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An evaluation of criteria for selecting vehicles fueled with diesel or compressed natural gas

Thomas Hesterberg¹, William Bunn¹, & Charles Lapin²
¹Navistar, Inc., 4201 Winfield Road, PO Box 1488, Warrenville, IL 60555 USA (email: tom.hesterga@navistar.com; william.bunn@navistar.com)
²Lapin & Associates, Glendale, CA 91208 USA (email: calapin@aol.com)

We reviewed selection criteria for diesel and compressed natural gas (CNG) fueled vehicles, comparing engine emissions, fire and safety, toxicity, economics, and operations. Diesel- and CNG-fueled vehicles with the latest emission-control technology, including engine-exhaust aftertreatment, have very similar emissions of regulated and unregulated compounds, particles through all size ranges, and greenhouse gases. Although toxicity data are limited, no significant toxicity differences of engine emissions were reported. Operating and maintenance costs are variable, with no consistent difference between diesel- and CNG-fueled vehicles. The main operating concern with CNG vehicles is that they are less fuel efficient. Higher infrastructure costs are involved with implementing a CNG-fueled vehicle fleet, giving diesel vehicles a distinct cost advantage over CNG vehicles. For a given budget, greater emissions reductions can thus be achieved with diesel+filter vehicles. Finally, diesel vehicles have a significant fire-and-safety advantage over CNG vehicles. In summary, infrastructure costs and fire-and-safety concerns are much greater for CNG-fueled vehicles. These considerations should be part of the decision-making process when selecting a fuel for a transportation system.

KEYWORDS: fuels, engines, automotive exhaust emissions, safety, greenhouse gases, cost-benefit analysis

Introduction

To improve air quality, many regions in the United States are considering alternative fuels such as compressed natural gas (CNG) to replace diesel. For example, California’s South Coast Air Quality Management District (SCAQMD), with a jurisdiction over an area that covers the counties of Los Angeles, Orange, Riverside, and San Bernardino, enacted rules several years ago encouraging government fleets to purchase natural gas vehicles (e.g., SCAQMD, 2001). In contrast to SCAQMD, other regions, such as the Massachusetts Bay Transit Authority (MBTA), have considered CNG to replace diesel to improve air quality, but decided to continue with diesel-fueled transit buses (Heywood et al. 2002). The opposite decisions of SCAQMD and MBTA may reflect different political forces and public perceptions in the respective outcomes (Hess, 2007; Valderrama & Beltran, 2007). Past decisions thus do not provide an objective path for fuel selection. To make the most beneficial fuel choice, several other criteria should ideally be considered, including, but not limited to, fire and safety, toxicity, economics, and operations. To aid decision makers in selecting a fuel for their transportation systems, this review summarizes the data available on these criteria and identifies substantiated similarities and differences between diesel- and CNG-fueled vehicles.

Emissions

Regulated and Nonregulated Compounds

Government officials frequently cite emissions benefits for the selection of CNG-fueled vehicles over their diesel alternatives. For example, SCAQMD favors CNG because, according to their research, diesel emissions account for 71-84% of the increase in cancer risk from toxic air pollutants (SCAQMD, 2000; 2008). In contrast, other studies of transit buses show that regulated and nonregulated emissions can be elevated with either diesel or CNG-fueled vehicles when there is no exhaust aftertreatment (Hesterberg et al. 2008). To meet emission standards set by the United States Environmental Protection Agency (EPA), new diesel- and CNG-fueled vehicles have exhaust emission-aftertreatment devices. The diesel-aftertreatment device is a catalyzed particulate filter (diesel+filter) that reduces particulate emissions. Similarly, the CNG-aftertreatment device is a catalyzed muffler (CNG+catalyst) that reduces total hydrocarbon emissions. These devices provide additional benefits by lowering the emissions of unregulated compounds...
Table 1 Regulated and related emissions and fuel economy in transit buses (in grams/mile).

| Compound                  | Diesel   | Diesel+Trap | CNG      | CNG+Three-Way Catalyst |
|---------------------------|----------|-------------|----------|-------------------------|
| Carbon                    | 7.71 ± 1.91a | 0.62 ± 1.66 | 14.16 ± 1.63 | 4.93 ± 2.34             |
| Monoxide                  | 21b      | 28          | 29       | 14                      |
| Total Hydrocarbons        | 1.11 ± 1.93 | 0.10 ± 1.84 | 18.95 ± 1.67 | 3.45 ± 2.36             |
| Particulate Matter        | 0.63 ± 0.04 | 0.03 ± 0.04 | 0.05 ± 0.04 | 0.04 ± 0.06             |
| Nitrogen Oxides           | 27.7 ± 3.1 | 26.2 ± 2.9  | 26.6 ± 2.8 | 7.7 ± 4.0               |
| Nitrogen Dioxide          | 1.68 ± 2.13 | 11.61 ± 1.35 | 4.12 ± 1.74 | 0.10 ± 3.69             |
| Carbon Dioxide            | 2384 ± 286 | 2836 ± 231  | 2703 ± 231 | 2291 ± 372              |
| Nonmethane Hydrocarbons   | 0.85 ± 0.65 | 0.03 ± 0.32 | 1.64 ± 0.25 | 0.29 ± 0.46             |
| Methane                   | 0.03 ± 12.63 | 0.00 ± 6.31 | 9.97 ± 10.30 | 2.75 ± 8.92             |
| Miles per Gallon          | 4.03 ± 0.29 | 3.22 ± 0.24 | 2.67 ± 0.29 | 3.43 ± 0.55             |

aMean ± standard error. bNumber of data points. cSignificantly different at p < 0.05 from 1-diesel, 2-diesel+trap, CNG, 4-CNG+TWC (Developed from data from Hesterberg et al. 2008).

(Tables 1 and 2). The exhaust-aftertreatment devices lower emissions for most compounds to similar levels in both diesel- and CNG-fueled buses. Hence, from a regulated and unregulated emissions standpoint, fuel choice offers no major advantage.

**Particle Size and Number**

In addition to regulated particle-mass emissions, air-quality regulators have shown a growing concern for particle size and number. Particular interest is focused on smaller particles in the ultratine [<100 nanometer (nm)] and nanoparticle (<50 nm) size ranges as they may present a greater health risk (Oberdorster et al. 1995; Seaton et al. 1995; Utell & Frampton, 2000). Several studies have compared emissions in terms of particle size and number (Holmen & Ayala, 2002; Holmen & Qu, 2004; Nylund et al. 2004; Thompson et al. 2004; Bose & Sundar, 2005; Nanzetta-Converse et al. 2005). The typical findings of Nylund et al. (2004) showed that diesel- and CNG-fueled transit buses equipped with exhaust aftertreatment (particulate filter and catalyzed muffler respectively) had 10-1,000-fold lower emissions of ultrafine particles and particles of other size ranges relative to diesel buses not equipped with exhaust aftertreatment (see Figure 1).

**Figure 1** Particle-size distribution of emissions from diesel- and CNG-fueled transit buses (Nylund et al. 2004).
Table 2 Selected nonregulated emissions in transit buses (milligrams/mile).

| Compound          | Diesel     | Diesel+Trap | CNG          | CNG+Three Way Catalyst |
|-------------------|------------|-------------|--------------|------------------------|
| Benzene           | 1.76 ± 1.54<sup>a</sup> | 0.41 ± 1.18 | 5.35 ± 0.94  | 0.00 ± 2.88            |
|                   | 7<sup>b</sup> | 12<sup>[3]</sup> | 19<sup>[2]</sup> | 2<sup>2</sup>          |
| Ethylene          | 37.42 ± 120.6 | 3.35 ± 112.81 | 653.5 ± 96.2 | 0.00 ± 225.63          |
|                   | 7<sup>7</sup> | 8<sup>[3]</sup> | 11<sup>[2,4]</sup> | 2<sup>[3]</sup>        |
| Propylene         | 2.66 ± 70.4  | 0.23 ± 64.31 | 184.08 ± 52.51 | 0.00 ± 111.39          |
|                   | 5<sup>[3]</sup> | 6<sup>[3]</sup> | 9<sup>[3]</sup> | 2<sup>2</sup>          |
| Ethylbenzene      | 2.05 ± 0.74  | 0.09 ± 0.52  | 0.74 ± 0.37  | 1.36 ± 1.05            |
|                   | 4<sup>7</sup> | 8           | 16<sup>2</sup> | 2<sup>2</sup>          |
| Toluene           | 0.33 ± 1.71  | 0.10 ± 1.21  | 4.79 ± 0.85  | 2.33 ± 2.41            |
|                   | 4<sup>7</sup> | 8           | 16<sup>2</sup> | 2<sup>2</sup>          |
| Formaldehyde      | 59 ± 209     | 3.42 ± 175   | 1113 ± 148   | 0 ± 391                |
|                   | 7<sup>7</sup> | 10          | 14<sup>[2,4]</sup> | 2<sup>[3]</sup>      |
| Acetaldehyde      | 27.91 ± 7.92 | 1.93 ± 6.63  | 37.28 ± 5.60 | 0.4 ± 14.82            |
|                   | 7<sup>[2]</sup> | 10          | 14<sup>[2,4]</sup> | 2<sup>[3]</sup>      |
| Total 2-Ring      | 7.200 ± 0.950 | 0.216 ± 0.623 | 0.385 ± 0.497 | 0.010 ± 1.170          |
| Polycyclic Aromatic Hydrocarbons | [2-4] | 7<sup>[1,3]</sup> | [1] | [1] |
| Total 3-Ring      | 0.650 ± 0.135 | 0.098 ± 0.105 | 0.102 ± 0.080 | 0.002 ± 0.234          |
| Polycyclic Aromatic Hydrocarbons | [2-4] | 10          | 17<sup>2</sup> | 2<sup>2</sup>          |
| Total 4- and Higher | 0.119 ± 0.026 | 0.10 ± 0.02  | 0.021 ± 0.016 | 0.000 ± 0.045          |
| Ring Polycyclic   | 6<sup>[2-4]</sup> | 10<sup>[1,1]</sup> | 17<sup>[1,1]</sup> | 2<sup>[1,1]</sup> |
| Aromatic Hydrocarbons<sup>d</sup> | [2-4] | 10<sup>[1,1]</sup> | 17<sup>[1,1]</sup> | 2<sup>[1,1]</sup> |

<sup>a</sup>Mean ± standard error. <sup>b</sup>Number of data points. <sup>c</sup>Significantly different at p < 0.05 from 1-diesel, 2-diesel+trap, 3-CNG, 4-CNG+TWC. <sup>d</sup>Fluoranthenes and pyrenes only (Developed from data from Hesterberg et al. 2008).

A California Air Resources Board (CARB) study noted that under certain test conditions, both diesel+filter and CNG-fueled buses had higher nanoparticle concentrations than the diesel without aftertreatment (Holmen & Ayala, 2002). This effect may be an artifact of the test conditions (Burtscher, 2005) and further research is needed to understand the significance of these findings. This ostensible problem may not be an issue, as recent research found that the latest model of diesel+filter aftertreatment devices readily removed nanoparticles from the exhaust (Kittelson et al. 2006).

An early particle-measurement study found that CNG-fueled transit buses had elevations of nanoparticles (Eastlake, 1999) and similar results were noted for liquefied natural gas (LNG) transit buses (Gautam et al. 2004). The source of the higher CNG nanoparticles was not identified, but oil consumption may play a role. Tonegawa et al. (2006) reported that improving oil consumption with better piston clearances, piston rings, and oil jets could reduce ultrafine and nanoparticle emissions in CNG engines. Alternatively, a recent study by Lanni et al. (2003) suggests that backfiring might explain the higher CNG-particle numbers. The addition of a catalyzed muffler (CNG+catalyst) to the CNG bus produced reductions in particle numbers to levels similar to the diesel+filter bus (Nylund et al. 2004). Finally, in a research application for a CNG bus, the combination of catalyzed particulate filter with a catalyzed muffler reduced particle numbers to ambient air levels (Gautam et al. 2005; Eaves, 2006; Gautam, 2006; Harris, 2006).

In summary, for vehicles equipped with new emission-control technology (diesels with catalyzed particulate filters and CNG with catalyzed mufflers), the numbers of particles, in all size ranges, in exhaust emissions are reduced similarly to levels 10-100 times lower than emissions levels from vehicles not equipped with exhaust aftertreatment. Thus, from the standpoint of emissions particle size and number, fuel choice seems to offer no major advantage.
Greenhouse Gas Emissions

The transportation sector is a major contributor of anthropogenic greenhouse gas (GHG) emissions, including carbon dioxide (CO₂), methane, and nitrous oxide (N₂O). Emissions are compared by measuring GHGs in engine exhaust (tailpipe studies) or by estimating fuel-lifecycle GHG emissions using well-to-wheels (WTW) methodologies (e.g., Ahlvik & Brandberg, 2000; Beer et al. 2000; 2001; 2002; Brinkman, 2001; General Motors Corporation et al. 2001; Seguelong et al. 2003; Brinkman et al. 2005; Pont, 2007). To make comprehensive comparisons, analysts usually convert GHG emissions to their CO₂ equivalents and then sum them. Fuel-lifecycle studies contrast the emissions effects of production, transportation, and distribution activities in addition to actual end use in vehicles.

Several GHG-tailpipe studies did not find significant differences between diesel- and CNG-fueled vehicles (Northeast Advanced Vehicle Consortium, 2000; Davies et al. 2005; Hesterberg et al. 2008). Side-by-side comparisons of GHG emissions weighted for global warming potential (a value used to compare the abilities of different GHGs to trap heat in the atmosphere) found similar emissions for transit buses (Northeast Advanced Vehicle Consortium, 2000; Davies et al. 2005; Hesterberg et al. 2008) and refuse trucks (Davies et al. 2005; Hesterberg et al. 2008) (Table 3). While most of the methane in CNG fuel is combusted, a small portion of it is unburned and emitted in the exhaust. In terms of direct global warming potential, methane is 23 times more potent than CO₂ over a 100-year time horizon (Ramawasamy et al. 2001), but methane emissions contribute less than 10-20% of a CNG vehicle’s emission-CO₂ equivalents, as much more CO₂ is emitted. Ullman et al. (2003) found that a diesel-school bus equipped with a catalyzed particulate filter had higher CO₂ emissions than a CNG bus. When a larger sample size was studied (18 diesel buses, 68 CNG buses), the results were less influenced by individual bus variability and the differences was not observed (Davies et al. 2005). Additionally, LeTavec et al. (2002) did not find an increase in CO₂ emissions from school buses that were retrofitted with traps. In passenger cars, CNG has lower vehicle lifetime CO₂ emissions for short trips (less than 160 kilometers), but higher emissions for longer trips due to lower fuel efficiency caused by their heavy fuel-storage systems (MacLean & Lave, 2000). Other factors that affect fuel efficiency, such as type of driving (stop-and-go versus cruising), will also affect CO₂ emissions.

Most of the lifecycle analyses (LCAs) of GHG emissions evaluated in this review have found no significant difference between diesel- and CNG-fueled vehicles (see Table 4). A minority of studies reported either diesel or CNG to have lower GHG emissions. For example, two investigations found that CNG-transit buses had 21-53% more GHG emissions than diesel (Ahlvik & Brandberg, 2000; Seguelong et al. 2003), while two studies reported no significant differences (Beer et al. 2000; Silva et al. 2006). For the analyses where CNG-fueled vehicles had higher GHG emissions, the differences were mostly from higher CNG methane emissions, both from methane production and engine exhaust. While methane has lower carbon content than diesel fuel, this GHG advantage is eliminated by the higher fuel use required by CNG engines due to their lower fuel efficiency (Ahlvik & Brandberg, 2000). Similar conflicting results were found for heavy-duty trucks; some analyses reported that CNG heavy-duty trucks had lower GHG emissions on a distance-driven basis than diesels (Beer et al. 2000; 2001; 2002; Pont, 2007). The reasons for the conflicting results are not clear-cut, but may arise from differences in assumptions, LCA-model design, or model inputs and parameters.

In several LCA studies of light-duty trucks (Brinkman, 2001; General Motors Corporation et al. 2001; Brinkman et al. 2005) and passenger cars (Lave et al. 2000; MacLean & Lave, 2000; Jackson et al. 2003; Beer et al. 2004; Edwards et al. 2004; Unnasch, 2006), diesel- and CNG-fueled vehicles had similar GHG emissions. When looking at contemporary vehicles, diesel-passenger cars appeared to have lower GHG emissions (Pickrell, 2003; Toyota & Mizuho, 2004). Perhaps more relevant in the longer term, 2010 CNG vehicles had slightly lower GHG emissions with the main difference attributable to fuel production rather than engine emissions (Edwards et al. 2007; Farrell et al. 2007).

Table 3 Greenhouse gas comparison in transit buses (in grams/mile).

| Fuel Types | Carbon Dioxide | Methane | CO₂ Equivalents |
|------------|----------------|---------|----------------|
|            | 2965 ± 401     | 0.02 ± 4.96 | 2966 ± 479 |
| Pooled Diesel (15) | 2587 ± 331 | 18.08 ± 4.09 | 2967 ± 395 |
| Pooled CNG (22) | N.S. | N.S. | N.S. |

aMean ± standard error. bNumber of data points. cN.S. = Not significantly different at p < 0.05 (Developed from data from Hesterberg et al. 2008).
Table 4: WTW comparisons of greenhouse gas emissions between diesel- and CNG-fueled vehicles.

| Vehicle Types   | Diesel (gCO2 eq/km) | CNG (gCO2 eq/km) | Greater than 10% Different (higher vehicle) | Reference                      |
|-----------------|---------------------|------------------|---------------------------------------------|--------------------------------|
| Transit Bus     | 1759                | 1604             | No                                          | Beer et al. 2000               |
|                 | 2277                | 2070             | No                                          | Silva et al. 2006              |
| 100%            | 121-142%           | Yes (CNG)        | Ahlvik & Brandberg, 2000                    |
|                  | 1759                | 2277             | Yes (CNG)                                   | Seguelong et al. 2003          |
| Heavy-Duty Truck| 1656                | 1397             | Yes (D)                                     | Beer et al. 2000               |
|                 | 2018                | 1553             | Yes (D)                                     | Pont, 2007                     |
| Light-Duty Truck| 298                 | 311              | No                                          | General Motors Corporation et al. 2001 |
|                 | 261                 | 261              | No                                          | Brinkman et al. 2005           |
| Passenger Car   | 248                 | 269              | No                                          | Beer et al. 2004               |
|                 | 166                 | 166              | No                                          | Edwards et al. 2004            |
|                 | 161                 | 171              | No                                          | Jackson et al. 2003            |
| 52,000 CO2 eq/lifetime | 55,000 CO2 eq/lifetime | No | Lave et al. 2000; MacLean & Lave, 2000 | Unnasch, 2006 |
| 227             | 233                 | No               |                                            |
| 91              | 68                  | Yes (D)          | Farrell et al. 2007                         |
| 166             | 145                 | Yes (D)          | Edwards et al. 2007                         |
| 497             | 609                 | Yes (CNG)        | Pickrell, 2003                              |
| 25% lower than gasoline | 20% lower than gasoline | Yes (CNG) | Toyota & Mizuho, 2004 |

In summary, the majority of tailpipe and LCA studies found small or insignificant differences for GHG emissions from diesel- and CNG-fueled vehicles. Where some LCA studies report significant differences, equally credible LCA studies report otherwise. The differences probably arise from the inherent complexity of the quantitative models used to estimate emissions over the two fuels’ life cycles (SAIC, 2006). Each study made different decisions on how to model fuel production, transportation and delivery systems, and end-use emissions. In their guidance on interpreting LCAs, EPA noted:

"[I]n some cases, it may not be possible to state that one alternative is better than the others because of the uncertainty in the final results. This does not imply that efforts have been wasted. The LCA process will still provide decision makers with a better understanding of the environmental and health impacts associated with each alternative. (SIAC, 2006)."

Fire and Safety

Given the much greater flammability of CNG fuel compared to diesel fuel, it is important to determine if flammability and its impact on fire and safety should be a decision criterion when selecting a fuel. Despite the use of CNG fuel for several decades, this question has only recently been studied. In 2002, researchers compared the fire-safety risks associated with typical CNG and diesel school-bus systems including bus and fuel infrastructure (Chamberlain et al. 2002; Chamberlain & Modarres, 2005). Because historical data were not available for CNG buses, the researchers used probabilistic risk-assessment methodologies as practiced in the nuclear and aerospace industries. A fire fatality-risk index for CNG buses was developed to allow comparisons to historical diesel-bus data for the United States. The researchers examined risks associated with gas distribution, refueling, and operational and maintenance practices. The methodology then entailed determining the likelihood of risk scenarios by using fault-tree and event-tree modeling techniques along with generic data. Consequence analysis considered accident locations and lethality from fires. The researchers estimated the subsequent effects on people located within a certain distance from such fires and determined total risk by summing the risk associated with each fire/accident scenario. The projected total fire-fatality risk for CNG buses was approximately 0.23 per 100-million miles of operation and 0.16 passenger fatalities per 100-million miles. While the CNG bus passenger-fatality risk was nearly 10 times lower than overall deaths from driving in the United States in 2007 (NCSA, 2009), it was 230 times higher than that for diesel buses. In addition, the total fire-fatality risk from diesel school-bus fires of 0.091 total fatalities per 100-million miles was 2.5 times lower than the CNG buses. Finally, for worst-case fire scenarios,
CNG buses had much higher fatalities than diesel buses. Diesel-fueled vehicles thus are clearly superior from a fire- and safety-aspect.

Comparative Toxicity Studies

Mutagenicity

Mutagenicity is a measure of a compound’s ability to cause permanent changes in the genetic information contained in living cells. Mutagenic compounds have been associated with adverse health effects such as cancer and birth defects. Emissions from diesel- and CNG-fueled engines contain mutagenic compounds (e.g., Lewtas, 1983; Gragg, 1995; Lapin et al. 2002). Lewtas (1983) first reported mutagenic activity in solvent extracts of diesel-particle matter. Braun et al. (1987) found that natural gas combustion also produces mutagenic materials. In addition, the mutagenic compound dinitrofluoranthene was found in diesel emissions and in incomplete combustion products of liquefied petroleum gas (LPG) (Nakagawa et al. 1987).

Prompted by these concerns, CARB conducted the first side-by-side comparison tests in 2001-2002 and these studies found that CNG-transit buses had mutagenic emissions 3-6 times higher on a mutations-per-mile basis than diesel+filter buses (Kado et al. 2005; Okamoto et al. 2006). The emitted particles from the CNG buses’ emissions were 7-20 times more mutagenic than the emissions from the diesel+filter bus (Table 5). When CNG transit-bus exhausts were equipped with a catalyzed muffler, mutagenic activity was lowered, an outcome that suggests some of the mutagenic compounds were destroyed by the catalyzed muffler. However, the levels were still higher than diesel+filter (Okamoto et al. 2006).

Studies from Italy (Turrio-Baldassarri et al. 2004; 2006) and Finland (Nylund et al. 2004) found little or no mutagenicity in CNG-particle emissions and higher mutagenicity in diesel emissions, the opposite trend observed in the CARB study. The difference may be due to the model year studied with the CARB CNG buses being the oldest. Recent improvements in CNG-aftertreatment devices may have resulted in more destruction of mutagenic compounds in the newer buses. Regardless, there are problems with overinterpreting mutagenicity test results (CARB, 2002). Mutagenicity tests provide an indication of potentially toxic compounds, but the results cannot be used directly to determine health risk. Because of this limitation, and the equivocal test results, mutagenicity potential may not be a useful fuel-selection criterion.

Table 5 Mutagenicity studies.

| Fuel + Aftertreatment | Mutations/mg |
|-----------------------|--------------|
|                       | TA 98+S9 | TA 98-S9 | TA 100+S9 | TA 100-S9 |
| CARB Study (Kado et al. 2005; Okamoto et al. 2006) | Central Business District Test Cycle |
| CNG no aftertreatment | 27 | 50 | 12 | 8 |
| CNG + aftertreatment | 7.6 | 15 | 9.5 | 5.9 |
| Diesel + filter | 2.8 | 6.7 | 0 | 0 |
| Steady State (55 mph) Test Cycle |
| CNG no aftertreatment | 40 | 80 | 12 | 10 |
| CNG + aftertreatment | 28 | 37 | 23 | 8 |
| Diesel + filter | 25 | 51 | 9.6 | 7.3 |
| Urban Dynamometer Driving Schedule Test Cycle |
| CNG no aftertreatment | 37 | 73 | 13 | 6 |
| Diesel + filter | 6.9 | 8.8 | 6.8 | 2.5 |
| New York City Bus Test Cycle |
| CNG no aftertreatment | 19 | 39 | 5 | 15 |
| Diesel + filter | 3.5 | 11 | 0 | 0 |
| VTT Study (Nylund et al. 2004) | Braunschweig Test Cycle |
| Diesel + filter | 1.1 |
| CNG + aftertreatment | 0.2 |

Acute Toxicity

There are limited toxicity data that provide direct comparisons between diesel- and CNG-fueled vehicles. Diesel-engine exhaust has been extensively studied over the last three decades, but CNG-engine emissions have only recently received similar attention. This disparity in data reflects public health concerns, the relatively greater use of diesel fuel, and the expense of toxicity tests. One recent study assessed acute toxicity of emissions from CNG, diesel, and gasoline vehicles in rat lungs (Seagrave et al. 2002; 2005). Lung responses to CNG were generally mild, with greater inflammation and cytotoxicity responses for the gasoline and diesel (no aftertreatment) samples. McDonald et al. (2004) found that equipping a diesel engine with a catalyzed particulate filter eliminated inflammation, cytotoxicity, tissue changes, and immune suppression. The reduction of emissions of compounds such as those listed in Tables 1 and 2 probably accounts for most of the reduced toxicity. While the diesel+filter and CNG results are not directly comparable because of different engine sizes and sample collection conditions, the data suggest that acute toxicity of engine emissions would be similar between CNG vehicles equipped with exhaust aftertreatment and new technology diesel.

Economics Studies

Diesel, with its established refueling infrastructure, has a distinct economic advantage over CNG-
fueled vehicles (Toy et al. 2000). CNG vehicles are more expensive to buy, US$320,000 compared to US$270,000 for a diesel-transit bus (Cannon & Sun, 2000; Eudy, 2002). Infrastructure changes for refueling stations can cost US$900,000 to US$5,000,000 and depot-modification costs can run US$300,000 to US$15,000,000 (Cannon & Sun, 2000; Watt, 2000; Eudy, 2002; Hunt, 2002; Barnitt & Chandler, 2006). The lack of an adequate refueling network, driven by the costs of building such a system, has hampered CNG development (Di Pascoli & Aldo, 2001; NREL, 2001; Chandler et al. 2002).

New York City Transit conducted a cost-comparison study based on its operating experiences with diesel- and CNG-fueled buses (Lowell et al. 2003). The agency found costs to be six times greater for CNG-transit buses compared to diesel+filter buses (annualized net present value of total costs for 200 buses at one depot: US$2,300,000 vs. US$300,000). The main contributors to the higher CNG costs include “increased capital costs for purchase of buses and installation of fueling infrastructure, and increased operating costs for purchase of fuel, bus maintenance, and fuel station maintenance.” Infrastructure changes included construction of a natural gas-fueling station and safety modifications of the bus depot (e.g., methane detectors, increased ventilation, removal of ignition sources). These costs may represent the high side as construction is more expensive in New York City than in most other parts of the country.

Cohen et al. (2003) estimated the incremental cost effectiveness of diesel- and CNG-transit buses relative to conventional diesel in the United States. The researchers calculated cost effectiveness as the ratio of acquisition and operating costs over health losses. Health losses (death and disease) were due primarily to particulate matter and ozone exposures. Cohen et al. (2003) found that while CNG provided 50% more health benefits per bus, the diesel bus was 5-8 times more cost-effective due to its lower costs. However, in school buses, CNG and diesel+filter buses had similar health benefits per bus, but the diesel+filter buses were 10 times more cost-effective because of their lower costs (Cohen, 2005). In commenting on Cohen et al. (2003), McClellan & Lapin (2003) observed that instead of using the same funds to upgrade a transit-bus fleet to CNG, one could get 6 times more particulate-emission reductions with the diesel+filter option. This outcome is because the additional costs of buying CNG buses are much greater than diesel+filter buses so a transit company can afford to replace more of its fleet with cleaner buses using the diesel+filter option. Furthermore, they noted that since budgets for the purchase of new buses are regularly subject to tight constraints, and because newer (post-2007) CNG and diesel buses both have similarly very low emissions, fleet managers should give extra emphasis to the added costs of buying CNG buses. Such circumstances favor diesel over CNG based on this selection criterion.

In contrast to Cohen et al. (2003), Johansson (1999) found that in Europe CNG had a cost-effectiveness advantage in urban settings, while diesel, with lower infrastructure costs, was more cost effective in rural settings. Some of the differences between the two studies may reflect regional difference between the United States and Europe. More importantly, Johansson did not use emission factors that reflect emission reductions achieved with current diesel particulate-filter technology. Schubert & Fable (2005) found no differences in the future lifecycle costs of diesel and natural gas heavy-duty engines for refuse haulers, transit buses, and short-haul trucks. The main shortcoming of the Schubert & Fable study was that it did not evaluate the far greater infrastructure costs for CNG.

In summary, diesel vehicles have a distinct cost advantage over CNG vehicles. For a given budget, more diesel+filter vehicles can be purchased providing more emissions reductions when older, higher emitting vehicles are replaced.

Operational Issues

The main operational issue with CNG vehicles is their lower fuel economy [i.e., miles per gallon (mpg): transit buses by 16%–25% (Barnitt & Chandler, 2006; Chandler et al. 2006), tractor-trailers by 23% (Lyford-Pike, 2003), and delivery trucks by 27% (Chandler et al. 2002)]. The lower energy content of CNG fuel, the extra weight of the CNG fuel tanks, and the lower efficiency of CNG engines contribute to the lower fuel economy of CNG vehicles (Pelkmans et al. 2002).

Given the lower fuel economy for CNG, it is not surprising that for early transit-bus fleets road calls were higher for CNG buses, mostly for fuel-system problems including running out of fuel (Motta et al. 1996). Improvements in engine design and better bus-driver training and awareness seem to have alleviated this problem, as recent CNG transit-bus fleets experienced 16-44% more miles between road calls than their diesel counterparts (Barnitt & Chandler, 2006; Chandler et al. 2006).

Maintenance and operating costs vary and give a mixed picture of CNG- versus diesel-fleets. In some cases, maintenance costs were 15–29% higher for CNG vehicles (replacement of spark plugs, spark wires, and fuel regulators and repairs of clutches and transmissions) (Chandler et al. 2002; Hunt, 2002). However, in another study maintenance was 12%
lower for CNG vehicles (Chandler et al. 2006), probably due to better preventative maintenance. The age of the buses is important, as older CNG buses need to adhere closely to preventative maintenance schedules to avoid significant emissions degradation (Hunt, 2002).

As with maintenance costs, UPS’s Hartford fleet reported total operating costs (including fuel and maintenance costs for running the trucks in service, but not including driver-labor costs) that were 19% higher for CNG vehicles (Chandler et al. 2002). This fleet consisted of early production models that had problems with spark plugs, spark wires, and fuel regulators. For the Washington Metropolitan Area Transit Authority, total operating costs for CNG buses were similar to diesel vehicles (Chandler et al. 2006). Interviews with 42 transit agencies identified training, fueling infrastructure, commitment to the CNG program, and public support as critical to successful operation of CNG fleets (Eudy, 2002).

In summary, the main operational issue with CNG vehicles is their 16–27% lower fuel efficiency. Operating and maintenance costs are variable with no consistent difference between diesel- and CNG-fueled vehicles.

**Summary**

We reviewed data potentially useful to choosing the most beneficial fuel, including data on emissions, fire and safety, toxicity, economics, and operations. Table 6 summarizes these observations. Diesel- and CNG-fueled vehicles with the latest emission-control technology, including engine-exhaust aftertreatment, have very similar emissions of regulated and unregulated compounds and particles through all size ranges. Likewise, GHG emissions, measured at the tailpipe and estimated over the fuel lifecycle, are similar. In addition, no important toxicity differences were reported. While operating and maintenance costs are variable, with no consistent differences between diesel- and CNG-fueled vehicles, CNG vehicles are less fuel-efficient. Significant infrastructure costs are involved with implementing a CNG fueled-vehicle fleet, potentially limiting availability of funds for vehicle replacement. Finally, diesel vehicles have a distinct fire- and safety-advantage over CNG vehicles. The selection factors with the clearest differences are thus infrastructure costs and fire and safety concerns, and these are much greater for CNG fuel. These considerations should be part of the decision-making process when selecting a fuel for a transportation system.

**Authors’ Note**

Thomas Hesterberg and William Bunn are employed by Navistar, a major manufacturer of diesel engines and vehicles. Charles Lapin is a consultant to Navistar. All authors declare no other financial interest in the subject matter of this study. Results and conclusions presented in this paper were drawn independent of the interests of the sponsor.

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