TRB-13-2945

FUEL CONSUMPTION AND COST SAVINGS OF CLASS 8 HEAVY-DUTY TRUCKS POWERED BY NATURAL GAS

November 15, 2012
Word Count: 7,543 (including 5 figures and 2 tables)

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Paper submitted for peer review for the 92nd Transportation Research Board Annual Meeting.
Resubmission Date: November 15, 2012

TRB 2013 Annual Meeting Paper revised from original submittal.
ABSTRACT

We compare the fuel consumption and greenhouse gas emissions of natural gas and diesel heavy-duty (HD) class 8 trucks under consistent simulated drive cycle conditions. Our study includes both conventional and hybrid HD trucks operating with either natural gas spark ignition (SI) or diesel engines, and we compare results of the simulated fuel efficiencies, fuel costs, and payback periods. While natural gas trucks achieve somewhat lower fuel economy than diesel, their CO$_2$ emissions and costs are significantly less than comparable diesel trucks. Both diesel- and natural gas-powered hybrid trucks have significantly improved fuel economy, reasonable cost savings and payback time, and lower CO$_2$ emissions under city driving conditions. However, under freeway-dominant driving conditions, the overall benefits of hybridization are considerably less. Based on payback period alone, non-hybrid natural gas trucks appear to be the most economic option for both urban and freeway driving environments. Economic considerations of the impact of using natural gas as a fuel for class 8 trucks on future natural gas supply and price are also presented, and the impact of a transition to natural gas use in the trucking sector is expected to be quite limited.
INTRODUCTION

Current U.S. petroleum consumption is approximately 19 million barrels per day, nearly 16% of which is used as fuel for heavy-duty (HD) trucks. However, domestic petroleum production is just 7.51 million barrel per day in 2010 (1). The remaining petroleum is obtained from foreign sources. Therefore, developing clean and sustainable alternative energy sources for HD trucks, particularly for Class 8 HD trucks, is necessary to achieve energy sustainability and support future economic development.

Natural gas is considered to be a cleaner burning fuel than either diesel or gasoline (2-6). Perhaps most importantly, natural gas (NG) can play a vital role in reducing our reliance on foreign oil by displacing the conventional oil-based fuels consumed in highway transportation (7). Although there is concern that the world’s conventional oil supply will begin to decline following a supply peak (8), there is a vast amount of natural gas available for domestic production. The U.S. Energy Information Administration (EIA) estimates that 2,214 trillion cubic feet (TCF) of natural gas are technically recoverable in the United States. At the current rate of U.S. natural gas consumption in 2010 (about 24 TCF per year), this volume of natural gas is sufficient to last more than 90 years (9). Of particular importance, U.S. natural gas production is currently growing even faster than consumption (7), which means the nation will have no need to import natural gas in the foreseeable future. Vehicle fuel use currently accounts for less than 0.1% of U.S. natural gas consumption (10). The present low-cost excess natural gas supply therefore represents a significant opportunity as a transportation energy source.

To evaluate whether HD truck transportation is an efficient and economically feasible application for natural gas use, it is important to understand the real-world fuel economy, engine efficiency, performance, and cost savings of Class 8 HD trucks powered by natural gas as an alternative fuel to the conventional diesel vehicle. It is also of interest to compare the benefits among natural gas engine technology, vehicle hybridization, and the combination of both technologies as a highly efficient HD truck powertrain option. This paper focuses on the simulation of both conventional and hybrid natural gas-powered Class 8 HD trucks powered by spark ignition (SI) engines over multiple city and freeway-dominant driving cycles. We compare the fuel consumption and greenhouse gas emissions of natural gas- and diesel-powered HD trucks for the same vehicle usage, and challenges associated with natural gas engine efficiency and potential improvements are identified. Additionally, an analysis is performed of the fuel cost savings and payback period for CNG-powered class 8 vehicles. The effect of the truck mass on fuel economy and cost savings is also studied. Finally, the impact of using natural gas as a fuel for class 8 trucks on the future natural gas supply and price is discussed.

Literature Review of Natural Gas Fuel Economy and Cost Analysis

Natural gas light-duty (LD) vehicles have been successfully developed by automobile manufacturers for many years (11-13). The latest natural gas LD vehicle in the current commercial market is the 2012 Honda Civic GX (vs. the gasoline-powered LX). These vehicles show that while meeting the Super Ultra Low Emission Vehicle (SULEV) exhaust emission standards, compressed natural gas (CNG) for LD vehicles achieves a comparable or slightly higher fuel economy than gasoline as a result of increasing the natural gas engine’s compression ratio. The higher compression ratio is possible since natural gas has a very high octane number, so knocking does not occur easily (12). Very limited studies have been conducted of hybrid technology integrated with natural gas LD vehicles (14).

The vehicles most suited for natural gas use are medium- and heavy-duty trucks, which are mainly powered by diesel. In the U.S., natural gas-powered HD trucks have been relatively uncommon in the past, although truck manufacturers have recently begun to provide additional natural gas vehicle offerings, including fuel storage options for both CNG and liquefied natural gas (LNG) (15). Among current natural gas vehicles that are commercially available are transit buses, school buses, garbage trucks, class 8 tractors, pickup trucks, and vans (3-6, 15-16). Diesel and CNG medium-duty (MD) city buses were compared and it was found that the CNG MD buses averaged 17% lower in-use fuel economy than the diesel buses (5). The result from a Viking Tractor powered by a 8.3-L CNG Cummins engine (6)
shows a 23.2% penalty in fuel economy for the natural gas tractors. Chassis dynamometer tests for a 15,500 kg bus powered by a combined CNG/diesel show 11% less fuel efficiency than a comparable diesel bus. The reports available for LNG/diesel vehicles are still limited, but the preliminary results illustrate that LNG’s higher energy density makes its use attractive for HD vehicles with high range requirements and limited fuel storage space (15, 17-18). Most of these experimental studies were carried out over lab chassis dynamometer and city driving cycles. Evaluations of natural gas-powered Class 8 trucks driving in typical freeway-dominant conditions are still insufficient. The studies available also did not account for the effect of truck mass or cargo load. Furthermore, comparison of the benefits among natural gas technology, hybrid technology, and their combination have not been conducted and reported, as far as we are aware.

Similar to the status of fuel economy for natural gas HD trucks, economic analyses of natural gas and hybridized Class 8 HD trucks are limited or inadequate since materials and manufacturing costs vary from year to year (4, 16, 19). A recent study found that more than 10 years were necessary to return the original investment cost of a 2012 Honda CNG Civic GX (vs. the gasoline-powered LX) (20). This return period is not likely to be perceived by the consumer as economically attractive. However, preliminary estimations show that natural gas savings are very substantial in heavy-duty vehicles, particularly Class 8 HD trucks (7). This is because of the significant fuel consumption resulting from the high mileages traveled annually with long-haul HD vehicles (7). Also, recent prices of natural gas have been less than half the cost of diesel on a fuel energy basis, and natural gas prices have been reasonably stable to slightly declining in recent years, while oil prices have been steadily rising (7, 9, 21). These price trends will make the fuel price ratio between natural gas and diesel even more favorable in the future. Therefore, utilizing accurate fuel economy data and up-to-date cost data to estimate the payback time and vehicle lifespan cost savings for natural gas HD trucks is of particular importance for decision makers, manufacturers, and HD truck fleets in order to evaluate the effectiveness and cost benefits of the technology (7, 19).

ANALYSIS METHODOLOGY

Truck Modeling

The use of steady-state engine maps for conducting fuel economy analysis provides simple and accurate performance estimates for vehicle transient fuel consumption simulations (22). One of the vehicle simulation packages utilizing such component steady-state maps is Autonomie (23), which is a plug-and-play vehicle model architecture designed to evaluate powertrain technologies for improving fuel economy, pollutant emissions reduction, and vehicle performance, and runs in the Matlab environment. Thus, Autonomie was chosen as our vehicle simulation platform for predicting and comparing fuel consumption and emissions from diesel and natural gas HD trucks.

A conventional Class 8 heavy-duty truck configuration was selected in Autonomie and the default model has been modified to represent our HD truck baseline case. The engine parameters for the model were tuned to be representative of a 15-L 6-cylinder Cummins ISX 475 diesel engine (engine rated power: 475hp) and an Eaton Fuller RT-11710B 10-Speed manual transmission was selected for the drivetrain. A HD diesel engine map available in Autonomie was used for the simulations, but the engine model was scaled using the rated engine power of the Cummins engine. The truck coefficients of drag and rolling resistance used in the simulation were 0.58 and 0.007, respectively, while the frontal area was taken to be 10 m². We also utilized Autonomie to develop a Class 8 heavy-duty hybrid truck model, the hybrid powertrain of which utilized a pre-transmission parallel configuration with a single motor between the clutch and gearbox and was based on details available in the open literature. The selected electric motor and battery were both rated at 200 kW (24). Other powertrain components and parameters are the same as those utilized in the conventional HD truck simulations, but the mass was increased by 400 kg to account for the battery, electric motor and control system in the hybrid version.
In simulating natural gas-powered HD trucks, a 15-L natural gas spark-ignited (SI) engine with a turbocharger replaced the Cummins ISX 475 engine in the above conventional and hybrid trucks without changing any of the other vehicle parameters in the model, except for the vehicle weight. The natural gas engine map was extracted from reference (17) and (23) and was implemented in the form of Simulink functions in Autonomie. We assume that (1) both the diesel and natural gas engines are compatible with the vehicle powertrain and drivetrain of the simulated vehicles; and (2) 400 kg accounts for the weight penalty of the natural gas fueling and storage system. With these simple assumptions, we expect the truck models can reasonably reflect the general performance trend of diesel and natural gas trucks.

**Transient Driving Cycles**

To evaluate the fuel consumption and greenhouse gas (GHG) emissions of class 8 trucks over real road conditions, we chose to simulate multiple driving cycles, including UDDS Truck and ORNL4S chassis dynamometer driving cycles and freeway-dominant driving cycles (FDDC), see Figure 1. The UDDS Truck cycle represents city driving conditions (i.e. 5.45 miles traveled during 1051 seconds of travel), and the ORNL4S cycle presented by ORNL (25) characterizes non-interstate highway driving conditions (i.e. 15.40 miles traveled during 1277 s of travel). Unlike UDDS Truck and ORNL4S cycles which do not consider real road conditions such as grade, two freeway-dominant driving cycles (FDDC) were selected from ORNL duty cycle data (25). The drive cycles were measured during normal operations from class-8 tractor-trailers in a fleet engaged in freight delivery. The data include transient fuel consumption, engine speed and torque, gear ratio, vehicle speed, elevation and so on. The first selected driving cycle (referred to as FDDC A) represents 139 miles of travel with a maximum speed of 84.7 mph over a 2.7 hour period (see Figure 1(c)). There was an overall elevation change (minimum to maximum elevation) of 133m measured during the actual driving, and the variations of elevation throughout the drive cycle were included in the analysis to account for the gravitational force acting on the vehicle. The second selected driving cycle (referred to as FDDC B) covers 202 miles with a maximum speed of 77.7 mph during about 4.7 hours of driving, and the cycle included an elevation change of 470m (see Figure 1(d)). The elevation variations during the drive cycle were modeled for the FDDC B analysis also. These driving cycles are able to reasonably reflect the impact of real road conditions on truck fuel consumption and GHG emissions over city and highway driving conditions.

**Cost-Savings Analysis Methodology**

The cost saving analysis focuses on the payback time and net vehicle lifespan cost savings for natural gas and hybrid technologies in Class 8 HD trucks. The analysis presented is based on a CNG fuel system but could be easily adjusted to consider a LNG fuel system as well. To simplify the analysis, we did not consider truck maintenance costs and assumed the fuel price differential between diesel and natural gas to be constant. The payback time was calculated using the initial investment cost for the natural gas fueling system, hybridization technology or both, divided by the annual fuel consumption cost savings for each vehicle relative to a conventional diesel vehicle. The net vehicle lifespan cost saving was then calculated as the difference between the vehicle lifespan fuel consumption cost saving and the initial investment cost.

The initial investment cost for natural gas fueling system accounts for fuel storage and non-storage-tank systems. The non-storage-tank incremental costs are assumed to be $30,000 for Class 8 vehicles, and fuel storage costs are about $350 per gallon diesel equivalent for CNG (26). For the hybridized vehicle cases, the OEM price of a typical hybrid system depends on the type and size of the vehicle, and the total vehicle can cost 40 - 70 percent more than a non-hybrid model (27). Thus we estimated a Class 8 HD hybrid truck adds $60,000, which was based on the following assumptions: (1) a typical heavy-duty truck chassis costs about $120,000; (2) hybrid technology increases the cost by 50% relative to a non-hybrid model. This hybrid cost is very close to the recent OEM analysis (19). It is expected, however, that all of these prices could be reduced with future increases in market demand.
The annual cost savings due to reduced fuel cost is calculated simply as the annual fuel cost with conventional diesel vehicle technology minus the annual fuel cost with the new vehicle technology. The annual fuel cost is calculated as the product of vehicle fuel economy, fuel price and annual mileage. Vehicle fuel economy is computed using Autonomie over the selected driving cycles. The assumed fuel price is based on the 2012 Clean Cities Alternative Fuel Price Report (28), which shows the average national CNG price (as of January 2012) as $2.38 on a diesel gallon equivalent (DGE) basis compared to $3.86 per gallon for diesel. Vehicle annual mileage is considered as an input. Finally, the vehicle lifespan consumption cost is taken as the product of the annual fuel cost and the vehicle lifespan. The vehicle lifespan is assumed to be 10-12 years.

RESULTS

Diesel Baseline Simulations

The baseline analysis cases for the diesel HD trucks were first conducted over the UDDS Truck and ORNL4S chassis dynamometer driving cycles to ensure proper characterization of the vehicle configuration in Autonomie. Test results from a vehicle with the same configuration as that simulated in the baseline case were used to provide a basic validation of the model results. The predicted results were compared with experimental measurements obtained by West Virginia University (WVU) of a 2005 18,700 kg Volvo VN 610 tractor powered by a Cummins ISX 475 15-L diesel engine with a 10-speed manual transmission (the same configuration used in the diesel vehicle model). The predicted and measured fuel economies were 4.58 mpg vs. 4.63 mpg (25), respectively, over the UDDS Truck cycle, while the predicted fuel economy was 6.35 mpg, compared to 6.10 mpg for the measured truck over the ORNL4S cycle (25). Figure 1(a) and 1(b) compare the fuel consumption and engine power energy (the integral of the engine power over the drive cycle) between the simulations and WVU measurements. The difference between the model prediction and the on-vehicle measurement of fuel consumption and engine power energy was within 5% for each complete drive cycle.

Since the UDDS Truck and ORNL4S cycles are chassis dynamometer drive cycles, which do not consider real road conditions such as grade, we further simulated the two freeway-dominant driving cycles (i.e. FDDC A and FDDC B). One of the important parameters in simulating the fuel economy of class-8 HD trucks is the vehicle mass. For FDDC A and B, the mass was determined by iteratively adjusting the total vehicle mass in the model until the simulated engine power energy was in agreement with the measured engine power energy in each case. Based on this approach, the total vehicle mass was estimated to be 21,000 kg in FDDC A. The predicted and measured fuel economies for this drive cycle were 5.20 mpg and 5.22 mpg (25), respectively. The comparison of the measured and predicted fuel consumption and engine power energy is shown in Figure 1(c). During FDDC B, the simulated truck weight was 16,000 kg. The predicted fuel economy is 6.56 mpg which corresponds to 8% less fuel consumption than from the measured data (25), as shown in Figure 1(d). Generally, the predictions are reasonably close to the measured HD truck data through most of the drive cycles, and the differences observed are likely the result of variations in road and weather conditions, accessory power use, and/or aftertreatment regenerations during the actual driving. Additionally, slight inaccuracies in the vehicle parameter values (coefficients of aerodynamic drag and rolling resistance, etc.) used in the model could contribute to the errors observed, although the parameters used have been found to provide very good fuel economy estimates for the vehicles tested.

Unfortunately, for this study there were no experimental data available for CNG and LNG HD trucks nor for diesel hybrid trucks. Since we have confirmed that the model using the selected parameters for the truck configuration compared well with experimental data reported in the open literature and ORNL on-road measurements, this gives us confidence that the baseline truck model is reasonable. In the subsequent natural gas truck simulations, a 15-L natural gas engine map generated from direct experimental measurement was used to replace the 15-L Cummins diesel engine map, so we expect that at least the predicted trends should be correct.
Conventional Natural Gas Truck Simulations

Two vehicle weight categories were considered to account for typical urban and highway usage: light-medium weight (i.e. 16,000kg-22,000kg) and heavy weight (i.e. 35,000kg). We first simulated the natural gas HD truck with light-medium weight over the UDDS Truck drive cycle, ORNL4S, and FDDC A and FDDC B presented previously. Their comparisons with conventional diesel baseline cases are summarized in Table 1.

Relative to the conventional diesel case, the HD trucks powered by the natural gas engine lose 6%-13% in fuel economy on a diesel gallon equivalent (DGE) basis. This is mainly because the natural gas engine used for the analysis is a spark-ignited engine, whose compression ratio is less than the direct injection compression ignition diesel engine, and throttling losses at lower load are higher than for the diesel engine. Thus the natural gas engine efficiency is generally lower than the diesel case. Figure 2 shows a 2.2% - 3.4% difference in the average engine efficiency between diesel and natural gas engines for the drive cycles evaluated. On the other hand, CO$_2$ emissions from the conventional natural gas truck are reduced 6-12.4% relative to those of the conventional diesel case. The CO$_2$ reduction for the natural gas case is less than expected. The latest natural gas engine technologies such as natural gas high pressure...
direct injection (HPDI) with pilot diesel injection ignition may significantly boost engine efficiency
performance (18), which is expected to further improve CO₂ emissions and fuel economy in the natural
gas HD trucks.

![Graph](image1.png)

![Graph](image2.png)

![Graph](image3.png)

![Graph](image4.png)

**FIGURE 2** Comparison of diesel and natural gas engine efficiencies over the UDDS Truck, ORNL4S, and freeway-dominant drive cycles.

To understand the effect that the vehicle’s total mass (e.g., if additional load is carried) has on the
fuel economy and CO₂ emissions, we also simulated a heavy weight (i.e., 35,000kg) case. With the
increased truck weight, the fuel economy values for both the diesel- and natural gas-powered trucks are
significantly reduced. In the heavy weight case, however, the natural gas truck’s fuel economy is 4.8%-11.1% lower than the diesel fuel economy (on a DGE basis), which is less than the 6%-13% decrease in
DGE fuel economy observed for the light-medium weight. Consequently, the CO₂ emissions reduction
benefit for the natural gas truck is greater for the heavy weight case, with a difference of 8.1%-14.6% in
CO₂ emissions relative to the heavy weight diesel case. The comparisons with the diesel cases are
summarized in Table 2.

In summary, the fuel economy of the conventional natural gas HD truck is less than the diesel
baseline case owing to the lower compression ratio and higher throttling loss at lower loads for the natural
gas engine. Nonetheless, natural gas can still achieve a considerable CO₂ emissions reduction. Even
greater energy and CO₂ emissions reduction can be achieved in Class 8 HD trucks through hybridization,
and we will discuss its impact on the performance of both diesel and natural gas trucks in the next section.
<table>
<thead>
<tr>
<th>Fuel</th>
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<th>UDDS Truck</th>
<th>ORNL4S</th>
<th>FDDC A</th>
<th>FDDC B</th>
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<td>Conventional diesel</td>
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<tr>
<td>(Baseline)</td>
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<td>5.68(^a) (1.55(^b))</td>
<td>4.85(^a) (1.33(^b))</td>
<td>5.94(^a) (1.62(^b))</td>
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<td></td>
<td>CO₂ (kg/mile)</td>
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<td>1.46</td>
<td>1.70</td>
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<td>CO₂ reduction %</td>
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<td>8.1%</td>
<td>12.4%</td>
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<td>CO₂ (kg/mile)</td>
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<td></td>
<td>mpg change %</td>
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<td>18.7%</td>
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<td>CO₂ reduction %</td>
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<td>15.7%</td>
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<td>9.1%</td>
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<td>Natural gas hybrid</td>
<td>Fuel economy (mpg)</td>
<td>6.03(^a) (1.65(^b))</td>
<td>6.82(^a) (1.86(^b))</td>
<td>5.41(^a) (1.48(^b))</td>
<td>6.73(^a) (1.84(^b))</td>
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<td>CO₂ (kg/mile)</td>
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<td>1.21</td>
<td>1.53</td>
<td>1.23</td>
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<td>37.7%</td>
<td>23.9%</td>
<td>21.1%</td>
<td>20.1%</td>
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</table>

\(^a\) mpg is diesel gallon equivalent consumption; \(^b\) mpg is CNG gallon consumption (3600 psi); \(^c\) mpg change % and CO₂ reduction % are relative to the conventional diesel (baseline) case.
### TABLE 2  Fuel Economy and CO$_2$ Emissions of Conventional Diesel and Natural Gas HD Trucks for the Heavy Weight Case over the UDDS Truck, ORNL4S, and Freeway-Dominant Drive Cycles

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Driving cycle</th>
<th>UDDS Truck</th>
<th>ORNL4S</th>
<th>FDDC A</th>
<th>FDDC B</th>
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<td><strong>Conventional diesel</strong>&lt;br&gt;(Baseline)</td>
<td>Fuel economy (mpg)</td>
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<td>4.64</td>
<td>4.21</td>
<td>4.55</td>
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<td></td>
<td>CO$_2$ (kg/mile)</td>
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<td>35,000</td>
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<td><strong>Conventional natural gas</strong></td>
<td>Fuel economy (mpg)</td>
<td>3.03&lt;sup&gt;a&lt;/sup&gt; (0.83&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>4.19&lt;sup&gt;a&lt;/sup&gt; (1.15&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>4.01&lt;sup&gt;a&lt;/sup&gt; (1.10&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>4.21&lt;sup&gt;a&lt;/sup&gt; (1.15&lt;sup&gt;b&lt;/sup&gt;)</td>
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<td>-11.1%</td>
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<td>CO$_2$ reduction %&lt;sup&gt;c&lt;/sup&gt;</td>
<td>8.1%</td>
<td>10.1%</td>
<td>14.6%</td>
<td>11.7%</td>
</tr>
<tr>
<td><strong>Natural gas hybrid</strong></td>
<td>Fuel economy (mpg)</td>
<td>4.14&lt;sup&gt;a&lt;/sup&gt; (1.13&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>5.01&lt;sup&gt;a&lt;/sup&gt; (1.37&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>4.36&lt;sup&gt;a&lt;/sup&gt; (1.19&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>4.62&lt;sup&gt;a&lt;/sup&gt; (1.26&lt;sup&gt;b&lt;/sup&gt;)</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ (kg/mile)</td>
<td>2.00</td>
<td>1.65</td>
<td>1.90</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>Truck weight (kg)</td>
<td>35,800</td>
<td>35,800</td>
<td>35,800</td>
<td>35,800</td>
</tr>
<tr>
<td></td>
<td>mpg change %&lt;sup&gt;c&lt;/sup&gt;</td>
<td>21.4%</td>
<td>8.0%</td>
<td>3.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ reduction %&lt;sup&gt;c&lt;/sup&gt;</td>
<td>32.4%</td>
<td>24.3%</td>
<td>20.8%</td>
<td>19.4%</td>
</tr>
</tbody>
</table>

<sup>a</sup> mpg is diesel gallon equivalent consumption; <sup>b</sup> mpg is CNG gallon consumption (3600 psi); <sup>c</sup> mpg change % and CO$_2$ reduction % are relative to the diesel (baseline) case.

### Hybrid Truck Simulation

We carried out our natural gas HD hybrid truck simulations using the light-medium and heavy weight load cases for the same set of drive cycles as in the conventional vehicle cases. A comparison of results from the diesel conventional and hybrid cases are listed together in Tables 1 and 2.

For the light-medium weight case, natural gas hybrid trucks achieve 11%-51% better DGE fuel economy than the non-hybrid natural gas trucks, while diesel hybrids achieve 10%-44% better fuel economy than the non-hybrid diesel trucks (see Figures 3 (a)-(b)). The slightly better efficiency benefit in natural gas hybrid trucks is due to the fact that hybrid technology reduces the throttling loss of the natural gas SI engine at low engine loads. It is observed from Figure 3 that both diesel and natural gas hybrid technologies achieve much better fuel economy over the UDDS truck cycle, which is representative of city driving conditions, than on the other cycles that contain significant portions of freeway driving. Although the fuel economy benefit on the freeway cycles is down to around 10%, this level of fuel savings is still quite significant for long-haul tractors with a significant annual mileage. It is noted that the DGE fuel economy of a natural gas hybrid truck is still 5.6%-9.5% less than the diesel hybrid vehicle (see Table 1). However, the natural gas hybrid achieves 2.6%-7.4% better DGE fuel economy than the non-hybrid diesel baseline case on ORNL4S and the measured highway cycles, and 31.7% better than the diesel baseline case on the city driving cycle. Compared to the non-hybrid diesel baseline case, the CO$_2$...
emissions reduction for the natural gas hybrid vehicle is 19.4%-32.4%, and the benefit is 6.8%-24.7% relative to the diesel hybrid (see Table 2).

For the heavy weight cases analyzed, the fuel economy benefits due to hybridization are less, on a relative basis, than in the light-medium weight cases for both the natural gas and diesel engines, but improvements of more than 30% were still achieved for the UDDS truck cycle (see Figures 3(c)-(d)). For the real-world cycles FDDC A and FDDC B, which include rather typical combinations of on- and off-freeway driving, in the heavy weight case hybridization yields gains of 7%-8% in fuel economy with the diesel engine while the natural gas hybrid gains 9%-10% DGE mpg. The corresponding values for the light-medium weight case are 10% improvement due to hybridization for the diesel and 11%-13% for the natural gas-powered vehicle. Relative to the non-hybrid diesel baseline case, the natural gas hybrid in the heavy weight configuration achieves a 1.5%-21.4% higher value of DGE mpg, vs. a 7.6%-11.1% reduction in DGE mpg for the non-hybrid natural gas case (see Table 2). From the pure perspective of saving energy, the hybrid technology is clearly effective in improving fuel economy and thereby reducing fuel consumption for Class 8 HD trucks. The fuel and emissions savings are greatest on a city cycle with frequent stops, but savings are not insignificant even for freeway operations, and the total reduction can be quite large for a vehicle with significant mileage traveled each year.

![Graphs showing fuel economy improvements](image)

**FIGURE 3** Impact of hybridization on diesel and natural gas fuel economy for the light-medium and heavy weight cases.

The reduction in CO₂ emissions for diesel hybrid, natural gas conventional and natural gas hybrid vehicles in a heavy weight configuration are also summarized in Table 2. The diesel hybrid achieves a considerable CO₂ emissions reduction for the UDDS truck cycle. However, on the freeway-based driving cycles, the benefit of the diesel hybrid for reducing CO₂ emissions is even less than the non-hybrid natural gas vehicle. Natural gas hybridization, on the other hand, resulted in a much greater improvement, with
19.4%-32.4% lower CO$_2$ emissions than for the diesel conventional truck and 7.7%-13.3% less than the
diesel hybrid truck.

These results show that hybrid technology is quite attractive for improving fuel economy not only
in city driving conditions, as one would expect, but it is also rather effective for reducing fuel
consumption on freeway drive cycles, for which many vehicles generate very significant annual mileages.
However, both natural gas technology and vehicle hybridization encumber the user with significant initial
costs relative to a conventional diesel HD truck. The up-front cost is a serious concern for any potential
customer, and an economic analysis is needed to evaluate the cost benefits of these technologies.

**Economic cost analysis and discussion**

Class 8 HD trucks can be classified into Class 8A and Class 8B. Class 8A includes dump, refuse,
concrete, furniture, and tow trucks, in addition to city buses and fire engines, and a typical mileage driven
each year is around 30,000-40,000 miles (29). Class 8B includes tractor trailers, which are frequently
driven around 80,000 - 120,000 miles per year. Class 8A trucks typically travel in cities, whereas the
Class 8B trucks often run on freeways at nearly constant speeds. In reality, different applications will
have differing degrees of urban vs. freeway usage, and a detailed evaluation of drive cycles is needed to
accurately determine a characteristic drive cycle. To simplify the analysis we consider the most basic
cases. Thus, we chose fuel economies corresponding to the UDDS truck cycle to estimate the fuel costs
for Class 8A vehicles, while fuel economies corresponding to the Cycle B drive cycle were used to
estimate the fuel costs of Class 8B. We expect this will reasonably reflect the general trend of costs for
these two categories of trucks.

For Class 8A HD trucks, a 45 DGE natural gas fuel system is assumed since these trucks travel in
cities and do not drive significant distances each day. The initial cost for such a system is $45,750
according to (26). The initial investment cost of a hybrid system for a Class 8 HD truck (incremental cost
relative to a non-hybrid system) is taken to be $60,000. The combined incremental cost of a natural gas
hybrid system would therefore be $105,750. Based on these values, Figure 4 compares the payback time
and the net vehicle lifespan savings among non-hybrid natural gas, diesel hybrid, and natural gas hybrid
trucks for different levels of annual vehicle mileage. The vehicle lifespan considered is 12 years. The fuel
economy values corresponding to the UDDS truck cycle listed in Tables 1 and 2 are used in estimating
the payback time and net vehicle lifespan savings. It is evident that the payback time and net vehicle
lifespan savings are strongly associated with the vehicle mileage traveled annually, with a higher annual
mileage leading to a shorter payback time. It is observed that the conventional natural gas truck payback
time is the shortest; diesel hybrid payback time is the longest; and the natural gas hybrid has an
intermediate payback period. It is also seen that the payback time is reduced for the heavy weight vehicle
configuration. For a typical Class 8A HD truck traveling 40,000 miles per year, the payback time for the
light-medium weight configuration for the conventional natural gas, natural gas hybrid, and diesel hybrid
trucks is 4.64 years, 5.90 years, and 6.19 years, respectively. For the heavy weight configuration, the
corresponding payback times are reduced down to 3.30 years, 4.75 years, and 5.36 years, respectively.
These results demonstrate that natural gas technology and hybridization both provide an effective means
to reduce fuel costs and can quickly reimburse the customer’s initial investment costs for Class 8A trucks.
FIGURE 4  Estimate of payback time, net vehicle lifespan savings, and ratio of net vehicle lifespan savings to initial investment cost for conventional natural gas, diesel hybrid and natural gas hybrid Class 8A HD trucks over the UDDS truck cycle.
FIGURE 5  Estimate of payback time, net vehicle lifespan savings, and ratio of net vehicle lifespan savings to initial investment cost for conventional natural gas, diesel hybrid and natural gas hybrid Class 8B HD trucks over FDDC B.

It is interesting that although the payback time of the natural gas hybrid powertrain option is longer than that of the conventional natural gas truck, it achieves the maximum net vehicle lifespan savings in most cases. On the other hand, its ratio of net vehicle lifespan savings to initial cost is still much less than the conventional natural gas technology option (see Figures 4(e) and (f)). This indicates that the conventional natural gas truck is the most economical technology in achieving cost savings with the least initial investment cost.
For Class 8B HD trucks, a 120 DGE natural gas fueling system was considered because these trucks normally travel for long distances each day on freeways and a severely limited range would not be acceptable for this application. The estimated installation cost for a 120 DGE natural gas fuel system is $72,000 (26). Since the incremental cost of the hybrid propulsion system is $60,000, the combined incremental cost of the natural gas hybrid configuration becomes $132,000, while the incremental costs of the diesel hybrid and natural gas conventional configurations are $60,000 and $72,000, respectively.

Figure 5 compares the payback time and net vehicle lifespan savings for the class 8B case. The prices of diesel and natural gas DGE used here are the same as above. The Class 8B truck lifespan considered here is 10 years, while the truck total lifespan mileage is taken to be 1 million miles. The truck fuel economy values corresponding to FDDC B, listed in Tables 2-3, are used in estimating the payback time and cost savings. If a Class 8B HD truck travels 100,000 miles per year, the payback time of the natural gas conventional configuration is only around 2.54 years for the heavy weight case and 3.96 years for the light-medium weight case. For the natural gas hybrid vehicle configuration, the payback period is 3.54 years for the heavy weight case and 5.62 years for the light-medium weight case (See Figures 5(a) and (b)). Unfortunately, the payback time for the diesel hybrid option is greater than 10 years, which is close to the truck lifespan. Based on the assumptions used in this analysis, it is not economically justified for customers to pursue this option, although rising diesel costs and decreasing incremental costs of the hybrid system could change this situation in the future. Figures 5(c)-(d) show that the net vehicle lifespan savings for the conventional natural gas and natural gas hybrid are very close to each other. This indicates again that the impact of Class 8B HD truck hybrid technology on cost saving is rather limited after considering its initial incremental cost, even though the fuel savings from hybrid technology is significant.

Given that there are concerns over natural gas price stability, it is appropriate to briefly discuss the impact of using natural gas as a fuel for HD vehicles on natural gas demand. Historically the U.S. transportation sector has used very little natural gas (1). However, increased natural gas use in transportation could make an important contribution toward achieving oil independence and utilizing the significant natural gas production increases (from 20.6 TCF in 2010 to 27.9 TCF in 2035) that are currently projected (9). According to the ORNL Transportation Energy Data Book (1), heavy trucks were responsible for fuel consumption corresponding to 6,151 trillion BTU in 2010. Class 8 trucks (primarily long-haul combination vehicles) represent more than 60% of all truck fuel consumption, i.e. long-haul vehicles use about 3600 trillion BTU annually. If 10% of Class 8 trucks converted to a natural gas power system, the corresponding consumption would be about 360 trillion BTU, which corresponds to about 0.35 TCF of natural gas (standard conditions with 1012 BTU/ft³ heating value at 14.73 psia and 20°C). This is only about 1% of the expected natural gas production in 2035. One would not expect this level of additional demand, by itself, to significantly influence natural gas prices, and with the projected increase in natural gas production, there is a need to identify additional uses for this domestically produced fuel supply.

CONCLUSION
Our Class 8 HD truck simulation results indicate that the fuel economy and engine efficiency of natural gas trucks are less than for conventional diesel-powered trucks of comparable size and configuration. However, natural gas engines can achieve lower CO₂ emissions due to the lower carbon fraction in the fuel. The simulated reduction in CO₂ emissions was less than expected due to the lower combustion efficiency of the natural gas spark ignition engine. This result highlights the need to further develop and utilize innovative natural gas combustion technologies that will improve fuel efficiency and CO₂ emissions. In spite of the lower fuel economy for a natural gas-powered truck, the fuel’s lower cost makes the natural gas technology economically favorable to diesel when annual mileage is at least 40,000 miles.

Both diesel and natural gas hybrid technologies are able to reduce fuel consumption for both city and freeway driving conditions. Application of hybrid technologies was estimated to provide a 40%-50% reduction in fuel consumption in city driving. Although the fuel economy benefit of hybridization was
found to be no more than 10% on freeway drive cycles, the fuel savings can nevertheless be considerable for Class 8 vehicles that travel more than 100,000 miles annually.

When considering cost savings, the story is rather different. Predicted lifetime cost savings depend strongly on the truck’s application. For predominantly city driving, e.g. Class 8A trucks, a non-hybrid natural gas powertrain configuration provides the shortest payback time, with no more than five years payback when the annual vehicle mileage is 40,000 miles or more. The payback time for diesel hybrid and natural gas hybrid technologies for the same category of trucks was estimated to be around six years.

For HD trucks engaged primarily in freeway-dominant driving, such as Class 8B long-haul combination vehicles traveling 100,000 miles or more per year, the natural gas conventional powertrain still gave the shortest payback time, at 2.5-3.9 years. Surprisingly, the payback time for natural gas hybrid technology was estimated to be only 4.0-5.6 years for this vehicle category. On the other hand, it would require nearly ten years to recover the initial hybridization cost for a typical diesel class 8B vehicle in long-haul usage. This result implies that hybridization of diesel-powered long-haul trucks may not be the optimal choice in the current unstable economic environment. Nonetheless, future changes in diesel fuel or natural gas costs and/or reductions in hybridization costs could significantly change the economic outlook.

In summary, our analysis reveals that fuel economy and costs are likely to act as opposing factors in the utilization of hybridization in HD Class 8 trucks. As long as the price differential between natural gas and diesel fuel remains at its current level, economics may tend to favor conventional (non-hybrid) natural gas powered trucks, even though hybridization of both diesel and natural gas trucks offers longer-term reductions in emissions and fuel consumption.

ACKNOWLEDGEMENTS

This project was sponsored by US. Department of Energy’s Office of Vehicle Technologies and Department of Transportation. The authors would also like to recognize J. Dong, C. Liu, O. Franzese, S. Das, and S.C. Davis for their assistance and suggestions.

Notice: This submission was sponsored by a contractor of the United States Government under contract DE-AC05-00OR22725 with the United States Department of Energy. The United States Government retains, by accepting this submission for publication, acknowledges that the United States Government retains, a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this submission, or allow others to do so, for United States Government purposes.

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