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Analysis of Medium Duty Hybrid-Electric Truck Technologies using Electricity, Diesel, and CNG/LNG as the Fuel for Port and Delivery Applications

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1 Abstract

This paper is concerned with the analysis of the fuel economy and greenhouse gas emissions from medium duty trucks (MDT) using various alternative powertrain/fuel combinations for deliveries in urban and inter-city service. The powertrain/fuel combinations considered included hybrid-electric designs consisting of a diesel engine, electric motor, and a lithium battery, a CNG engine, electric motor, and lithium battery, battery powered, and a hydrogen fuel cell. Simulation were performed for a number of driving cycles appropriate for these applications using a special version of the ADVISOR program developed at UC Davis. Comparisons are given of the economics of the various options in terms vehicle initial price differences and the breakeven fuel prices for the various alternative fuels. The comparisons are made for today's costs (2014) and future costs (2025) including expected improvements in technology. Special attention is given to the use of natural gas in the delivery trucks. For the medium-duty trucks, the economic results using today's technologies and costs indicated that CNG conventional trucks are attractive in most urban applications for a range of annual VMT and payback time combinations. CNG-hybrid vehicles were also attractive under 26K VMT/3 year payback scenarios. In 2025, all the powertrain/fuel combinations are attractive in varying degrees due to the improvements in fuel economy and the reduction in component costs.

Keywords: list 3-5 keywords from the provided keyword list in 9,5pt italic, separated by commas

1 Introduction

In the United States, medium duty trucks (Class 4 to Class 6) are those with GVWR from 10,000 lbs. to 26,000 lbs., including city delivery trucks, school buses, etc. Medium duty trucks are the workhorses for the American economy and are commonly visible within communities. They drop packages at homes, deliver supplies to grocery stores, and transport people to their working places. Although medium duty trucks account for less 5 percent of the total fuel consumption from road vehicles, they emit an average of 13 metric tons of carbon dioxide per vehicle each year. Hence it is important to consider the alternative fuel pathways and powertrain systems for these trucks with the objective to reduce their GHG emissions. In this study, UPS and FedEx parcel delivery trucks are the prime focus. UPS operates a fleet of over

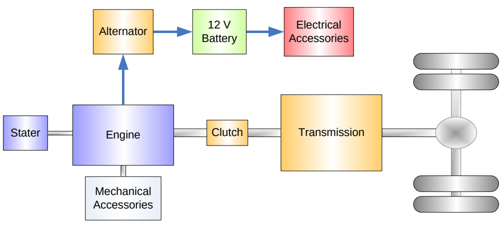
100, 000 ground vehicles and spends over $3 billion on fuel annually. UPS and FedEx have a large share of the 2,000 hybrid medium duty vehicles running on road. Over the years, they have continued to invest in alternative fueled vehicles using natural gas, electricity and hydrogen.

This paper is based on the research summarized in [1] and is follow-on to a similar paper on heavy-duty trucks given in EVS27 [2]. The approach taken to study medium-duty trucks (MDT) was parallel to that used to study the heavy-duty trucks. The paper is concerned with determination of the fuel economy and GHG emissions for MDTs using various alternative fuels, including natural gas, electricity, and hydrogen. Hybrid-electric designs consisting of a CNG spark ignition (SI) engine, an electric motor and associated electronics, 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 urban and suburban delivery. The simulations and economic analyses are based on current available technologies, vehicle designs, and component costs as well as projected technology improvements and cost reductions in the future (2025-2030).

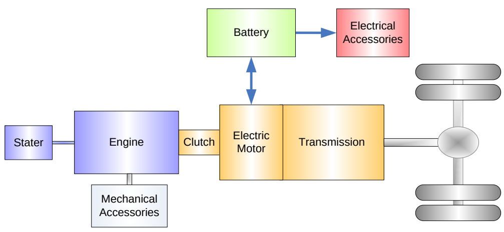
2 Vehicle simulations and fuel economy

Simulations of MDTs were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis [3-4]. The simulation program has been used to prepare a number of previous papers on light-duty and heavy-duty vehicles using alternative drivelines [2-4]. Schematics for the drivelines simulated are shown in Figure 1. Simulations were run for both diesel and natural gas (CNG) fueled vehicles and hydrogen fueled fuel cell vehicles. Efficiency maps for those engines are shown in Figure 2. Charge sustaining hybrid and battery powered vehicles were also considered.

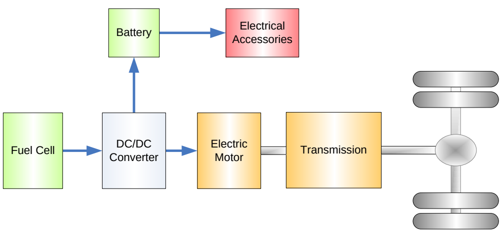
The hybrid trucks are modeled as parallel hybrids. In the parallel hybrid configuration, the engine is positioned with a clutch on the same shaft as the electric motor and the transmission. The electric machine and the battery are sized to meet the maximum power required in the electric-only mode. The vehicle is propelled by the electric machine, the engine, or both at the same time. The control strategy used for the hybrids assumed electric only operation at low speeds (less than 20 mph) and engine, electric motor assisted operation at higher speeds maintaining the engine near to optimum efficiency. All accessories were electrically driven. The battery charging power is selected to assure that the motor/generator operates only at high efficiency. This is done utilizing a look-up table. The battery SOC is maintained between 0.5 and 0.9. Modeling is done for both diesel and CNG fueled engines. The driving cycles used in the simulations are shown in Figure 3. These driving cycles are appropriate for deliveries in urban areas (5). The inputs used in the simulations of today's and 2025-2030 MDTs using the various alternative drivelines are given in Table 1 and 2. The truck road load parameters are based on those of the present UPS vehicles.



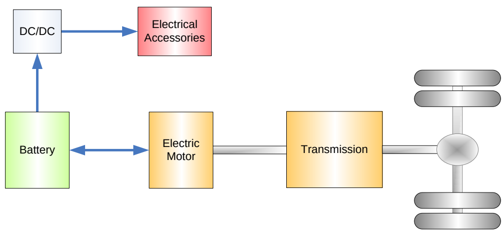
Conventional Powertrain Configuration



Pre-transmission Parallel Hybrid Configuration

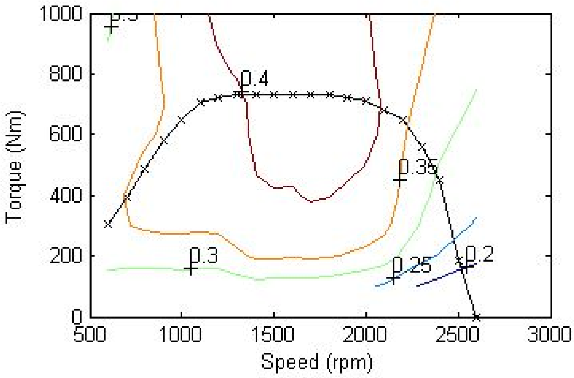


Fuel Cell Electric Powertrain Configuration

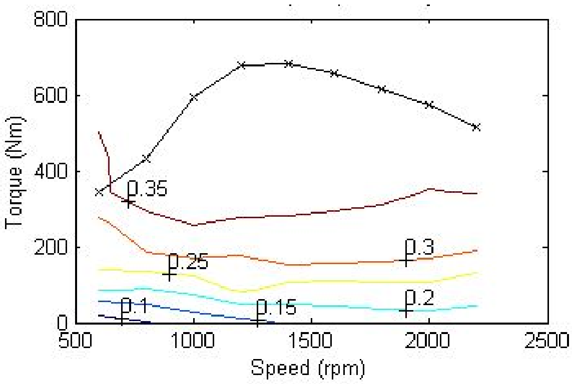


Battery Electric Powertrain Configuration

Figure 1: Schematics of the alternative drivelines

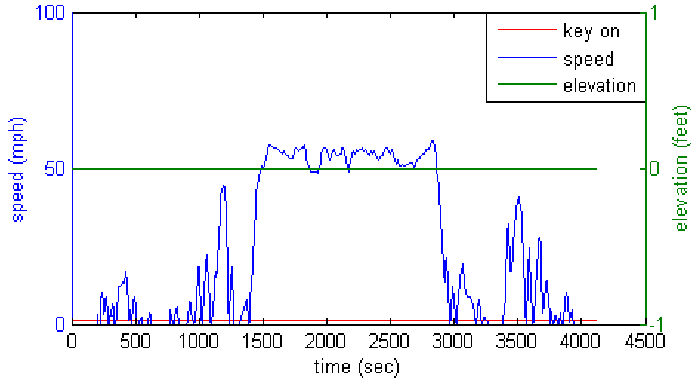


(a) 7 liter CI diesel engine

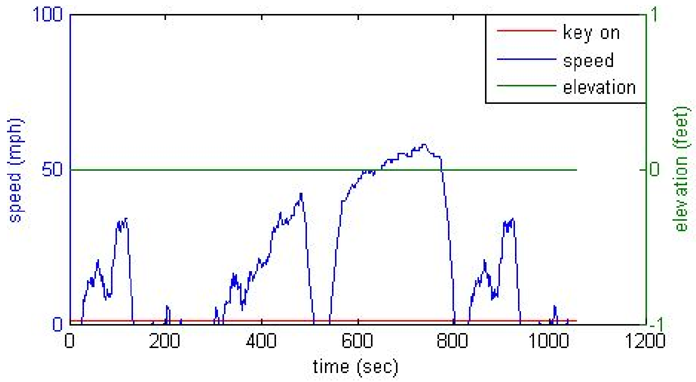


(b) 8.1 liter SI natural gas engine

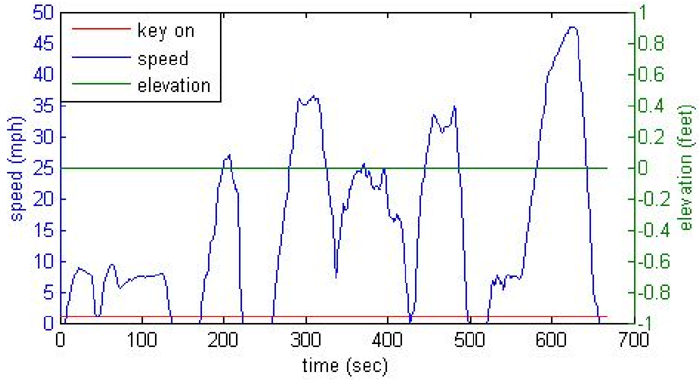
Figure 2: Engine models used in the medium duty truck simulation



(a) Daily driving cycle



(b) UDDSHDV driving cycle



(c) ARB transient driving cycle

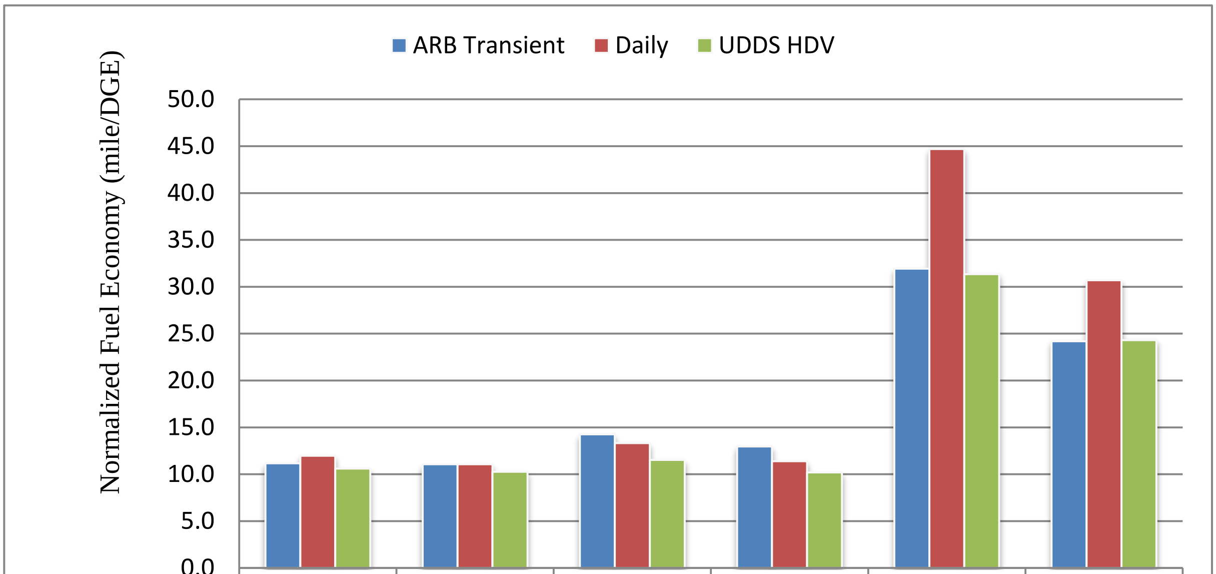
Figure 3: Driving cycles for medium duty truck simulations

Table 1: Inputs for today's MDTs with different alternative powertrains

Vehicle Powertrain Configuration						
Vehicle Type	**Diesel-Conv**	**CNG-Conv**	**Diesel-Hyb**	**CNG-Hyb**	**BEV**	**Fuel Cell**
Front Area (m^2)	7.8				4.7	4.7
Air Drag Coef.	0.6				0.4	0.4
Roll. Res. Coef.	0.0077				0.0077	0.0077
Wheel Radiu(m)	0.419				0.419	0.419
Final Drive Ratio	*2.85*				1	1
Transmission	6 Speed mannual (9.01, 5.27, 3.22, 2.04, 1.36, 1)				4 speed	4 speed
Overal Weight (Kg)[1]	6813	7293	7222	7653	7930	7381
Engine Power (Kw)[8]	149	149	100	100	NA	NA
Engine Peak Therm. Eff. (%)	42	38	42	38	NA	NA
Electrical Accessory Load (Kw)	0.3	0.3	1.22	1.22	1.22	1.22
Mechanical Accessory Load (Kw)	1	1	0	0	0	0
Motor Powe Continuous/Peak (Kw)	NA	NA	30/58	30/58	60/100	60/100
Battery Maximum Power (Kw)	NA	NA	60	60	120	60
Battery Capacity (Kwh)[2]	NA	NA	2.5	2.5	50	2.5
Fuel Cell Power (Kw)	NA	NA	NA	NA	NA	100
Fuel Type/Tank	Single 40 gallon diesel tank	single 10.9 GGE CNG tank[3]	Single 40 gallon diesel tank	single 10.9 GGE CNG tank[3]	NA	3 Kg
Fuel Volume(gallon) /Weight(Kg)	40	10GGE	40	10GGE	NA	3 Kg
Veh Range fully loaded(mile)	400	100	400	100	50[4]	50[5]
1. Weight compensate calculation for each type of powertrain could be found in Appendix Figure 5.2.1						
2. 20 Ah EIGNiCo, HEV and FCV:50 in a series, 2 in parallel; BEV: 100 in a series, 7 in a parallel						
3. 100% steel CNG tank, durable for scrathes						
4. 50 miles from simulation result, for BEV when SOC reaches 0.3 from full charge;						
5. 3 Kg based on average fuel economy from the simulation						

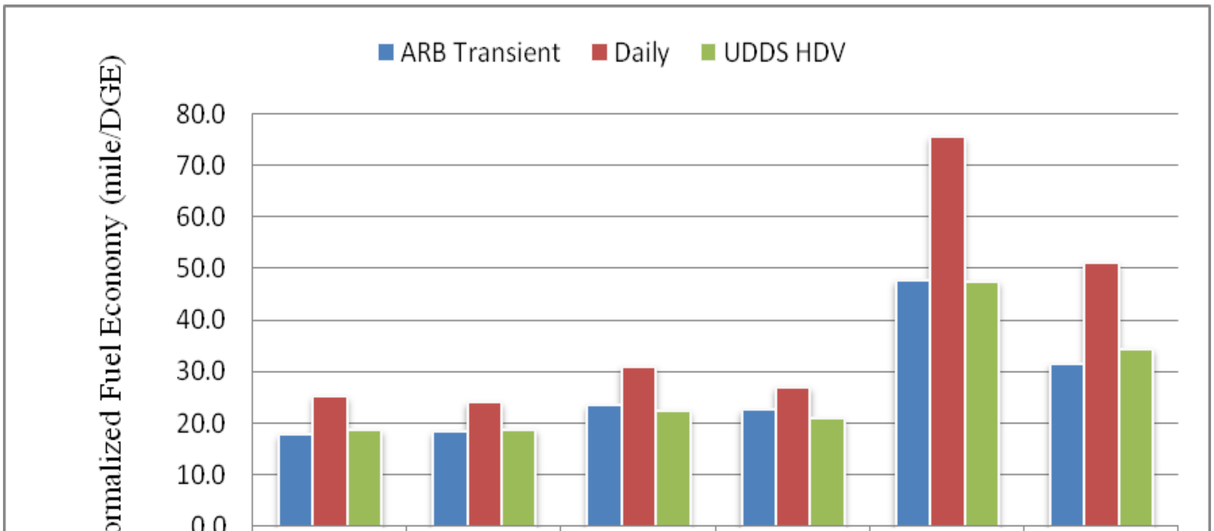
Table 2: Inputs for 2025-2030 MDTs with different alternative powertrains

Vehicle Powertrain Configuration						
Vehicle Type	**Diesel-Conv**	**CNG-Conv**	**Diesel-Hyb**	**CNG-Hyb**	**BEV**	**Fuel Cell**
Front Area (m^2)	3.5					
Air Drag Coef.	0.35					
Roll. Res. Coef.	0.0045					
Wheel Radiu(m)	0.419					
Final Drive Ratio	*2.85*				1	1
Transmission	6 Speed mannual (9.01, 5.27, 3.22, 2.04, 1.36, 1)				4 speed	4 speed
Overal Weight (Kg)	6132	6564	6500	6888	6603	6643
Engine Power (Kw)[8]	134	134	90	90	NA	NA
Engine Peak Therm. Eff. (%)	0.52	0.48	0.52	0.48	NA	NA
Electrical Accessory Load (Kw)	0.2	0.2	1	1	1	1
Mechanical Accessory Load (Kw)	0.9	0.9	0	0	0	0
Motor Power Continuous/Peak (Kw)	NA	NA	50	50	90	90
Battery Maximum Power (Kw)	NA	NA	50	50	100	50
Battery Capacity (Kwh)	NA	NA	2.2	2.2	45	2.2
Fuel Cell Power (Kw)	NA	NA	NA	NA	NA	90
Fuel Type/Tank	Single 40 gallon diesel tank	single 9 GGE CNG tank	Single 40 gallon diesel tank	single 9 GGE CNG tank	NA	2.5
Fuel Volume(gallon) /Weight(Kg)	35	9GGE	35	9GGE	NA	2.5
Veh Range fully loaded(mile)	600	150	600	150	75	75



	Diesel-Conv	CNG-Conv	Diesel-Hyb	CNG-Hyb	BEV	Fuel Cell
ARB Transient	11.2	11.1	14.3	13.0	31.9	24.2
Daily	12.0	11.1	13.3	11.4	44.7	30.7
UDDS HDV	10.6	10.3	11.5	10.2	31.4	24.3

Figure 4: Fuel economy for different fuel pathways for today's MDT



	Diesel-Conv	CNG-Conv	Diesel-Hyb	CNG-Hyb	BEV	Fuel Cell
ARB Transient	17.7	18.2	23.4	22.4	47.5	31.5
Daily	25.1	23.9	30.9	26.9	75.4	51.0
UDDS HDV	18.6	18.7	22.4	20.8	47.4	34.3

Figure 5: Fuel economy for different fuel pathways for 2025-2030 MDTs

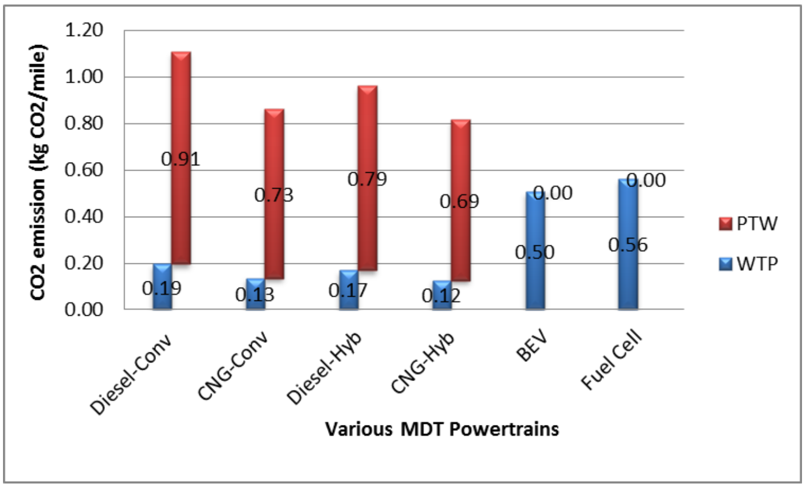


Figure 6: WTW CO2 emissions for different fuel pathways for today's MTDs

3 Vehicle economics and Breakeven Energy costs

3.1 Economic Analysis

The economics analysis takes the diesel conventional medium-duty truck as the baseline and determines the breakeven fuel price for the different alternative fuel/powertrain combinations with consideration of vehicle capital cost difference, discount rate, incentives and average diesel price. The initial vehicle cost differences were calculated from the component costs. The OEM cost differences were evaluated first and a markup of 1.5 was applied in order to get the current market cost difference for each of the alternative fueled powertrain vehicles. The initial capital cost differences for today's and 2025-2030 MDTs are given in Tables 3 and 4. The detailed component unit costs are given in [1]. The payback periods and annual miles VMT used in the cost analysis are given in Table 5.

3.2 Breakeven fuel cost results

The breakeven fuel results for today's and 2025-2030 MDTs are shown in Tables 6 and 7, respectively. Note that for vehicles using alternative fuels, a fuel/powertrain combination is economically attractive if the breakeven fuel price/cost is higher than the present cost of the fuel/energy. In the case of vehicles using diesel fuel, the powertrain is attractive if the breakeven price of diesel fuel is less than the present cost of diesel fuel. In Tables 6 and 7, the economically attractive cases are shown in darker shades. The breakeven fuel price results can be summarized as follows.

Today's MDTs

The economic results using today's technologies and costs indicated that CNG conventional trucks are attractive in most urban applications for a range of annual VMT and payback time combinations. CNG-hybrid vehicles were attractive under 26K VMT/3 year payback scenarios. The other fuel/powertrain combinations were not attractive because the fuel cost saving with fuels other than diesel did not compensate for the high initial cost differentials associated with the alternative powertrains.

2025-30 MDTs

For future medium-duty delivery trucks, diesel and CNG conventional, diesel and CNG hybrid-electric, battery electric, and fuel cell trucks had fuel economy improvements of 81%, 88%, 97%, 104%, 56% and 46%, respectively, compared with the corresponding 2014 vehicles. The economic analyses indicated that most of the fuel/powertrain combinations were attractive with the advanced technologies primarily due to the reductions in the component costs. The fuel cell trucks are economically attractive for almost all applications if the cost of hydrogen is less than about $6/kg. The CNG conventional and hybrid-electric trucks are also attractive under a number of circumstances especially in urban applications. Even the battery powered trucks are economically viable for a three year payback and electricity less than about 12 cents/kWh in urban applications.

Table 3: Capital cost difference for various fuels/powertrains for today's MDTs

Cost	Conventional		Hybrid		Other	
	Diesel-Conv	CNG-Conv	Diesel-Hyb	CNG-Hyb	BEV	Fuel Cell
Engine	$5,000	$6,000	$3,000	$3,600	$0	$0
Tank	$150	$1,500	$150	$1,500	$0	$1,500
Battery	$0	$0	$1,500	$1,500	$30,000	$1,500
Motor	$0	$0	$3,480	$3,480	$6,000	$6,000
Fuel Cell	$0	$0	$0	$0	$0	$4,700
Accessories	$0	$0	$1,000	$1,000	$1,000	$1,000
Incentives[2]	$0	$0	$0	$0	$0	$0
Alternative fuel scenarios and hybridization scenarios						
OEM Additional Cost	NA	$2,350	$3,980	$5,930	$31,850	$9,550
Today's Additional Cost[1]	NA	$3,525	$5,970	$8,895	$47,775	$14,325
1. Markup rate 1.5						
2. After Dec 31, 2013, there's no more incentives on captital cost of the alternative fueled vehicles; however, there are some tax credit on fuels which could be applied on the breakeven price						

Table 4: Capital cost differences for various fuels/powertrains for 2025-2030 MDTs

Cost	**Conventional**		**Hybrid**		**Other**	
	Diesel-Conv	**CNG-Conv**	**Diesel-Hyb**	**CNG-Hyb**	**BEV**	**Fuel Cell**
Engine	$6,000	$6,000	$4,000	$4,500	$0	$0
Tank	$120	$1,000	$150	$1,000	$0	$250
Battery	$0	$0	$440	$440	$9,000	$440
Motor	$0	$0	$1,847	$1,847	$2,951	$2,951
Fuel Cell	$0	$0	$0	$0	$0	$2,700
Accessories	$0	$0	$800	$800	$800	$800
Alternative fuel scenarios and hybridization scenarios						
OEM Additional Cost	NA	$880	$1,117	$2,467	$6,631	$1,021
Today's Additional Cost[1]	NA	$1,320	$1,676	$3,701	$9,947	$1,532

Table 5: Payback year and annual VMT used in the cost analysis

Payback time (Years)	**Daily VMT (miles)**	**Running Period (days)[1]**	**Annual VMT (miles)**
5	30	260	7800
3	60	260	15600
2	100	260	26000
3	100	260	26000
1. Running days=52 weeks/year*5 days/week			

Table 6: Summary of breakeven prices for various fuels/powertrains for today's MDTs

Fuel/Powertrain	**ARB Transient**				**Daily**				**UDDSHDV**			
Annual VMT (mile/year)	**7.8K**	**15.6K**	**26K**	**26K**	**7.8K**	**15.6K**	**26K**	**26K**	**7.8K**	**15.6K**	**26K**	**26K**
Payback Period (year)	**5**	**3**	**2**	**3**	**5**	**3**	**2**	**3**	**5**	**3**	**2**	**3**
Breakeven fuel price ($/DGE, with discount rate 4% and CNG price incentive applied)												
Diesel-Hyb	*$8.9*	*$7.1*	*$6.3*	*$4.3*	*$20.4*	*$16.4*	*$14.5*	*$9.8*	*$22.8*	*$18.3*	*$16.2*	*$11.0*
CNG-Conv	$3.4	$3.6	$3.7	$4.0	$3.1	$3.4	$3.5	$3.7	$3.4	$3.6	$3.7	$3.9
CNG-Hyb	*$1.9*	$2.5	$2.9	$3.6	*$1.5*	*$2.0*	*$2.3*	$3.0	*$1.8*	*$2.3*	$2.6	$3.2
BEV	*-$32.5*	*-$23.8*	*-$19.7*	*-$9.7*	*-$46.6*	*-$34.4*	*-$28.6*	*-$14.7*	*-$31.3*	*-$22.8*	*-$18.7*	*-$8.9*
Fuel Cell	*-$1.3*	*$0.7*	*$1.6*	*$3.9*	*-$2.4*	*$0.1*	*$1.3*	*$4.2*	*-$0.9*	*$1.1*	*$2.1*	*$4.3*

Table 7: Summary of breakeven prices for various fuels/powertrains for 20-25-2030 MDTs

Fuel/Powertrain	ARB Transient				Daily				UDDSHDV			
Annual VMT (mile/year)	11.7K	23.4K	39K	39K	11.7K	23.4K	39K	39K	11.7K	23.4K	39K	39K
Payback Period (year)	5	3	2	3	5	3	2	3	5	3	2	3
Breakeven fuel price ($/DGE)												
Diesel-Hyb	$2.3	$1.9	$1.7	$1.1	$4.3	$3.4	$3.0	$2.1	$3.5	$2.8	$2.5	$1.7
CNG-Conv	$4.0	$4.1	$4.1	$4.2	$3.5	$3.6	$3.7	$3.8	$3.9	$3.9	$4.0	$4.1
CNG-Hyb	$3.9	$4.2	$4.3	$4.7	$2.7	$3.1	$3.3	$3.7	$3.3	$3.6	$3.8	$4.1
BEV	*$2.5*	$4.3	$5.1	$7.2	$3.3	*$1.4*	*$2.7*	$6.0	*$1.9*	$3.7	$4.6	$6.6
Fuel Cell	$6.7	$6.9	$7.0	$7.2	$7.2	$7.5	$7.7	$8.0	$6.9	$7.1	$7.2	$7.5

Table 8: Reference fuel prices for today (2014)

Fuel Price	LHV (MJ/Kg)	Original Price $/diverse unit		Reference Price $/DGE[1]	convert ratio ($/DGE)/original unit
Diesel	42.6	$4.0	$/DGE	$4.0	1
CNG	47.1	$2.1	$/GGE	$2.4	1.14
Hydrogen[2]	120.2	$8.0	$/Kg	$9.1	1.14
Electricity[3]	NA	$0.12	$/Kwh	$4.6	38.3
1. Price conversion is on a energy equivalent basis					
2. $8/Kg hydrogen=$5/[(120.2MJ/Kg hyrogen/42.6MJ/Kg diesel)/(0.85Kg/L*3.785 L/gallon)]=$9.1/DGE					
3. $0.12/Kwh=$0.12/{[(1000*3600J=3.6MJ)/42.6MJ/Kg diesel]/(0.85 Kg/L*3.785 L/gallon)}=$4.6/DGE					

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