standards for LD spark-ignition vehicles
[a]*Total HC*
N/A = No cold transient test on heavy-duty engine certification cycle due to a substantial body of data showing little or no difference between cold transient and stabilized emissions of criteria pollutants from a naturally aspirated heavy diesel engine. However, more recent data from emission tests of modern direct injection (e.g., common rail) engines may not be fully consistent with these previous results.

[Source: U.S. EPA certification database for 1998-2000 model years]

Figure 4. Fuel-to-fuel Vehicular Emission Comparisons on a Percentage Basis



across the modeling and transport domain of the Ozone Transport Advisory Group region, include mitigation of emissions of NOx from fossil-fueled electric power generating plants and other major elevated sources well upwind of non-attainment urban areas (but deemed responsible for precursor emissions transported into them), together with more localized control of VOC. Reduction of morning VOC emissions near urban cores apparently knocks down ozone peak concentrations by suppressing the morning TNHMC concentration that is highly correlated (perhaps as high as 72%)[6] with variability in daily O_3 maxima.

The NOx emission effect of gaseous-fueled light duty vehicles (cars and light trucks) may be either positive or slightly negative relative to conventionally fueled model-year cohorts, depending on how the vehicle is tuned. Because (aftertreatment) reduction catalysts do not perform optimally in a lean (oxygen-rich) exhaust environment, they may not remove as much NO as if installed a gasoline-fueled vehicle traveling the same distance (hence the higher NOx for the CNG sedan in Table 1). A gaseous-fueled vehicle *can* be tuned to meet comfortably all applicable NOx limits while achieving substantial reductions in CO and VOC (relative to gasoline). However, its NOx performance is likely to be *consistently* superior only in comparison to counterpart compression ignition-engined units fueled by diesel, because diesel vehicles have no reduction catalysts. (Compression ignition engines combust diesel fuel both leaner and hotter than gasoline or natural gas in a spark ignition engine, resulting in very low CO and unburned VOC even without catalytic aftertreatment.) In fact, when gaseous-fueled heavy trucks and transit buses are substituted for diesel counterparts, substantial net NOx reductions *may* ensue. This argues for targeting replacement of diesel-fueled units to outlying areas, where reductions of NOx and VOC precursors may have equal benefit. Reinforcing this consideration is that toxic and fine particle emissions associated with diesel combustion have been deemed a direct and potentially more dangerous insult to human health, especially among vulnerable younger populations.[7]

Sulfur and other corrosives in gaseous fuels as extracted are usually removed at or near the wellhead to obviate chemical attack to the interior surfaces of pipelines or pressure vessels (the latter in the case of propane). Thus, the quality of natural gas delivered at the end of a distribution network is often characterized as a function of its methane and other paraffin content, as the only remaining "impurities" are tiny amounts of nitrogen and carbon dioxide. To perform adequately as a transportation fuel, natural gas should consist of at least 92% methane, with the remainder ethane, propane and butane plus higher paraffins. (LPG is predominantly propane, C_3H_8, with a small amount of butane, C_4H_{10}.) When delivered gas is so constituted, it contains *no aromatics, no readily available condensation nuclei for fine particles,* and *no fuel toxins*. Its ozone-precursor reactivity index on the Carter MIR scale[8] is around 0.06 (based on 92% methane at 0.01, 2% each ethane, propane, and butane at 0.35, 0.64, and 1.44 respectively, plus 2% inert content), compared to values in excess of 1.0 for even the most stringently reformulated gasolines. The resulting removal of identified health insult from the breathing zone approaches 100 percent.

Durability of Benefits

Table 2 shows the net reduction of ozone precursor emissions respectively attributable to 1000 and 2500 model year 1999 and 2000 natural-gas-fueled light trucks, and, respectively, 100 and 250 model year 1999 and 2000 transit buses (all in service as of May 1, 2001) operating six days per week, 100 miles per day in the Houston, TX metropolitan area for each summer ozone season from 2001 through 2005. The calculation is based on comparison with equally-powered new conventionally-fueled counterparts that would otherwise have been placed in service.[9] For the light trucks, the benefit relative to gasoline-fueled units that would otherwise have been purchased increases through time because of lower mileage accrual rates (and hence a lower emission deterioration rate) over an entire year. For transit buses, whose diesel competition (according to EPA) is not subject to emission deterioration, the benefit remains constant. In each year, the buses represent about 97 percent of the NOx benefit, while the natural gas trucks represent 100% of both CO and HC benefit.

Table 2. Net emission reduction of kg/ozone season day attributable to 1000/***2500*** NG LDTs and 100/***250*** NG transit buses in Houston, TX operating through 2005

POLLUTANT Year	VOC	NOx	CO
2001	48/***120***	147/***297***	179/***448***
2002	51/***127***	151/***306***	223/***558***
2003	52/***129***	153/***311***	251/***628***
2004	55/***137***	155/***316***	276/***690***
2005	58/***144***	156/***320***	301/***753***

[Source: U. S. DOE Clean Cities "AirCred" calculation tool]

While not especially impressive, these totals show both that fuel substitution in the original equipment market (the comparison excludes retrofits) yields a continuous increase in benefit as numbers in service increase, and that specific mobile source precursor emission reductions CAN be targeted by location within a metropolitan area. That is, for purposes of ambient modeling, a finer level of precision and testing of micro- and meso-scale control strategies is achievable in hour-by-hour gridded inventories when it is known where AFV fleets are operating.

The net reductions shown in Table 2 are applicable to vehicles that met the U.S. emission standards in place as of the end of 2000. Beginning in 2001, all U.S. light-duty vehicles (outside California) have been certified under the National Low Emission Vehicle (NLEV) Program, which assigns extra credit to any vehicle that can meet super low (so called "LEV" and "ULEV"—ultra low) emission targets. The reduction benefit of a gaseous-fueled vehicle relative to a LEV- or ULEV-certified conventionally fueled vehicle is much diminished compared to (pre-2001) Tier 1 certification, even in the cold transient phase. With the national introduction of Tier 2 standards in 2004, the benefit may disappear entirely without further optimization of gaseous engines and emission control systems. By contrast, heavy-duty vehicles need not begin to meet tighter standards until 2006, and the relatively slow phase-in of tighter controls implies that gaseous-fueling benefits for transit buses and heavy trucks could persist on a model-year to model-year basis into the second decade of the century.[10] The emerging controversy about availability of ultra low-sulfur diesel fuel could further delay emissions equality between gaseous and diesel fuels in heavy-duty application.

LIMITATIONS IN ATTEMPTS TO ESTIMATE ACTUAL REDUCTION IN HEALTH DAMAGE

We have no available example of a well-controlled test program in a major urban area in which diesel-powered vehicles were replaced for a fixed period of time by gaseous-fueled counterparts then returned to all diesel operation. Worldwide, conversion or replacement of diesel transit buses by CNG-, LNG- and/or LPG-fueled units is an ongoing process that promises to be in place for a relatively long period. Thus, measuring air quality/health benefits specifically attributable to a fuel changeover will be precluded as long as this changeover process does not reverse itself (say, due to a sudden abundant availability of super-clean diesel fuel at a reasonable cost). The test case closest to being able to offer some direct insight on this issue is that of the period of the 1996 Summer Olympic Games held in Atlanta, GA. In conjunction with that event, over 250 shuttle and mass transit vehicles that would otherwise have been diesel-engine units, and 300 support vehicles that would otherwise have operated on gasoline, were powered by natural gas, as transit agencies and fuels providers from around the country donated NG-powered units to Atlanta for the duration of the Games. These vehicle totals represented about 17% and 7.5%, respectively, of the bus and support vehicle fleets required in Atlanta to service the Games.[11] In some cases, kilometers driven by CNG replaced those of normal MARTA transit routes, but bus operation tended to be oriented about the scattered event sites across the metro area, rather than predominantly near downtown.

Although many factors contributed to air quality conditions in Atlanta during the 2½-week duration of the Games (not the least of which was an overall reduction in daily traffic that would otherwise have been driven by residents who instead took out-of-town holidays during this event), meteorology was not atypical of mid-summer Atlanta. Thus, a comparison of ozone air quality on two weekend days in Atlanta during that summer of 1996—one preceding the Games and the other in the middle of them—may help illuminate the cold start and NOx emission reduction effects discussed above. On June 30, peak one-hour ozone concentration northwest of downtown Atlanta reached 125 ppb between 3:30 and 4:30 p.m., thus exceeding the one-hour standard of 120 ppb. On July 20, with comparable overall traffic volumes across the metropolitan area but now including approximately 2% fleet participation by non-petroleum vehicles (over 30,000 km by NG buses alone), peak ozone concentration reached only 60 ppb. There is indication that both reduced traffic and the emissions properties of the gaseous-fueled vehicles were an important factor in this difference. In general, significant reduction of morning VOC and NOx transients by either eliminating actual trip starts or *virtually* eliminating them by gaseous fuel use has been shown to be an effective tool against ozone.

McCubbin and Delucchi[12] report that, for the United States urban areas as a whole, reducing motor vehicle combustion emissions of ozone precursors and fine particles by 10 percent from 1990 levels would yield a health cost reduction range of, respectively, \$0.02 to \$0.14 and \$13.74 to \$187.48 per kilogram emitted. (The higher values for particles reflect an association between uptake of ambient pollutant and mortality that is not yet established for ozone.) Every 10 kWh (about 4.6 km) of operating a late-model natural gas fueled transit bus rather than its diesel fueled counterpart thus saves up to 19 cents of health insult cost (Table 1).

CONCLUSIONS

Although gaseous-fueled vehicles may in the short run be more costly to acquire than their conventional counterparts, the longer-run health benefits of consistently operating these vehicles may outweigh their initial cost penalties by a wide margin, even in years after promulgation of stringent new emission standards for all light- and most heavy-duty vehicles. Applying the McCubbin-Delucchi metric to the Houston example of Table 2, potential daily health cost reductions due to lower precursor emissions in the summer 2005 ozone season range from just over $4 to $30 per day in the lower substitution case and from just under $10 to $65 in the higher case. However, a hundred natural gas transit buses each traveling 200 km/day saves 4.3 kg of fine PM, or up to $800 in health-related damages daily *throughout the year*. Even at $8 in health cost savings per bus per day, inducement for a fuel switch may be sufficient for those urban areas in need of stringent cuts in fine particle emissions in order to meet current and proposed ambient standards. The inducement should be even stronger in developing nations with urban areas plagued by chronically high loading of this pernicious pollutant.

NOTES AND REFERENCES

1. The Intergovernmental Panel on Climate Change (IPCC) has assigned a greenhouse warming potential of 21 to methane, where the value for carbon dioxide is one. This means that, mole for mole during its residency in the air, CH_4 will contribute 21 times the greenhouse effect of a corresponding mole of CO_2.

2. E.g., Royal Dutch/Shell Group, "Energy Needs, Choices and Possibilities: Scenarios to 2050" (2001), available at http://www.shell.com/library/publication/1,5833,,00.html?type=publication& siteid=1160&article=51852&archive=&year=&moduleid=1136

3. For example, the 2001 forum in Orlando featured panels on lead phase-out in Djakarta, Indonesia, diesel emissions mitigation in Hong Kong, alternative fuels in many Asian and Latin American cities, and ambient urban particle management throughout the developing world.

4. "Commuter chaos looms in New Delhi," *CNN.com MainPage,* 29 March 2001.

5. "New Delhi commuters torch buses as crisis hits transport," *Straits Times*, 4 April 2001.

6. Aneja, V.P., B.E Hartsell, D. -S. Kim and D. Grosjean, *J. Air & Waste Mgmt.* 49, 177-184 (February 1999).

7. Air Resources Board (California). Resolution 98-35, 27 August 1998.

8. Carter, W.P.L., "Updated Maximum Incremental Reactivity Scale for Regulatory Applications," report to California Air Resources Board, 6 August 1998.

9. DOE/Clean Cities "AirCred" AFV emission reduction credit calculation model, accessed 9/25/01 at *http:/appserver.es.anl.gov/aircred.html*.

10. Saricks, C. L., "Time Horizon for AFV Emission Savings Under Tier 2," Proc. 93rd Ann. Mtg. & Exhib., Air & Waste Mgmt. Assn., Salt Lake City, UT, 18-22 June, 2000.

11. Smith, Dennis, National Clean Cities Program, U.S. Department of Energy, unpublished information, 16 January 2002.

12. McCubbin, D.R., and M.A. Delucchi, *J. Transp. Econ. & Pol.* 33, 253-86 (September 1999).