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Analysis of Class 8 Hybrid-Electric Truck Technologies Using Diesel, LNG, Electricity, and Hydrogen, as the Fuel for Various Applications

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Abstract

Class 8 trucks using various powertrains and alternative fuel options have been analysed to determine their fuel economy, greenhouse gas emissions, and economic attractiveness at the present time (2013) and in the future. This was done by modelling the vehicles and simulating their operation on day, short haul, and long haul driving cycles. The economic attractive was determined by calculating the differential vehicle cost of each powertrain option and the corresponding breakeven alternative fuel price needed to recover the additional cost in a specified payback period with a fixed discount rate. The baseline vehicle was a diesel engine truck of the same weight and road load using $4/gallon diesel fuel. The use of some of the powertrains resulted in an energy saving and others resulted in higher energy consumption, but **c**ompared to the conventional Class 8 diesel trucks, conventional LNG-CI trucks, LNG-SI and LNG-CI hybrids, battery electric trucks, and fuel cell trucks can reduce CO_2 emission by 24-39% over the day drive cycle and 12-29% over the short haul and the long haul drive cycles.

The breakeven fuel price was calculated for all the powertrain/fuel options. The economic results indicate that at “today’s” differential vehicle costs, none of the alternative powertrains/fuels are economically attractive except for the LNG-CI engine in the long-haul application (VMT=150,000 miles) for which the DGE cost is $2.98/DGE and the LNG cost is $1.70/LNG gallon. If the differential costs of the alternative powertrains are reduced by ½, their economics is improved markedly. In the case of LNG-CI engine, the breakeven fuel costs are $3.42/GDE, $1.96/LNG gallon for the long haul applications (VMT= 150,000 miles) with payback periods of 2-3 years. This makes LNG cost competitive at 2013 prices of diesel fuel and LNG. The fuel cell powered truck is also nearly cost competitive at VMT= 150,000 miles, but this requires a fuel cell cost of less than $25/kW. Hybridizing is not attractive except for the conventional diesel vehicle operating on the day cycle (some stop and go operation) for which the breakeven diesel price is about $2/gallon at ½ today’s differential vehicle costs. The regulated exhaust emissions from the LNG-CI engines will meet the same standards (EPA 2010) as the new diesel engines and use the same exhaust emission technology.

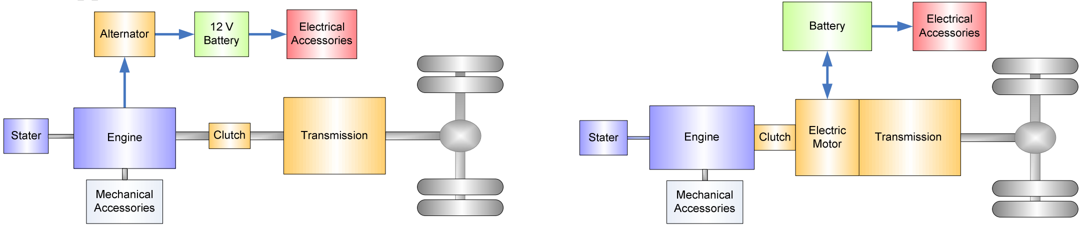
Keywords: Class 8 truck, hybridization, alternative, fuel cell, fuel economy, emissions

1 Introduction

There is increasing need to improve the fuel economy and reduce greenhouse gas (GHG) emissions of heavy duty Class 8 trucks due to high fuel prices, regulatory pressures, and climate change. Three approaches can be used to improve the fuel economy and/or reduce GHG emissions of heavy-duty trucks: non-electrification efficiency-improving technologies on conventional powertrains and vehicles [1-3], hybrid powertrain technologies [3-4], and the substitution of natural gas, electricity or hydrogen for diesel fuel [5-6]. All of these approaches have the potential to reduce GHG emissions from the transportation sector. In addition, there is a great need to reduce diesel emissions on and in the vicinity of seaports. This paper is concerned with the analysis of the fuel economy and emissions from hybrid-electric and all-electric Class 8 trucks (tractor trailers) to be used in seaports and urban area deliveries as well as short and long haul freight applications. Hybrid-electric designs consisting of a diesel engine or a LNG engine with spark ignition (SI) or compression ignition (CI) combustion, an electric motor, and a lithium-ion battery and all-electric designs including battery electric and fuel cell powertrains were analyzed for a number of driving cycles appropriate for port, day, short haul, and long haul applications. To explore the most efficient and environment-friendly way of using natural gas in heavy-duty freight truck applications, CO$_2$ emissions of Class 8 battery electric and fuel cell trucks were evaluated considering electricity generated from natural gas fired power plants and hydrogen produced from natural gas steam reforming. The simulations and analyses are based on current available technologies and related data. *Non-electrification efficiency-improving technologies such as improving engine efficiency and reducing aerodynamic drag and rolling resistance are not considered in this study.*

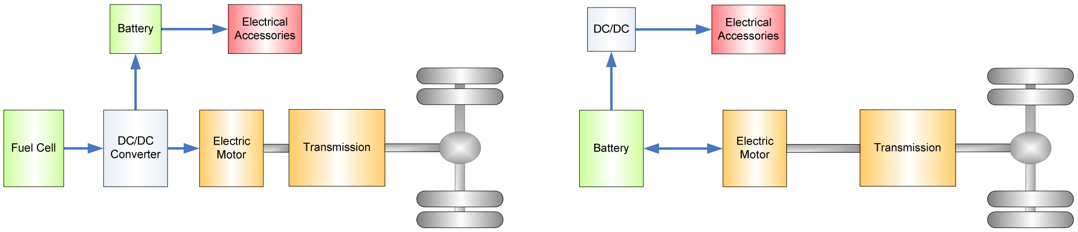
2 Powertrain Configurations and Control Strategy

The most attractive hybrid architecture to consider for Class 8 trucks is the parallel hybrid powertrain using one electric motor in the pre-transmission position, as shown in Figure 1. The engine is positioned with a clutch on the same shaft as the electric motor and the transmission. The clutch is used to connect/disconnect the engine from the powertrain. The vehicle can be propelled by the engine, the electric machine, or both at the same time. The electric machine and the battery are sized to meet the maximum power required in the electric-only mode. Compared to the conventional tractor trailer in which most of accessories are engine-driven, the hybrid electric drive system provides an opportunity of electrifying the engine-driven accessories such as the air conditioner and air compressor. The powertrain configurations of both hybrid-electric and all-electric trucks, shown in Figure 1, were simulated by using PSAT software.



Conventional Powertrain Configuration

Pre-transmission Parallel Hybrid Configuration



Fuel Cell Electric Powertrain Configuration

Battery Electric Powertrain Configuration

Figure 1 Conventional and Pre-transmission Parallel Hybrid Model

The use-pattern of Class 8 trucks is completely different from that of light-duty vehicles. Most applications of Class 8 tractor trailers are for the delivery of freight between cities and in the vicinity of ocean ports and warehouses. These applications feature near constant high speeds on the highway and a combination of low speed driving and frequent idling on the port for pickup and delivery of the freight. The operating strategy employed in this study for the parallel hybrid Class 8 truck is to operate the truck in the electric-only mode at speed less than 18 mph with the engine off and with the engine alone when possible at higher vehicle speeds where the engine operates at high efficiency and the battery can be charged when necessary. Unlike light-duty hybrid-electric vehicles, no attempt is made to maintain the battery in a narrow range of state of charge (SOC) and the battery is steadily depleted at low speed and charged when the engine is on. Optimization of engine operation for heavy-duty hybrid trucks is much less important than for light-duty hybrid-electric vehicles because the engine operates relatively near optimum efficiency even with a conventional powertrain.

3 Simulation Inputs

3.1 Driving cycles

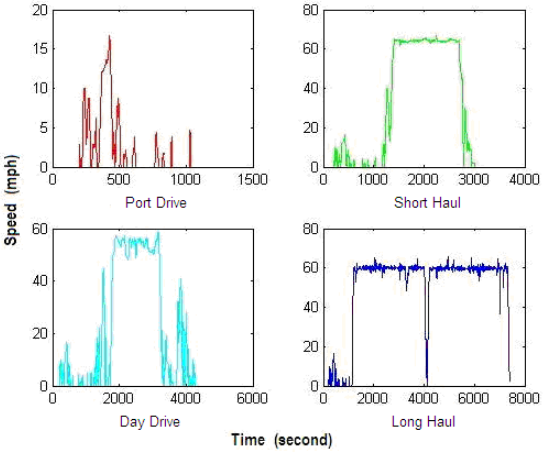


Figure 2: Constructed driving cycles/trips of Class 8 freight trucks

The fuel economy and exhaust emissions of heavy-duty vehicles can be tested on a chassis dynamometer using different emission test schedules such as EPA's transient Urban Dynamometer Driving Schedule (UDDS) and California ARB's Heavy-Duty Diesel Truck (HHDDT) driving cycles. These driving cycles include the basic operating conditions of heavy-duty trucks. However, they do not reflect real driving conditions for the Class 8 trucks. In this study, Class 8 truck operations are classified into four categories based on actual fleet use: seaport drive, day drive, short haul, and long haul. The port, day, short haul, and long haul driving cycles were constructed using truck industry statistics and the standard test schedules to reflect particular operating modes of Class 8 trucks. The constructed driving cycles used in the analysis are shown in Figure 2.

3.2 Vehicle Parameters

The emergence of hybrid-electric powertrain technology, LNG engines with SI and CI combustion technologies, fuel cells, and high energy density batteries for use on Class 8 trucks has spurred great interests regarding greenhouse gas (GHG) emission reduction and energy security. Hybridization of conventional diesel/LNG trucks can reduce fuel consumption through elimination of low efficiency internal combustion engine (ICE) operation, regenerative braking energy recovery, and electrification of accessory loads. LNG as a low-carbon, clean-burning fuel can reduce GHG emissions in the heavy-duty vehicle transportation sector, but current natural gas engines suffer a peak efficiency penalty of 2-3% (points) for CI engine technology and 8-9% (points) for SI engine technology at high load operation compared to diesel engines. The battery electric drivetrain is the most efficient and zero-emission, but is limited by short range, long charging time, and heavy battery weight. The fuel cell truck is also zero-emission and has moderate range and fast refueling compared to the battery electric truck. These different truck powertrain technologies will be compared for the same truck design.

The advanced Class 8 trucks will be compared with conventional diesel engine trucks in terms of energy equivalent fuel economy and exhaust emissions. The baseline diesel truck has drag coefficient of 0.6, a frontal area of 10 m^2 and test weight of 30,000 kg (see Table 1). The test weight was adjusted according to the powertrain configuration and the fuel tank size. For hybrid trucks, the electric motor and the battery are sized to meet the maximum power required in the electric-only mode. The speed threshold for the all-electric operation is set at 18 mph. The engine is not downsized in hybrid-electric trucks due to the limited energy stored in the battery. The vehicle inputs used in the simulations are given in Table 1.

There is considerable uncertainty regarding the efficiency maps for the LNG engines. The map used for the LNG-CI engine, shown in Figure 3, was constructed from [11-14]. The LNG-CI engine map was constructed from [12] and modified slightly after discussion with Westport, a company developing that engine technology. The LNG-CI engine has similar efficiency as a diesel engine at part load and a small efficiency penalty at full load. The 6% pilot diesel fuel injected to ignite the natural gas in the LNG-CI engine was included in the calculation of the CO_2 emissions. Considering weight penalty and cost, a 400 kWh battery and a 35 kg hydrogen tank were selected for the battery electric and the fuel cell trucks, respectively, which would achieve a range of 120 miles for the battery electric truck and 200 miles for a fuel cell truck under full load.

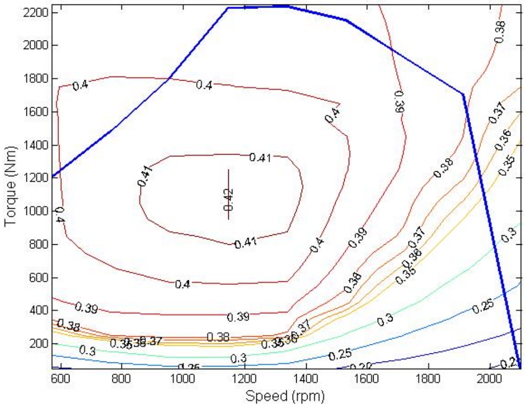
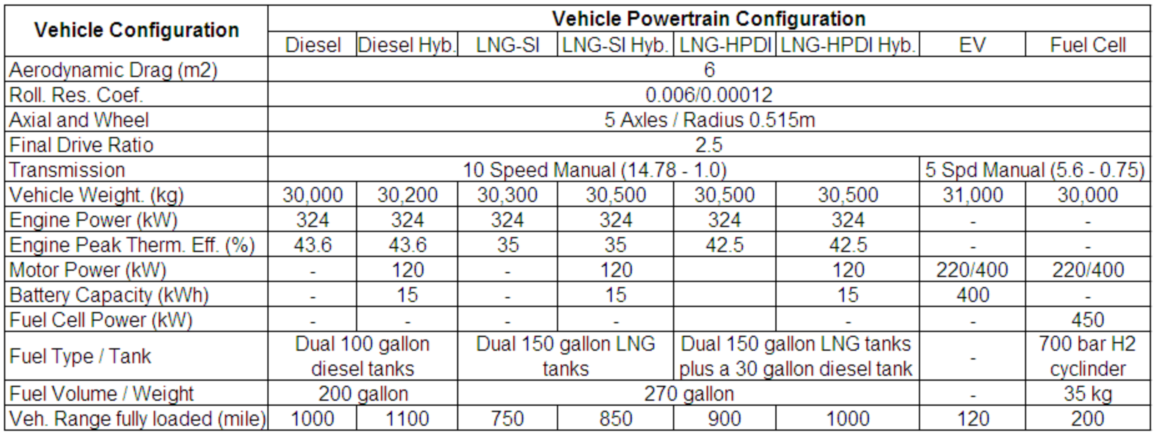


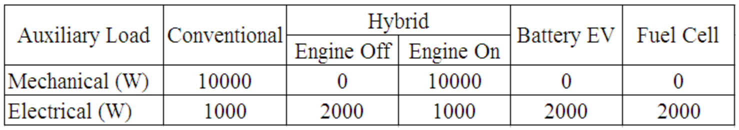
Figure 3: Brake thermal efficiency map of LNG-CI (HPDI) Engine

Table 1: Simulation inputs



Vehicle Configuration	Vehicle Powertrain Configuration							
	Diesel	Diesel Hyb.	LNG-SI	LNG-SI Hyb.	LNG-HPDI	LNG-HPDI Hyb.	EV	Fuel Cell
Aerodynamic Drag (m2)	6							
Roll. Res. Coef.	0.006/0.00012							
Axial and Wheel	5 Axles / Radius 0.515m							
Final Drive Ratio	2.5							
Transmission	10 Speed Manual (14.78 - 1.0)						5 Spd Manual (5.6 - 0.75)	
Vehicle Weight. (kg)	30,000	30,200	30,300	30,500	30,500	30,500	31,000	30,000
Engine Power (kW)	324	324	324	324	324	324	-	-
Engine Peak Therm. Eff. (%)	43.6	43.6	35	35	42.5	42.5	-	-
Motor Power (kW)	-	120	-	120		120	220/400	220/400
Battery Capacity (kWh)	-	15	-	15		15	400	-
Fuel Cell Power (kW)	-	-	-	-		-	-	450
Fuel Type / Tank	Dual 100 gallon diesel tanks		Dual 150 gallon LNG tanks		Dual 150 gallon LNG tanks plus a 30 gallon diesel tank		-	700 bar H2 cyclinder
Fuel Volume / Weight	200 gallon		270 gallon				-	35 kg
Veh. Range fully loaded (mile)	1000	1100	750	850	900	1000	120	200

Table 2: Accessory loads in Class 8 tractor trailers



Auxiliary Load	Conventional	Hybrid		Battery EV	Fuel Cell
		Engine Off	Engine On		
Mechanical (W)	10000	0	10000	0	0
Electrical (W)	1000	2000	1000	2000	2000

3.3 Auxiliary Loads

Accessory loads such as those for the air conditioner, radiator fan, cooling pump, etc. can be affected by weather and driving cycles. Engine idling is necessary for a conventional tractor-trailer to provide heating, air conditioning, ventilation, or electric power during federally-mandated driver breaks. Electrification of some mechanical accessories such as pumps, compressors, and engine cooling fan can make a significant difference in the accessory loads due to their higher efficiency. In this study, average accessory loads obtained from the tests [3] of Class 8 tractor trailer trucks are used in the simulations. Table 2 lists the accessory loads used for conventional, hybrid, and all-electric Class 8 trucks.

4 Simulations and Discussions

To evaluate the Class 8 trucks with the various powertrains technologies and fuel pathways, conventional baseline diesel engine truck, diesel hybrid-electric, conventional LNG engine trucks with SI and CI combustion, LNG hybrid-electric trucks with SI and CI engines, battery electric trucks, and fuel cell trucks were modeled and simulated over the day drive, the short haul drive, and the long haul drive cycles. The fuel economies (miles per gallon diesel fuel equivalent) for the various truck technologies are summarized in Table 3.

Table 3: Fuel economy-diesel gallon equivalent

Vehicle Type	Drive Cycles		
	Day	Short-Haul	Long-Haul
Diesel	5.19	4.89	5.59
LNG-SI	3.73	3.69	4.37
LNG-CI	5.33	4.8	5.39
EV	14.07	11.41	12.23
FC	7.22	6.22	7.15
Diesel-Hyb.	6.44	5.39	5.81
LNG-SI-Hyb.	4.99	4.28	4.62
LNG-CI-Hyb.	6.33	5.16	5.6

The fuel economies, normalized to the baseline conventional diesel truck, are shown in Figure 4 for the day drive and short and long haul driving cycles. The diesel equivalent fuel economy was 22-28% lower for the LNG-SI trucks and nearly the same for the LNG-CI trucks compared to the conventional diesel trucks over the same drive cycles. Hybridization of conventional trucks with diesel, LNG SI, and LNG CI engines can improve fuel economy by 24%, 33%, and 18% for the day drive cycle and 10%, 14%, and 8% for the short haul cycle, respectively. Hybridization of diesel and LNG trucks can increase fuel economy by 3-6% over the long haul applications. The simulation results indicate that the battery electric truck can achieve a diesel equivalent fuel economy that is higher by a factor of 2.2-2.7 than the baseline conventional truck; the hydrogen fuel cell truck can improve the diesel equivalent fuel economy by 27-39% over the day drive, the short haul, and the long haul drive cycles.

Simulations for various truck powertrain technologies were also performed for the port drive cycle. The port drive cycle consists of low speed crawling and idling most of the time. The simulations show that hybridization and electrification of truck drivetrains (see Figure 5) can significantly improve fuel economy and reduce CO_2 emissions of conventional diesel and LNG trucks. Due to the limited range and zero exhaust emissions, the battery electric truck is the best option for yard truck applications.

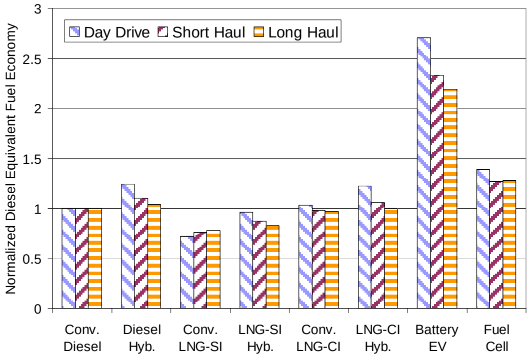


Figure 4: Comparison of fuel economy over the day, short haul and long haul cycles

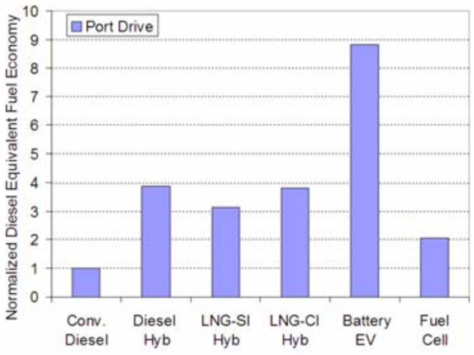


Figure 5: Comparison of fuel economy over the port drive cycles

In addition to using natural gas directly as the fuel in internal combustion engines, there are several other pathways for natural gas to displace fossil diesel fuel in the freight transportation sector: synthetic diesel fuel produced from natural gas via Gas-To-Liquid (GTL) processes, electricity generated from natural gas fired power plants, and hydrogen produced from the Steam Methane Reforming (SMR) process. Synthetic diesel fuel produced from natural gas via GTL process is clean and sulfur and nitrogen free. However, compared to fossil diesel fuel, synthetic diesel from GTL processes having an efficiency of 60% will increase CO_2 emission by 22%. For the electricity pathway, it is assumed that the electricity for charging the battery electric trucks is generated from natural gas fired power plants with an efficiency of 42% and 2% loss on power transmission. The distributed SMR process technology is assumed to have an efficiency of 80% and the on-site hydrogen compression up to 700 bars with an efficiency of 90%. Since the U.S. natural gas pipeline network is highly developed and can transport high pressure natural gas to and from any location in the lower 48 States, it is assumed that the CNG comes from high pressure natural gas transmission pipelines. The LNG for refuelling the LNG trucks is produced by pressure let-down liquefiers or compressor based liquefiers in place of the pressure regulator station between high pressure natural gas transmission lines and low pressure natural gas distribution lines. The energy from pressure drop can liquefy 10-27% of natural gas flow without external energy. The Lower Heating Values (LHV) of CNG and LNG used in this study are 47 MJ/kg and 49.7 MJ/kg, respectively. The CO_2 emissions for the different powertrain configurations and fuel pathways were calculated according to the simulated diesel equivalent fuel economies given in Table 3. The results are shown in Figure 6.

Figure 6 indicates that compared to conventional Class 8 diesel trucks, conventional LNG-CI trucks, LNG-SI and LNG-CI hybrids, battery electric trucks, and fuel cell trucks can reduce CO_2 emission by 24-39% over the day drive cycle, and 12-29% over the short haul and the long haul drive cycles. If no Carbon Capture and Storage (CCS) is considered during the production of electricity and hydrogen, LNG-CI hybrids can compete with battery electric and fuel cell trucks over the day drive and the short and long haul cycles in terms of CO_2 emissions. However, battery electric and fuel cell trucks are exhaust emission free and are the cleanest options for the port drive and the urban drive applications. Compared to conventional Class 8 diesel trucks, conventional LNG-SI trucks have no apparent benefit in terms of CO_2 emission reduction.

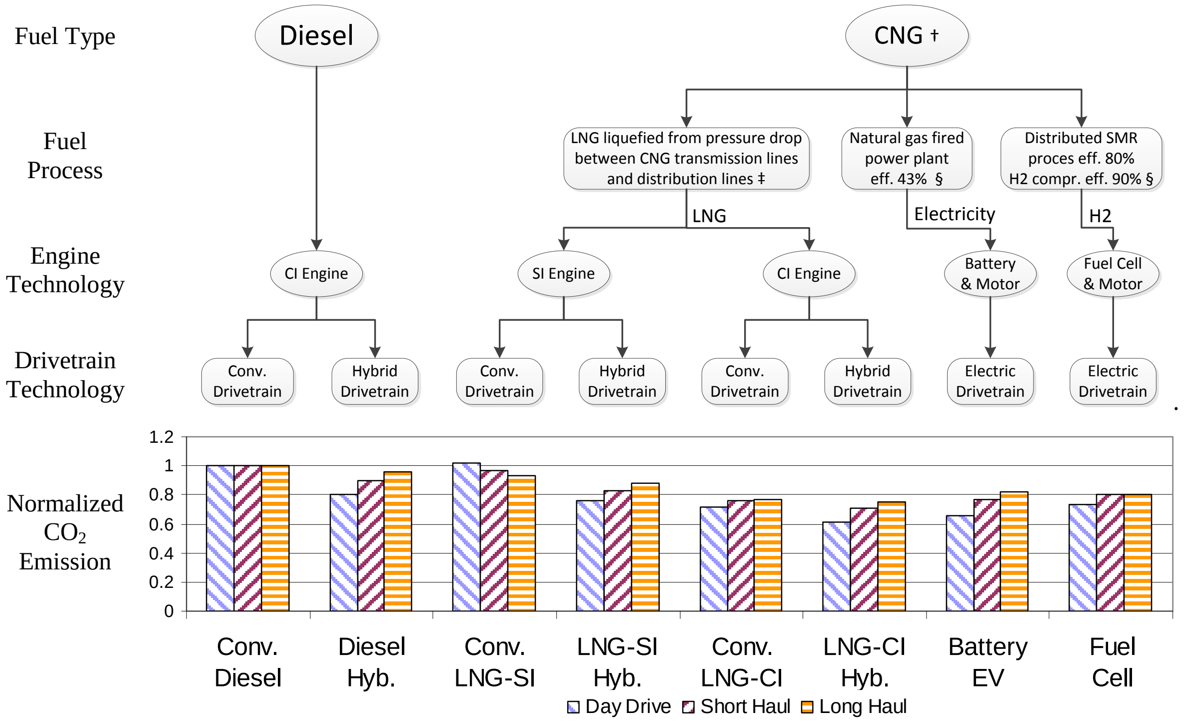


Figure 6: Comparison of different powertrain configurations and fuel pathways in terms of CO_2 emissions

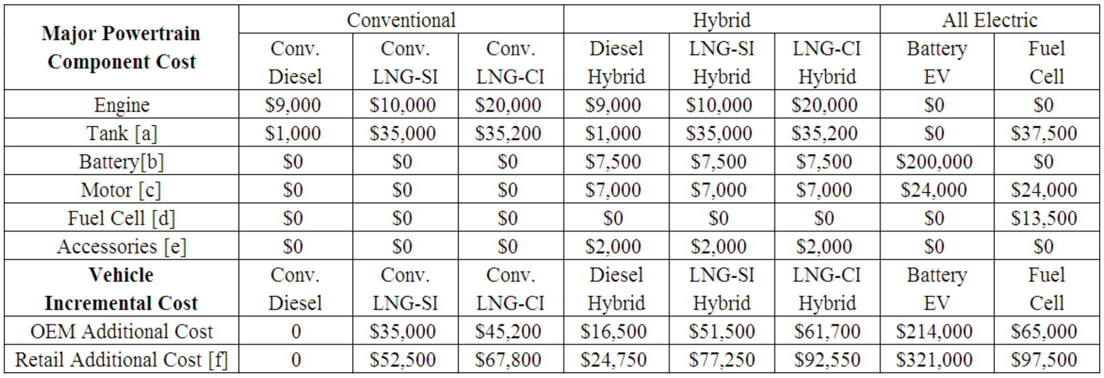
† CNG comes from current natural gas high pressure transmission lines (200 – 15000 psig).
‡ LNG is produced by liquefying a portion of the natural gas stream with the pressure drop energy.
§ No CCS is employed in electricity generation and hydrogen production processes.

5 Economic analysis and breakeven fuel costs

The economics of the various powertrain and fuel options for the Class 8 trucks are analyzed in this section for specific driving patterns (drive cycles and miles/year) and discount rate. The VMT (miles traveled per year) is a key factor in determining the economics for a particular application. Unfortunately there is considerable uncertainty in determining this factor. According to the highway statistics 2010 (Federal Highway Administration, 2011), Class 8 combination trucks have a national average VMT of 68,907 miles and 77% of the 80,000 lb weight allowed. Typically, combination trucks operating in urban, short-haul operations have lower annual VMT than those in long-haul use. In the cost analysis, the operation patterns of tractor-trailers are classified into four broad categories: the day drive, the short trip, the long trip, and combination of the day drive, the short trip and the long trip. In this analysis, it is assumed that Class 8 tractor-trailers have the annual VMTs of 30,000, 60,000, and 120,000-150,000 miles for the day drive, the short haul, and the long haul cycles, respectively. Based on these VMT assumptions and the simulated fuel economies, the operational cost of the Class 8 trucks using the various powertrains and fuels have been evaluated. A discount rate of 4% and appropriate payback periods are assumed in the economic calculations for the different applications.

The cost of each of the powertrains (conventional, electric, and hybrid) is calculated from the size/power rating of the components in the powertrain (Table 1). The costs assumed for each of the powertrain components and the resulting differential vehicle costs for the various powertrain options are given in Table 4. There are considerable uncertainties in most of these costs especially for the large components needed for Class 8 truck powertrains which are assembled / sold in low volumes. The costs shown are thought to be illustrative of costs today (2013) and are reasonable values to use in the cost analyses to follow. Because the costs will decrease in the future as the volume of the components and the truck sales increase, the sensitivity of the economic results to the cost inputs is of considerable interest. Hence the economics are also analysed for ½ today's cost as an indication of how much cost reduction is needed to make the various powertrain and fuel options economically attractive. In estimating the differential retail cost of advanced trucks, a mark-up factor of 1.5 is used to include the additional cost of integrating components of the drivetrain from outside suppliers and the profit to the OEM.

Table 4: Powertrain component cost and vehicle incremental cost



Major Powertrain Component Cost	Conventional			Hybrid			All Electric	
	Conv. Diesel	Conv. LNG-SI	Conv. LNG-CI	Diesel Hybrid	LNG-SI Hybrid	LNG-CI Hybrid	Battery EV	Fuel Cell
Engine	$9,000	$10,000	$20,000	$9,000	$10,000	$20,000	$0	$0
Tank [a]	$1,000	$35,000	$35,200	$1,000	$35,000	$35,200	$0	$37,500
Battery[b]	$0	$0	$0	$7,500	$7,500	$7,500	$200,000	$0
Motor [c]	$0	$0	$0	$7,000	$7,000	$7,000	$24,000	$24,000
Fuel Cell [d]	$0	$0	$0	$0	$0	$0	$0	$13,500
Accessories [e]	$0	$0	$0	$2,000	$2,000	$2,000	$0	$0
Vehicle Incremental Cost	Conv. Diesel	Conv. LNG-SI	Conv. LNG-CI	Diesel Hybrid	LNG-SI Hybrid	LNG-CI Hybrid	Battery EV	Fuel Cell
OEM Additional Cost	0	$35,000	$45,200	$16,500	$51,500	$61,700	$214,000	$65,000
Retail Additional Cost [f]	0	$52,500	$67,800	$24,750	$77,250	$92,550	$321,000	$97,500

a. Dual 100 gallon tanks for conventional diesel and diesel hybrid trucks; dual 150 gallon tanks for conventional and hybrid LNG-SI or -CI trucks; a 50 kg H2 tank for a fuel cell truck.

b. The battery pack of 15 kWh is used for the hybrid trucks and 400 kWh for the battery electric truck. Battery price is $500/ kWh.

c. A PM motor of 120 kW peak power is used for hybrid powertrains, a PM motor with 220 kW continuous power / 400 kW peak power for all electric trucks. Motor price is $60/kW;

d. Fuel cell: 450 kW; fuel cell price: $47/ kW

e. Incremental cost for electrifying mechanical accessories.

f. A mark-up factor of 1.5 is applied to the OEM additional cost.

The economics of the various powertrains and fuels is analyzed in terms of the breakeven fuel price needed to offset the additional cost of the vehicles for the different driving cycles and *VMT*. The fuel costs are discounted over the appropriate (assumed) years for the different applications. The fuel cost discount factor (*DF*) is given by

$$DF = [1-(1+d)^{-n}] / nd$$

where d is the annual discount rate and n is the payback years.

For the alternative fuel cases, the equation for the calculation of the breakeven fuel price ($P_{\mathrm{Deqv,\ Alt}}$) is

$$P_{\mathrm{Deqv,\ Alt}} / (mpg)_{\mathrm{Deqv,Alt}} = P_{\mathrm{Dref}}/(mpg)_{\mathrm{Dref}} - Diff_{\mathrm{Veh\ cost}} / (n(DF)\ VMT) \qquad (1)$$

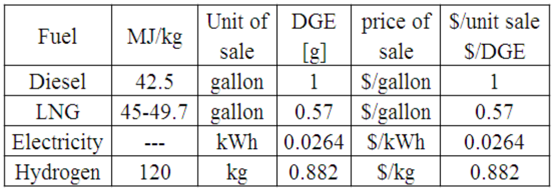
In cases in which the same fuel is used for the baseline and new powertrains (ex. hybridization of the baseline diesel truck), eq. (1) simplifies to the following.

$$P_{\mathrm{D,bkeven}} = [Diff_{\mathrm{Veh\ cost}} / (n(DF)\ VMT)] / (1/mpg_{\mathrm{baseline}} - 1/mpg_{\mathrm{adv}}) \qquad (2)$$

The simulation results for the fuel economies for the various powertrains and fuel options have been shown in Table 3. The fuel economies are given as diesel gallons equivalent per mile (DGE/mi) in all cases.

The breakeven fuel price calculations are performed in terms of the cost of a diesel equivalent fuel (DGE) on an energy basis. The sale price of the different alternative fuels – LNG, hydrogen, and electricity- are related to that of the DGE fuel as shown in Table 5.

Table 5: Energy & price characteristics of alternative fuels

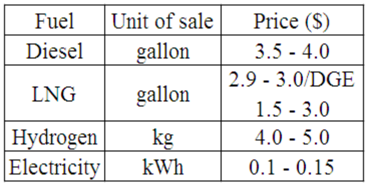


Fuel	MJ/kg	Unit of sale	DGE [g]	price of sale	$/unit sale $/DGE
Diesel	42.5	gallon	1	$/gallon	1
LNG	45-49.7	gallon	0.57	$/gallon	0.57
Electricity	---	kWh	0.0264	$/kWh	0.0264
Hydrogen	120	kg	0.882	$/kg	0.882

[g] 1 gal diesel = 136 MJ=37.8 kWh

The breakeven fuel costs for Class 8 trucks using the various engine powertrains, including the fuel cell, and fuels have been calculated via an EXCEL spreadsheet using Eqns (1) and (2) with the inputs from Tables 3 and 4. Hybrid-electric powertrains are treated separately later. The calculations are made for a discount rate of 4% and payback periods appropriated for the different heavy-duty vehicle applications. The baseline vehicle is a conventional diesel engine powered Class 8 truck (Table 1) using diesel fuel costing $4/gallon. The results of the calculations are given in Table 7. Breakeven fuel cost values are shown in terms of $/gal DGE and $/ sales fuel unit using sales units appropriate for each alternative fuel (see Table 5). Current prices (2013) of the alternative fuels are given in Table 6. For a fuel/powertrain combination to be economically attractive, the breakeven price of the fuel should be greater than the market value given in Table 6.

Table 6: Current (2013) prices of the alternative fuels



Fuel	Unit of sale	Price ($)
Diesel	gallon	3.5 - 4.0
LNG	gallon	2.9 - 3.0/DGE 1.5 - 3.0
Hydrogen	kg	4.0 - 5.0
Electricity	kWh	0.1 - 0.15

Results are not shown in Table 7 for the EV battery cases because in all cases, the calculated breakeven fuel cost was negative meaning that the differential vehicle cost could not be recovered even if the electricity to recharge the batteries was free. Results are shown for three driving cycles- day, short haul, long haul (see Figure 2). The day and short haul cycles represent driving in and around urban areas and the long haul cycle corresponds to inter-city driving. The day and short haul cycles exhibit some stop-go vehicle operation. In most cases, the effect of the discount rate on the results is not large and the essence of the results can be seen from the values shown in the columns labeled “without discount rate”. The results in Table 7 are those for “today’s” component costs which are quite high. The results for lower costs (1/2 today’s) which are expected in the future are given in Table 8. It should be noted that for the alternative fuels, high values of the breakeven fuel price are advantageous, because the economics are favorable for alternative market fuel prices below the breakeven value. For example, for LNG, at the present time (2013) a breakeven price of about $ 3.0/DGE or $1.75/gal LNG is needed for favourable economics.

The economic results in Table 7 indicate that at "today's" differential vehicle costs, none of the alternative powertrains/fuels are economically attractive except for the LNG-CI engine in the long-haul application (VMT=150,000 miles) for which the DGE cost is $2.98/DGE and the LNG cost is $1.70/LNG gallon. The results for the fuel cell truck in Table 7 are not as attractive as for LNG because a breakeven price of about $5/DGE is needed to make the fuel cell truck using hydrogen economically attractive. As shown in Table 8, the economics of the alternative fuels become more favourable if the differential vehicle costs are reduced by ½. In the case of LNG-CI, the breakeven fuel costs are $3.42/GDE, $1.96/LNG gallon for the long haul applications (150,000 miles) with payback periods of 3 years. This makes LNG cost competitive at 2013 prices of diesel fuel and LNG. The fuel cell powered truck is also nearly cost competitive at VMT= 150,000 miles, but this requires a fuel cell cost of less than $25/kW.

The economics of the hybrid-electric diesel and LNG Class 8 trucks were also evaluated using the same approach as previously discussed for conventional engine alone powertrains. The results of those evaluations are given in Tables 9 and 10 and summarized in Table 11. For the hybrid vehicle economic comparisons, the baseline vehicle in all cases was the same truck powered by a diesel engine using diesel fuel costing $4/gallon. The VMT and payback period for each case is indicated in the table. In all cases, the discount rate was 4%.

As indicated in Table 3, the fuel economies were higher using the hybrid-electric powertrains than the conventional engine/transmission systems. The fractional improvements due to hybridization varied widely with the driving cycle, but in all cases hybridization saved fuel/energy. The differences were the largest for the day driving cycle and the smallest by far for the long haul highway driving cycle. This was true for all the alternative fuels. The results shown in Table 11 indicate that hybridizing the LNG fueled powertrains is not attractive, that is, the breakeven alternative fuel prices are lower in all cases. This remains true even when the costs of the hybrid system components are reduced by ½. The long haul application (VMT=150,000 mi./yr) is the most attractive for both today's and ½ today's costs, but the effect of hybridization on the breakeven fuel price is also small in that case. When the cost of hybridizing is reduced by ½, hybridizing the conventional baseline diesel truck is economically attractive for the day driving cycle (urban use with some stop-go operation) and even for long haul use if the VMT is 150,000 miles or greater.

6 Summary and conclusions

Class 8 trucks using various powertrains and alternative fuel options have been analysed to determine their fuel economy, greenhouse gas emissions, and economic attractiveness at the present time (2013) and in the future. This was done by modelling the vehicles and simulating their operation on day, short haul, and long haul driving cycles. The economic attractive was determined by calculating the differential vehicle cost of each powertrain option and breakeven alternative fuel price needed to recover the additional cost in a specified payback period with a fixed discount rate. The baseline vehicle was a diesel engine truck of the same weight and road load characteristics using $4/gallon diesel fuel. The powertrain and fuel options included liquefied natural gas (LNG) used in SI and CI combustion engines, hybrid-electric vehicles with diesel and LNG engines, fuel cell vehicles using hydrogen, and battery powered electric vehicles.

The use of some of the powertrains resulted in an energy saving and others resulted in higher energy consumption. All powertrain/fuel options resulted in lower greenhouse gas emissions. The diesel equivalent fuel economy was 22-28% lower for the LNG-SI trucks and nearly the same for the LNG-CI trucks compared to the conventional diesel trucks over the same drive cycles. Hybridization of conventional trucks with diesel, LNG-SI, and LNG-CI engines can improve fuel economy by 24%, 33%, and 18% for the day drive cycle and 10%, 14%, and 8% for the short haul cycle, respectively. Hybridization of diesel and LNG trucks can increase fuel economy by 3-6% over the long haul applications. The simulation results indicate that the battery electric truck can achieve a diesel equivalent fuel economy that is higher by a factor of 2.2-2.7 than the baseline conventional truck; the hydrogen fuel cell truck can improve the diesel equivalent fuel economy by 27-39% over the day drive, the short haul, and the long haul drive cycles. Compared to conventional Class 8 diesel trucks, conventional LNG-CI trucks, LNG-SI and LNG-CI hybrids, battery electric trucks, and fuel cell trucks can reduce CO2 emission by 24-39% over the day drive cycle, and 12-29% over the short haul and the long haul drive cycles.

The breakeven fuel price was calculated for all the powertrain/fuel options. The economic results indicate that at "today's" differential vehicle costs, none of the alternative powertrains/fuels are economically attractive except for the LNG-CI engine in the long-haul application (VMT=150,000 miles) for which the DGE cost is $2.98/DGE and the LNG cost is $1.70/LNG gallon. If the differential costs of the alternative powertrains are reduced by ½, their economics is improved markedly. In the case of LNG-CI engine, the breakeven fuel costs are $3.42/GDE, $1.96/LNG gallon for the long haul applications (VMT= 150,000 miles) with payback periods of 3 years. This makes LNG cost competitive at 2013 prices of diesel fuel and LNG. The fuel cell powered truck is also nearly cost competitive at VMT= 150,000 miles, but this requires a fuel cell cost of less than $25/kW. Hybridizing is not attractive except for the conventional diesel vehicle operating on the day cycle (some stop and go operation) for which the breakeven diesel price is about $2/gallon at ½ today's hybridization cost. The regulated exhaust emissions from the LNG-CI engines will meet the same standards (EPA 2010) as the new diesel engines and use the same exhaust emission technology. The LNG-SI engines utilize three-way catalysts and can be as clean as gasoline engines.

Table 7: Breakeven fuel price results for the “today” vehicle cost differences

Payback Year	Annual VMT	Vehicle Type	Additional Cost ($)	Cycle Type	Fuel Economy (mile/DGE)	Energy based break even price ($/DGE) Reference diesel price $4/gal		Break even alternative fuel price (LNG: $/ gallon LNG; Electricity: $/ kWh; Hydrogen: $/kg)	
						Without Discount Rate	With Discount rate	Without Discount Rate	With Discount rate
		Baseline Diesel vehicle	NA	day	5.19	NA	NA	NA	NA
				short-haul	4.89	NA	NA	NA	NA
				long-haul	5.59	NA	NA	NA	NA
5 yr. d=.04	30,000 mi/yr	LNG-SI LNG	$52,500	day	3.73	$1.57	$1.41	$0.90	$0.81
				short-haul	3.69	$1.73	$1.57	$0.99	$0.90
				long-haul	4.37	$1.60	$1.41	$0.91	$0.81
		LNG-CI LNG	$67,800	day	5.34	$1.70	$1.41	$0.97	$0.80
				short-haul	4.80	$1.76	$1.49	$1.00	$0.85
				long-haul	5.39	$1.42	$1.12	$0.81	$0.64
		Fuel cell H_2	$97,500	day	7.22	$0.87	$0.30	$0.77	$0.26
				short-haul	6.22	$1.05	$0.55	$0.92	$0.48
				long-haul	7.15	$0.47	-$0.10	$0.41	-$0.09
3 yr. d=.04	60,000 mi/yr	LNG-SI LNG	$52,500	day	3.73	$1.79	$1.70	$1.02	$0.97
				short-haul	3.69	$1.94	$1.86	$1.11	$1.06
				long-haul	4.37	$1.85	$1.75	$1.06	$1.00
		LNG-CI LNG	$67,800	day	5.34	$2.10	$1.94	$1.20	$1.11
				short-haul	4.80	$2.12	$1.97	$1.21	$1.13
				long-haul	5.39	$1.83	$1.67	$1.05	$0.95
		fuel cell H_2	$97,500	day	7.22	$1.66	$1.34	$1.45	$1.17
				short-haul	6.22	$1.72	$1.45	$1.51	$1.27
				long-haul	7.15	$1.25	$0.93	$1.09	$0.82
2yr. d=.04	120,000 mi/yr	LNG-SI LNG	$52,500	day	3.73	$2.06	$2.01	$1.18	$1.15
				short-haul	3.69	$2.21	$2.16	$1.26	$1.24
				long-haul	4.37	$2.17	$2.11	$1.24	$1.21
		LNG-CI LNG	$67,800	day	5.34	$2.61	$2.52	$1.49	$1.44
				short-haul	4.80	$2.57	$2.49	$1.47	$1.42
				long-haul	5.39	$2.34	$2.25	$1.34	$1.28
		Fuel cell H_2	$97,500	day	7.22	$2.63	$2.46	$2.31	$2.15
				short-haul	6.22	$2.56	$2.41	$2.25	$2.11
				long-haul	7.15	$2.21	$2.04	$1.94	$1.79
3 yr. d=.04	150,000 mi/yr	LNG-SI	$52,500	day	3.73	$2.44	$2.40	$1.39	$1.37
				short-haul	3.69	$2.59	$2.56	$1.48	$1.46
				long-haul	4.37	$2.62	$2.58	$1.50	$1.47
		LNG-CI	$67,800	day	5.34	$3.31	$3.25	$1.89	$1.85
				short-haul	4.80	$3.20	$3.14	$1.83	$1.80
				long-haul	5.39	$3.05	$2.98	$1.74	$1.70
		Fuel cell H_2	$97,500	day	7.22	$4.00	$3.87	$3.51	$3.40
				short-haul	6.22	$3.74	$3.63	$3.28	$3.19
				long-haul	7.15	$3.57	$3.44	$3.13	$3.02

Table 8: Breakeven fuel price results for the "1/2 today" vehicle cost differences

Payback Year	Annual VMT	Vehicle Type	Additional Cost ($)	Cycle Type	Fuel Economy (mile/DGE)	Energy based break even price ($/DGE) Reference diesel price $4/gal		Break even alternative fuel price (LNG: $/ gallon LNG; Electricity: $/ kWh; Hydrogen: $/kg)	
						Without Discount Rate	With Discount rate	Without Discount Rate	With Discount rate
		Diesel	NA	day	5.19	NA	NA	NA	NA
				short-haul	4.89				
				long-haul	5.59				
5 yr. d=.04	30000 mi/yr	LNG-SI	$26,250	day	3.73	$2.22	$2.14	$1.27	$1.22
				short-haul	3.69	$2.37	$2.30	$1.36	$1.31
				long-haul	4.37	$2.36	$2.27	$1.35	$1.30
		LNG-CI	$33,900	day	5.34	$2.91	$2.76	$1.66	$1.58
				short-haul	4.80	$2.84	$2.71	$1.62	$1.55
				long-haul	5.39	$2.64	$2.49	$1.51	$1.42
		FC	$48,750	day	7.22	$3.22	$2.93	$2.82	$2.57
				short-haul	6.22	$3.07	$2.82	$2.69	$2.47
				long-haul	7.15	$2.80	$2.51	$2.45	$2.20
3 yr. d=.04	60000 mi/yr	LNG-SI	$26,250	day	3.73	$2.33	$2.29	$1.33	$1.31
				short-haul	3.69	$2.48	$2.44	$1.42	$1.39
				long-haul	4.37	$2.49	$2.44	$1.42	$1.39
		LNG-CI	$33,900	day	5.34	$3.11	$3.03	$1.78	$1.73
				short-haul	4.80	$3.02	$2.95	$1.73	$1.68
				long-haul	5.39	$2.85	$2.76	$1.63	$1.58
		FC	$48,750	day	7.22	$3.61	$3.45	$3.17	$3.03
				short-haul	6.22	$3.41	$3.27	$2.99	$2.87
				long-haul	7.15	$3.18	$3.03	$2.79	$2.65
2 yr. d=.04	120000 mi/yr	LNG-SI	$26,250	day	3.73	$2.47	$2.44	$1.41	$1.40
				short-haul	3.69	$2.62	$2.59	$1.50	$1.48
				long-haul	4.37	$2.65	$2.62	$1.51	$1.50
		LNG-CI	$33,900	day	5.34	$3.36	$3.32	$1.92	$1.89
				short-haul	4.80	$3.25	$3.21	$1.86	$1.83
				long-haul	5.39	$3.10	$3.05	$1.77	$1.74
		FC	$48,750	day	7.22	$4.10	$4.01	$3.60	$3.52
				short-haul	6.22	$3.83	$3.75	$3.36	$3.29
				long-haul	7.15	$3.67	$3.58	$3.22	$3.14
3 yr. d=.04	150000 mi/yr	LNG-SI	$26,250	day	3.73	$2.66	$2.64	$1.52	$1.51
				short-haul	3.69	$2.81	$2.79	$1.60	$1.59
				long-haul	4.37	$2.87	$2.85	$1.64	$1.63
		LNG-CI	$33,900	day	5.34	$3.71	$3.68	$2.12	$2.10
				short-haul	4.80	$3.56	$3.53	$2.04	$2.02
				long-haul	5.39	$3.46	$3.42	$1.97	$1.96
		FC	$48,750	day	7.22	$4.78	$4.72	$4.20	$4.14
				short-haul	6.22	$4.42	$4.36	$3.87	$3.83
				long-haul	7.15	$4.34	$4.28	$3.81	$3.76

Table 9: Breakeven fuel price results for the “today” vehicle cost differences for vehicles using hybrid powertrains compared to the baseline diesel truck

Payback Year	Annual VMT	Vehicle Type	Additional Cost ($)	Cycle Type	Fuel Economy (mile/DGE)	Energy based break even price ($/DGE) Reference diesel price $4/gal		Break even alternative fuel price (LNG: $/ gallon LNG; Electricity: $/ kWh; Hydrogen: $/kg)	
						Without Discount Rate	With Discount rate	Without Discount Rate	With Discount rate
Baseline		Diesel	NA	day	5.19	NA	NA	NA	NA
				short-haul	4.89				
				long-haul	5.59				
5 yr. d=.04	30000 mi/yr	LNG-SI hybrid	$77,250	day	4.99	$1.28	$0.96	$0.73	$0.55
				short-haul	4.28	$1.29	$1.02	$0.74	$0.59
				long-haul	4.62	$0.93	$0.64	$0.53	$0.36
		LNG-CI hybrid	$92,550	day	6.34	$0.98	$0.50	$0.56	$0.28
				short-haul	5.16	$1.04	$0.65	$0.59	$0.37
				long-haul	5.60	$0.55	$0.13	$0.32	$0.07
3 yr. d=.04	60000 mi/yr	LNG-SI hybrid	$77,250	day	4.99	$1.71	$1.53	$0.98	$0.88
				short-haul	4.28	$1.66	$1.51	$0.95	$0.86
				long-haul	4.62	$1.32	$1.16	$0.76	$0.67
		LNG-CI hybrid	$92,550	day	6.34	$1.63	$1.36	$0.93	$0.78
				short-haul	5.16	$1.57	$1.35	$0.90	$0.77
				long-haul	5.60	$1.13	$0.90	$0.65	$0.51
2 yr. d=.04	120000 mi/yr	LNG-SI hybrid	$77,250	day	4.99	$2.24	$2.15	$1.28	$1.23
				short-haul	4.28	$2.12	$2.04	$1.21	$1.16
				long-haul	4.62	$1.82	$1.73	$1.04	$0.99
		LNG-CI hybrid	$92,550	day	6.34	$2.44	$2.30	$1.40	$1.31
				short-haul	5.16	$2.23	$2.11	$1.28	$1.21
				long-haul	5.60	$1.85	$1.72	$1.06	$0.98
3 yr. d=.04	150000 mi/yr	LNG-SI hybrid	$77,250	day	4.99	$2.99	$2.92	$1.71	$1.67
				short-haul	4.28	$2.76	$2.70	$1.58	$1.54
				long-haul	4.62	$2.51	$2.45	$1.44	$1.40
		LNG-CI hybrid	$92,550	day	6.34	$3.58	$3.48	$2.05	$1.99
				short-haul	5.16	$3.16	$3.08	$1.81	$1.76
				long-haul	5.60	$2.86	$2.76	$1.63	$1.58

Table 10: Breakeven fuel price results for the “1/2 today” vehicle cost differences for vehicles using hybrid powertrains compared to the baseline diesel truck

Payback Year	Annual VMT	Vehicle Type	Additional Cost ($)	Cycle Type	Fuel Economy (mile/DGE)	Energy based break even price ($/DGE) Reference diesel price $4/gal		Break even alternative fuel price (LNG: $/ gallon LNG; Electricity: $/ kWh; Hydrogen: $/kg)	
						Without Discount Rate	With Discount rate	Without Discount Rate	With Discount rate
		Diesel	NA	day	5.19	NA	NA	NA	NA
				short-haul	4.89	NA	NA	NA	NA
				long-haul	5.59	NA	NA	NA	NA
5 yr. d=.04	30000 mi/yr	LNG-SI hybrid	$38,625	day	4.99	$2.56	$2.41	$1.47	$1.38
				short-haul	4.28	$2.40	$2.26	$1.37	$1.29
				long-haul	4.62	$2.12	$1.97	$1.21	$1.13
		LNG-CI hybrid	$46,275	day	6.34	$2.93	$2.69	$1.68	$1.54
				short-haul	5.16	$2.63	$2.43	$1.50	$1.39
				long-haul	5.60	$2.28	$2.07	$1.30	$1.18
3 yr. d=.04	60000 mi/yr	LNG-SI hybrid	$38,625	day	4.99	$2.78	$2.69	$1.59	$1.54
				short-haul	4.28	$2.58	$2.50	$1.47	$1.43
				long-haul	4.62	$2.32	$2.24	$1.32	$1.28
		LNG-CI hybrid	$46,275	day	6.34	$3.26	$3.13	$1.86	$1.79
				short-haul	5.16	$2.90	$2.79	$1.65	$1.59
				long-haul	5.60	$2.57	$2.45	$1.47	$1.40
2 yr. d=.04	120000 mi/yr	LNG-SI hybrid	$38,625	day	4.99	$3.05	$3.00	$1.74	$1.71
				short-haul	4.28	$2.81	$2.77	$1.60	$1.58
				long-haul	4.62	$2.56	$2.52	$1.46	$1.44
		LNG-CI hybrid	$46,275	day	6.34	$3.67	$3.59	$2.09	$2.05
				short-haul	5.16	$3.23	$3.17	$1.84	$1.81
				long-haul	5.60	$2.93	$2.86	$1.67	$1.64
3 yr. d=.04	150000 mi/yr	LNG-SI hybrid	$38,625	day	4.99	$3.42	$3.39	$1.96	$1.94
				short-haul	4.28	$3.13	$3.10	$1.79	$1.77
				long-haul	4.62	$2.91	$2.88	$1.66	$1.64
		LNG-CI hybrid	$46,275	day	6.34	$4.24	$4.18	$2.42	$2.39
				short-haul	5.16	$3.69	$3.65	$2.11	$2.09
				long-haul	5.60	$3.43	$3.39	$1.96	$1.93

Table 11: Summary of the breakeven fuel costs ($/DGE) with discount for conventional LNG trucks and hybrid powertrains using the conventional diesel engine powered truck as the baseline

Powertrain / Fuel	Day Drive		Short Haul		Long Haul Drive		
VMT(mile/year)	30k	60k	30k	60k	30k	60k	150k
year payback	5	3	5	3	5	3	3
Today's vehicle incremental costs							
Diesel Hybrid	4.94	3.96	9.74	7.81	26.4	21.17	8.47
LNG-SI Conventional	1.41	1.7	1.57	1.86	1.41	1.75	2.58
LNG-SI Hybrid	0.96	1.53	1.02	1.51	0.64	1.16	2.45
LNG-CI Conventional	1.41	1.94	1.49	1.97	1.12	1.67	2.98
LNG-CI Hybrid	0.5	1.36	0.65	1.35	0.13	0.9	2.76
½ Today's vehicle incremental costs							
Diesel Hybrid	2.47	1.98	4.87	3.91	13.2	10.59	4.23
LNG-SI Conventional	2.14	2.29	2.3	2.44	2.27	2.44	2.85
LNG-SI Hybrid	2.41	2.69	2.26	2.5	1.97	2.24	2.88
LNG-CI Conventional	2.76	3.03	2.71	2.95	2.49	2.76	3.42
LNG-CI Hybrid	2.69	3.13	2.43	2.79	2.07	2.45	3.39

Abbreviations

ARB	Air Resources Board
CCS	Carbon Capture and Storage
CI	Compression Ignition
CO_2	Carbon Dioxide
DGE	Diesel Gallon Equivalent
EPA	Environmental Protection Agency
EV	Electric Vehicle
GHG	Greenhouse Gas
GTL	Gas to Liquid
HHDDT	Heavy Heavy-Duty Diesel Truck
ICE	Internal Combustion Engine
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
PSAT	Powertrain Systems Analysis Toolkit
SI	Spark Ignition
SMR	Steam Methane Reforming
SOC	State of Charge
UDDS	Urban Dynamometer Driving Schedule

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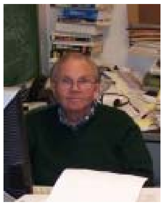

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