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Fuel Economy Analysis of Medium/Heavy-duty Trucks: 2015-2050

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Fuel Economy Analysis of Medium/Heavy-duty Trucks - 2015-2050

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Summary

This paper is concerned with projecting the fuel economy of various classes/types of medium- and heavy-duty trucks and buses that use the conventional engine/transmission and advanced alternative energy technologies from the present to 2050. The alternative truck technologies including hybrid-electric, electric, and fuel cells were simulated over driving cycles appropriate for the applications of each vehicle class and type. Annual fuel and energy savings and reductions in greenhouse gas emissions between the conventional and alternative fuels/technologies are calculated. The results indicate that the CO2 emissions for medium and heavy-duty trucks and buses can be reduced significantly using advanced powertrain technologies and electricity and hydrogen as fuels. The largest reductions of 50-60% are in urban stop-go driving for battery-powered delivery trucks and transit buses. The reductions are somewhat smaller using fuel cells and hydrogen produced by SMR in the urban vehicles.

Keywords: medium-duty, heavy-duty, powertrain, energy consumption, simulation

1 Introduction

Many countries are establishing fuel economy standards for medium duty and heavy duty (MD/HD) trucks as part of programs to reduce greenhouse gas emissions. This paper is concerned with projecting the fuel economy of various classes/types of MD/HD trucks and buses that use the conventional engine/transmission and advanced alternative energy technologies from the present (2015) to 2050. The alternative technologies included are hybrid-electric, electric, and fuel cells. The fuels considered are diesel, natural gas, electricity, and hydrogen. The fuel economy projections were made using the UC Davis version of Advisor which has been used in past studies of advanced car and truck technologies [1-3]. The present fuel economy projections have utilized the information in the literature from the USEPA/DOE truck standards documents (Phase I and II), Supertruck papers and reports, National Academy 21st Century truck book, second addition, selected reports on the aerodynamic drag of trucks and buses, and battery test data from UC Davis. This information and data permitted the projection of the vehicle road load parameters and the powertrain component characteristics for the 2015-2050 time periods. The hybrid-electric control strategies were intended to optimize engine efficiency. The fuel cell characterization assumed a maximum efficiency of 60%. Simulations of the various classes and types of trucks and buses were made for several driving cycles appropriate for the applications of each vehicle class and type. The results of the simulations are summarized and discussed in detail with emphasis on the annual fuel and energy savings and reductions in greenhouse gas emissions between the conventional and alternative fuels/technologies. The importance of selecting the proper driving cycles for the analyses is also considered.

2 Truck types and powertrain technologies

The truck types considered in the simulations is broad. The vehicle powertrains considered for the trucks was also varied and included the following:

1. Conventional engine/ multi-speed transmission
2. Hybrid-electric (HEV and PHEV)
3. Battery-electric (EV)
4. Hydrogen fuel cells

The fuels considered are diesel/gasoline/NG, electricity, and hydrogen. In the case of the hybrid-electric powertrains, the control strategies utilized were intended to maximize the engine operating efficiency over multiple driving cycles. The trucks and technologies considered in the paper are summarized in Table 1.

Table 1: Trucks and Technologies considered in the study

Truck Type	Technologies	Description / Example	MPDGE (2015 MY)	DOE/EPA baseline 2010
Long Haul	Diesel, hybrid, CNG SI, LNG CI, FC	Class 8 sleeper cab	6.6	6.6
Short haul	Diesel, hybrid, CNG, FC, BEV	Class 8 non sleeper cab	6.5	7.0
MD urban	Diesel, Gas, diesel hybrid, CNG, FC, BEV	Delivery truck (UPS)	8.6	8.8
Transit Bus	Diesel, hybrid, CNG, FC, BEV	Transit Bus	4.6	6.7
Other Bus	Diesel, hybrid, CNG, FC, BEV	Coach Greyhound	8.6	
HD pickup	Diesel, Gas, CNG, Hybrid, FC, BEV, PHEV	Ford F250	18	13.5
MD vocational	Diesel, PHEV, BEV, FC	No simulation (mpg Data from EMFAC)	8.4	
HD vocational	Diesel, CNG, BEV, FC	No simulation (mpg Data from EMFAC)	6.7	

3 Approaches and methods of analysis

3.1 UCD Advisor program

The **UCD ADVISOR** program was originally developed by DOE/NREL and made available widely to groups doing vehicle research. UC Davis utilized Advisor in many studies and until recently primarily for the study of light-duty vehicles [7-9] using various advanced powertrains. During the course of those studies, many modifications were made to ADVISOR and subroutines written for special powertrain arrangements and control strategies of the powertrains. In addition, the energy storage options were extended to include supercapacitors and lithium batteries tested in the lab at UC Davis. This enhanced version of ADVISOR has been used in the present study of MD/HD trucks.

3.2 Road load parameters

The results for fuel economy obtained in the vehicle simulations are highly depended on the inputs used for the road load parameters, such as the weight including load, the aerodynamic drag coefficient and frontal area, and the tire rolling resistance. These parameters vary widely with truck type and are expected to change/improve markedly in future years in order to reduce the fuel consumption of MD/HD trucks. The present fuel economy projections have utilized information in the literature from the USEPA/DOE truck standards documents (Phase I and II) [5-6], Super-Truck papers and reports [10-12], National Academy 21st Century truck book, third report [13], and selected reports on the aerodynamic drag of trucks and buses [14-15]. This information and data permitted the projection of the vehicle road load parameters and the powertrain component characteristics for the 2015-2050 time periods given in Table 2. The input values are given for 2017 (present), 2030, and 2050 for each of the truck types simulated. The same road load parameters were used for the trucks using the advanced powertrains as used for the trucks using diesel engines for each year.

3.3 Powertrain characteristics

The powertrains being simulated utilize engines, transmissions, electric motors, batteries, and fuel cells in various combinations. These components will be improved in the coming years as part of the advanced vehicle development programs. The improvements of primary interest in the simulations are the efficiencies of the components. The most important of these improvements are those in the maximum engine efficiency for diesel engines that have been indicated in the Supertruck reports [10-12]. There will also be improvements in the efficiencies of electric motors and fuel cells, but those improvements will be smaller and less important.

The **Advisor** simulation program utilizes efficiency maps for both the engines and electric motors. The map used for the diesel engines was one of the engines used in the EPA MD/HD truck studies (CI149-EPA-7L-200HP). The map used for the electric motor was for the motor used in the GM EV1 (MC-AC124-EV!). The transmission map used for the conventional vehicles was for a Eaton transmission (TX-10spd-Eaton-2). The contours in the maps were scaled from the maximum efficiency in the inputs for the simulations (see Table 2).

The batteries used in the EV and PHEV vehicles were of the LiNiCoAl chemistry with the voltage and resistance characteristics as a function of state-of-charge based on tests of EIG cells in the lab at UC Davis [15-16]. The resistances and cell weights were scaled based on the Ah rating of the cells. The batteries used in the hybrid-electric and fuel cell vehicles were of the lithium titanate oxide (LTO) chemistry with characteristics based on tests of Altairnano cells in the lab at UC Davis. The LTO batteries were used for all powertrains that required high power and very long cycle life.

In the fuel cell simulations, the fuel cell model that is part of the original Advisor program was used with a maximum efficiency of 60%. This is a simple model in which the fuel cell efficiency at a particular power level is just a function of the power ratio (P/P_{max}). More sophisticated fuel cell simulation tools [17-18] have been developed at UC Davis that can be used in future studies.

The inputs describing the various powertrains and truck types for the simulations are given in Table 3. The engine and transmission characteristics for the conventional vehicles and the electric motor, battery, and fuel cell characteristics for advanced powertrain vehicles are given for the 2017-2050 time periods. The same road-load parameters were used for all the simulations for a particular truck type and time period. As indicated in Table 3, the driving cycles simulated for each truck depended on whether the truck was used primarily in the city (urban) and suburbs or on the highway. Driving cycles for the simulations were selected from those used by EPA and the National Labs.

3.4 Powertrain control strategies

In a hybrid-electric vehicle, the strategy that controls the power split between the engine and the electric motor is important in determining the fuel economy improvement that can be expected using a hybrid-electric powertrain (HEV). The objective of the control strategy is to increase the average efficiency of the engine over the appropriate driving cycle. Different control strategies were used for medium-duty (MD) and heavy-duty (HD) trucks primarily because of the differences in their acceleration rate capability. In the case of the MD trucks, the control strategy was to utilize the electric drive whenever the vehicle power demand could be met by the electric motor and the battery state-of-charge (SOC) was in the acceptable range (usually near 50%). For higher power demands and when the battery required recharging, the engine would meet both demands and operate at high efficiency even when the vehicle power demand alone was relatively low. In this way, the average engine efficiency would be near the maximum for driving cycles with frequent starts and stops. In the case of large HD vehicles like short haul or refuse collection trucks, the control strategy is that the vehicle is operated at low speeds (usually less than 20 mph) using the electric motor and on the engine alone at higher speeds and/or when the battery needs recharging. The electric motor and battery storage (kWh) are sized in the HD vehicles to permit operation on electric electricity for a signifcant range on appropriate city driving cycles. The HD strategy keeps the diesel engine from operating in the low efficiency region of its map, does not require idle, and permits energy recovery by regenerative braking. This strategy can result in a significant improvement in fuel economy for urban driving cycles.

Table 2: Advisor simulation inputs for conventional engine/transmission trucks of various types for 2017-2050

Truck type	Test weight kg	C_DA (m^2) C_D /A_F	f_r(kg/kg)	Tire diameter (m)	Final drive ratio	Access Power kW	Engine kW/mxeff.	Transm. Number. Speeds/ effic.
Long haul	**Diesel**							
2017	30000	.6/10	.0065	1.8	3.8	1.5	320/43	10/.95
2020								
2025								
2030	29500	.55/9.5	.0055	1.8	3.8	1.5	320/.50	10/.96
2035								
2040								
2050	29000	.45/9.5	.005	1.8	3.8	1.5	320/.52	10/.96
MD city Deliv.	**Diesel**							
2017	7500	.75/7.8	.008	..85	2.85	1.3	150/.42	6/.95
2020								
2025								
2030	6900	.6/7.8	.007	.85	2.85	1.3	150/.46	6/.96
2035								
2040								
2050	6750	.55/7.2	.006	.85	2.85	1.3	150/.48	6/.96
City transit bus	**Diesel**							
2017	14600	.79/7.9	.009	1.5	3.8	6	280/.43	10/.92
2020								
2025								
2030	13750	.65/7.1	.0075	1.5	3.8	6	280/.48	10/.95
2035								
2040								
2050	13225	.55/7.1	.006	1.5	3.8	6	280/.50	10/.96
Inter-city coach bus	**Diesel**							
2017	15200	.7/7.5	.008	1.5	3.8	6	280/.43	10/.92
2020								
2025								
2030	14800	.6/7.7	.006	1.5	3.8	6	280/.48	10/.96
2035								
2040								
2050	14200	.55/7.7	.005	1.5	3.8	5	280/.50	10/.96
Reuse collection								
		Diesel						
2017	19000	.60/10	.009	1.8	2.8	1.2	200/.42	6/.95
2030	18500	.55/9.5	.0075	1.8	2.8	1.2	200/.48	6/.96
2050	18000	.45/9.0	.006	1.8	2.8	1.2	200/.52	6/.96

Table 3: Advisor inputs for hybrid-electric, battery electric and fuel cell trucks and buses

Truck type	Vehicle weight kg	Engine kW, effic.	Transm., effic,	Electric motor kW	Battery kwh	Electric range miles	Fuel cell kW	Type of driving cycles
Long haul								
Conv-diesel	30000-29000	320, .43-.52	10 speed, .95-.96					highway
Fuel cell	30000-29000			300	5		320	highway
MD city Deliv.								
Conv-diesel	7500-6750	150, .42-.50	6 speed, .95-.96					Urban, highway
Hybrid-diesel	7500-6750	150, .42-.50	6 speed, .95-.96	75	2			Urban, highway
EV	7500-6750		2 speed, .95-.96	125	50-100	50-100		Urban, highway
Fuel cell	7500-6750		2 speed, .95-.96	125	2		150	Urban, highway
City transit bus								
Conv-diesel	14600-13225	280, .53-.50	10 speed, .95-.96					Urban
Hybrid-diesel	14600-13225	280, .53-.50	10 speed, .95-.96	120	5			Urban
EV			2 speed, .95-.96	250	150-300	100-200		Urban
Fuel cell	14600-13225		2 speed, .95-.96	250			300	Urban
Refuse collection								
Conv-diesel	18000-19000	200/ .43-.52	6/ .95-.96					Port and city
Hybrid-diesel	18000-19000	200/ .43-.52	6/ .95-.96	200	15	5-10		Port and city

4 Fuel economy simulation results for various trucks and buses 2017-2050

4.1 Baseline conventional diesel trucks

The fuel economy simulation results for various trucks and buses using a conventional engine/transmission powertrain are given in Table 4. These fuel economy values for each time period will be used as the baseline for that time period for comparison with the fuel economies using the alternative advanced powertrains. Most of the trucks and buses use diesel engines except where noted the vehicles use gasoline or NG engines. All energy use comparisons will be made based on mi/galD. For all the vehicles, the simulations were run for several driving cycles which are appropriate for the applications for that vehicle. The primary distinction was between city/urban and highway cycles. The effect of the driving cycle on the projected fuel economy can be significant and should be considered carefully in applying the simulation results in the scenario studies. The EPA/NHTSA Phase I and II and the EMFAC fuel economy values are given for the vehicles when available. In most cases, the agreement with the corresponding simulation fuel economy is reasonable even though it is often not clear on what driving cycle the EPA/NHTSA Phase I and II fuel economies correspond.

Table 4: Fuel economy simulation results for trucks and buses using conventional engine/transmission powertrains 2017-2050

Long	**haul**		**HD trucks**				
2017	mpg		2030	mpg		2050	mpg
Sim. GEM65	6.1		Sim. GEM65	8.2		Sim. GEM65	9.5
Sim. GEM55	7.0		Sim. GEM55	9.2		Sim. GEM55	10.6
EPA baseline	6.6		EPA/NHTSA Phase I	8.0			
EMFAC	6.6		EPA/NHTSA Phase II	8.5			
MD	**delivery**		**Trucks**				
2017	**mpg**		**2030**	**mpg**		**2050**	**mpg**
Delivery cycle	9.6		Delivery Cycle	11.0		Delivery Cycle	12.1
Non-FW 15mphav.	8.9		Non-FW 15mphav.	10.7		Non-FW 15mphav.	11.5
ARB-Transition	9.8		ARB-Transition	12.1		ARB-Transition	13.1
EPA baseline	8.8		EPA/NHTSA Phase I	9.6			
EMFAC	8.6		EPA/NHTSA Phase II	13.1(urban)			
city	**transit**		**Bus**				
2017	**mpg**		**2030**	**mpg**		**2050**	**mpg**
Manhattan	3.7		Manhattan	4.4		Manhattan	4.8
NYbus	2.5		NYbus	2.9		NYbus	3.1
NYcomp	4.5		NYcomp	5.4		NYcomp	5.9
ARB-transition	6.1		ARB-transition	7.6		ARB-transition	8.5
HHDT-cruise	7.8		HHDT-Cruise	11.3		HHDT-cruise	13.8
EPA baseline	6.7		EPA/NHTSA Phase I	7.35			
EMFAC	4.6		EPA/NHTSA Phase II	9.4			
Refuse	**collection**						
2017	**mpg**		**2030**	**mpg**		**2050**	**mpg**
diesel							
Port-drayage	3.6		Port-Dryage	4.2		Port-dryage	4.7
WVUCity	4.8		WVUCity	5.8		WVUCity	6.7
WVUSub	5.8		WVUSub	7.0		WVUSub	8.4
CNG	**Diesel equiv mpg**						
Port-dryage	3.2		Port-dryage	3.7		Port-dryage	4.4
WVUCity	4.0		WVUCity	4.6		WVUCity	5.8
WVUSub	4.7		WVUSub	5.5		WVUSub	7.2

4.2 Hybrid-electric truck and buses

The fuel economy simulation results for various trucks and buses using a hybrid-electric powertrain are given in Table 5. The batteries used for energy storage are of the lithium titanate chemistry with characteristics based on testing of Altairnano cells in the laboratory at UC Davis. The control strategy used was intended to optimize the efficiency of the engine in stop-go traffic. When the engine was “on”, it powered the vehicle and recharged the battery most of the time.

Fuel economy results are given for trucks and buses which operate in urban environments with significant stop-go driving. Driving cycles for the runs were selected to be appropriate for the particular vehicles. Significant improvements in fuel economy are projected using the hybrid-electric powertrains. The improvements compared to conventional engine powertrains for various trucks and driving cycles are given in Table 6.

Table 5: Fuel economy simulation results for trucks and buses using hybrid-electric powertrains with lithium titanate oxide batteries

MD	**delivery**		**Trucks**				
2017	**mpg**		**2030**	**mpg**		**2050**	**mpg**
Delivery cycle	13.6		Delivery Cycle	17.6		Delivery cycle	20.0
Non-FW 15mphav.	12.3		Non-FW 15mphav.	15.5		Non-FW 15mphav.	17.0
ARB-Transition	14.6		ARB-Transition	18.2		ARB-Transition	20.5
HHDT- transition	11.5		HHDT- transition	15.2		HHDT- transition	18.0
EPA baseline	8.8		EPA/NHTSA Phase I	9.6			
EMFAC	8.6		EPA/NHTSA Phase II	13.1(urban)			

city	**transit**		**Bus**				
2017	**mpg**		**2030**	**mpg**		**2050**	**mpg**
Manhattan	7.0		Manhattan	8.7		Manhattan	9.9
NYbus	5.0		NYbus	6.2		NYbus	6.2
NYcomp	7.3		NYcomp	9.5		NYcomp	11.0
ARB-transition	9.0		ARB-transition	12		ARB-transition	14.0
HHDT-cruise	8.0		HHDT-Cruise	11.5		HHDT-cruise	14.2
EPA baseline			EPA/NHTSA Phase I	7.35			
EMFAC			EPA/NHTSA Phase II	9.4			
Inter-city	**bus**						
2017	**mpg**		**2030**	**mpg**		**2050**	**Mpg**
Const. 65mph	7.3		Const. 65mph	10.0		Const. 65mph	11.7
ARB-transition	7.9		ARB-transition	9.8		ARB-transition	10.6
HHDDT-cruise	9.3		HHDDT-Cruise	12.6		HHDDT-cruise	14.7
HHDT-CR	21.4		HHDT-CR	27.1		HHDT-CR	31.5
EPA/NHTSA Phase I	12.1		EPA/NHTSA Phase II	17.8			
Refuse	**collection**						
2017	**mpg**		**2030**	**mpg**		**2050**	**Mpg**
diesel							
Port-drayage	8.7		Port-Drayage	10.7		Port-dryage	12.7
WVUCity	8.3		WVUCity	9.7		WVUCity	11.5
WVUSub	8.3		WVUSub	9.4		WVUSub	11.5
CNG	**Diesel equiv mpg**						
Port-drayage	7.9		Port-Dryage	10.5		Port-drayage	12.0
WVUCity	7.2		WVUCity	8.3		WVUCity	9.4
WVUSub	7.1		WVUSub	8.9		WVUSub	9.5

Table 6: Comparisons of the fuel economy of hybrid-electric and the baseline conventional vehicles for 2017-2050

Short haul heavy-duty trucks

	HEV 2017, 2030, 2050	**CONV Diesel 2017, 2030, 2050**	**HEV/CONV Diesel 2017, 2030, 2050**
Driving cycles			
HHDT-TR	6.7, 8.0, 8.6	5.6, 6.6, 7.0	1.2, 1.21, 1.23
HHDT-CR	8.2, 10.6, 12.0	8.2, 10.6, 11.8	1.0, 1.0, 1.02
GEM65	7.0, 8.6, 9.8	7.0, 8.9, 9.8	1.0, 1.04, 1.0
GEM55	8.1, 10.4, 11.7	8.1,10.1, 11.1	1.0, 1.03, 1.05

Medium-duty delivery trucks

	HEV 2017, 2030, 2050	**CONV Diesel 2017, 2030, 2050**	**HEV/CONV Diesel 2017, 2030, 2050**
Driving cycles			
Delivery cycle	13.6, 17.6, 20.0	9.6, 11, 12.1	1.42, 1.6, 1.65
Non-FW 15mpg av.	12.3. 15.5, 17.0	8.9, 10.7, 11.5	1.38, 1.45, 1.48
ARB-Trans.	14.6, 18.2, 20.5	9.8, 12.1, 13.1	1.49, 1.5, 1.56

City transit buses

	HEV 2017, 2030, 2050	**CONV Diesel 2017, 2030, 2050**	**HEV/CONV Diesel 2017, 2030, 2050**
Driving cycles			
NYcomp	4.5, 5.4,5.9	7.3, 9.5, 11.0	1.6,1.76, 1.86
ARB-TR	6.1, 7.6, 8.5	9, 12, 14	1.48, 1.58, 1.65
HHDT-CR	8.0, 11.5, 14.2	7.8,11.3, 13.8	1.03, 1.03, 1.03

Inter-city coach buses

	HEV 2017, 2030, 2050	**CONV Diesel 2017, 2030, 2050**	**HEV/CONV Diesel 2017, 2030, 2050**
Driving cycles			
65 mph const.	7.3, 10, 11.7	7.4, 10.1, 11.9	1.0, 1.0, 1.0
ARB-TR	7.9, 9.8, 10.6	6.1, 7.4, 8.0	1.3, 1.32, 1.33
HHDT-CR	9.3, 12.6, 14.7	8.8, 11.9, 13.7	1.06, 1.06, 1.07

4.3 Battery-electric trucks and buses

Simulation results for various trucks and buses using a battery-electric powertrain are given in Table 7. The batteries used for energy storage are of the lithium nickel cobalt aluminum chemistry with characteristics based on testing of several cells of that chemistry in the laboratory at UC Davis. The energy use results are given in terms of Wh/mi from which the energy storage kWh for a specific range can be calculated. Results are shown for 2030 and 2050 for batteries with energy densities of 150 Wh/kg and 225 Wh/kg , respectively. The driving cycles for the simulations were selected to be appropriate for the particular vehicles studied.

4.4 Hydrogen Fuel cell trucks and buses(FCV)

Simulation results for various trucks and buses using a hydrogen fuel cell powertrain are given in Table 8. The batteries used for energy storage are of the lithium titanate oxide chemistry with characteristics based on testing of several cells of that chemistry in the laboratory at UC Davis. The energy use results are given in terms of mi/gal gasoline equiv. converted to kgH_2/mi. The hydrogen storage requirements for several specified ranges are calculated from the simulation results for the various vehicles. Driving cycles for the runs were selected to be appropriate for the particular vehicles studied.

Table 7: Simulation results for battery powered trucks and buses (EVs)

Transit buses

2030

Transit bus EV*	kWh/mi	**kWh for 100 miles	**kWh for 200 miles
Manhattan	2.2	275	550
NYcomp	1.8	240	480
ARB-TR	1.43	180	360
HHDT-CR	1.2	150	300
65mph const.	1.33	166	332

* C_D =.35, A_F =7.5, wt. =15,000 kg, f_r =.0075, 6 kW access. load

**80% of battery capacity is used initially, 150 Wh/kg 2030, 225 Wh/kg 2050

2050

Transit bus EV*	kWh/mi	kWh for 100 miles	kWh for 200 miles
Manhattan	1.83	230	460
NYcomp	1.46	182	364
ARB-TR	1.1	138	276
HHDT-CR	.86	108	216
65mph const.	1.04	130	260

* C_D =.30, A_F =7.5, wt. =14,000 kg, f_r =.005, 6 kW access. load

City delivery trucks

2030

City delivery EV*	kWh/mi	kWh for 75 miles	kWh for 150 miles
Delivery cycle	.83	78	155
ARB-TR	.75	70	140
HHDT-CR	1.1	103	206
Non-FW 15mphav.	.83	78	155

* C_D =.75, A_F =7.8, wt. =6900 kg, f_r =.007, .8 kW access. load

2050

City delivery EV*	kWh/mi	kWh for 75 miles	kWh for 150 miles
Delivery cycle	.70	66	132
ARB-TR	.62	58	116
HHDT-CR	.79	74	148
Non-FW 15mphav.	.73	68	136

* C_D =.45, A_F =7.0, wt. =6750 kg, f_r =.006, .8 kW access. Load

**80% of battery capacity is used initially, 150 Wh/kg 2030, 225 Wh/kg 2050

HD pickup truck

2030

HD pickup EV*	kWh/mi	kWh for 75 miles	kWh for 150 miles
FUDS	.43	40	80
HW	.42	39	78
ARB-TR	.405	38	76
HHDT-CR	.42	39	78

* C_D =.41, A_F =3.1, wt. =3950 kg, f_r =.0075, .8 kW access. Load

2050

City delivery EV*	kWh/mi	kWh for 75 miles	kWh for 150 miles
Delivery cycle	.394	37	74
ARB-TR	.384	36	72
HHDT-CR	.368	34	68
Non-FW 15mphav.	.381	36	72

* C_D =.40, A_F =3.1, wt. =3875 kg, f_r =.006, .8 kW access. load

Table 8: Simulation results for hydrogen Fuel cell trucks and buses(FCV)

Transit buses

2030

Transit bus* **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 150 miles	kgH_2 for 300 miles
Manhattan cycle	8.8	8.4	19.8	39.6
NY comp	11.4	10.9	15.3	30.6
ARB-TR	14.6	13.9	12.0	24
HHDT-CR	18.1	17.3	9.6	19.2
65mph const.	15.1	14.4	11.6	23.2

* C_D =.35, A_F =7, wt. =15000 kg, f_r =.006, 6 kW access. load

**90% of H_2 capacity is used, mi/kgH_2 = mi/gal gasol. equiv./1.0475

2050

Transit bus*	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 150 miles	kgH_2 for 300 miles
Manhattan cycle	9.5	9.1	18.3	36.3
NY comp	12.0	11.5	14.5	29
ARB-TR	15.6	14.9	11.2	22.4
HHDT-CR	21.1	20.1	8.3	16.6
65mph const.	17.8	17.0	9.8	19.6

* C_D =.30, A_F =7, wt. =14500 kg, f_r =.005, 6 kW access. load

Medium-duty City delivery trucks

2030

MD city delivery * **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 75 miles	kgH_2 for 150 miles	kgH_2 for 400 miles
Delivery cycle	20.8	19.9	4.2	8.4	22.3
ARB-TR	20.9	20.0	4.2	8.4	22.2
HHDT-CR	22.4	21.4	3.9	7.8	20.8

* C_D =.60, A_F =7.8, wt. =6900 kg, f_r =.007, 1.5 kW access. load

**90% of H_2 capacity is used, mi/kgH_2 = mi/gal gasol. equiv./1.0475

2050

MD city delivery * **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 75 miles	kgH_2 for 150 miles	kgH_2 for 400 miles
Delivery cycle	22.4	21.4	3.9	7.8	20.8
ARB-TR	22.7	21.7	3.8	7.6	20.5
HHDT-CR	24.5	23.4	3.6	7.2	19.0

* C_D =.55, A_F =7.2, wt. =6750 kg, f_r =.006, 1.5 kW access. load

Heavy-duty pickup trucks

2030

HD pickup diesel * **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 75 miles	kgH_2 for 150 miles
FUDS	34.4	32.8	2.29	4.6
HW	34.6	33.0	2.27	4.5
ARB-TR	33.4	31.9	2.35	4.7
HHDT-CR	34.8	33.2	2.26	4.5

* C_D =.41, A_F =3.1, wt. =3950 kg, f_r =.0075, .8 kW access. load

2050

HD pickup diesel * **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 75 miles	kgH_2 for 150 miles
FUDS	39.9	38.1	1.97	3.9
HW	38.3	36.6	2.05	4.1
ARB-TR	35.9	34.3	2.19	4.4
HHDT-CR	38.7	37.0	2.03	4.1

* C_D =.40, A_F =3.1, wt. =3850 kg, f_r =.006, .8 kW access. load

Long haul (highway) trucks

2030

Long haul* **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 100 miles	kgH_2 for 300 miles	kgH_2 for 500 miles
GEM65	8.9	8.5	13.07	39	65
GEM55	9.4	9.0	12.35	37	62
HHDT-CR	9.9	9.45	11.76	35	59
65mph const	8.8	8.4	13.23	40	66

* C_D =.55, A_F =9.5, wt. =29500 kg, f_r =.0055, 1.5 kW access. load

2050

Long haul * **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 100 miles	kgH_2 for 300 miles	kgH_2 for 500 miles
GEM65	9.2	8.78	12.66	38	63
GEM55	10.1	9.64	10.37	31	52
HHDT-CR	10.9	10.41	10.67	32	53
65mph const	9.3	8.8	11.36	34	57

* C_D =.45, A_F =9.5, wt. =29000 kg, f_r =.005, 1.5 kW access. load

5 Comparisons of the energy use of the various trucks and powertrains

The energy use of various trucks and buses utilizing the different powertrains and fuels are compared in Table 10 in terms of equivalent mi/gal Diesel. The comparisons are made for both city and highway driving at 65 mph. In all cases, the energy use per mile decreases significantly with the use of the advanced powertrains with EVs showing the lowest energy use from the battery.

Table 9: Projected relative equivalent fuel economy (mi/galD) of various trucks and buses in city and highway driving (2030)

City driving conditions

MD delivery truck

powertrain	mi/galD	Ratio
Diesel	11.0	1.0
Hybrid diesel	17.6	1.6
H2FC	23.3	2.1
EV*	41.7	3.8

*battery charging efficiency 90%

Transit bus

Powertrain	mi/galD	Ratio
Diesel	7.6	1.0
Hybrid diesel	12.0	1.6
H2FC	16.4	2.2
EV	24.3	3.2

HD pickup truck

powertrain	mi/galD	Ratio
Diesel	13,3	1.0
Hybrid diesel	32.9	2.5
H2FC	37.4	2.8
EV	85.8	6.5

Highway driving at 65 mph

Long haul heavy-duty truck

powertrain	mi/galD	Ratio
Diesel	8.2	1.0
H2FC	9.9	1.21

Intercity bus

powertrain	mi/galD	Ratio
Diesel	10.1	1.0
H2FC	16.9	1.7
EV	26.1	2.6

HD pickup truck

powertrain	mi/galD	Ratio
Diesel	23.5	1.0
Hybrid diesel	31	1.3
H2FC	38.7	1.7
EV	82.7	3.5

6 CO2 emissions for trucks/buses of various types and powertrains

The fuel economy and energy consumption of the various vehicles using different powertrains have been discussed in previous sections. In this section, the CO_2 emissions will be considered. These emissions depend not only on the fuel economy of the vehicle, but also on how the fuel used was produced. This is particularly true of electricity and hydrogen. The CO_2 emissions, $kgCO_2$/mi, for the various fuels can be expressed as follows:

Diesel: $kgCO_2/mi = kgCO_2/galD/(mi/galD)$
Electricity: $kgCO_2/mi = kgCO_2/kWh/(mi/kWh)$
Hydrogen: $kgCO_2/mi = kgCO_2/kgH_2/(mi/ kgH_2)$

Both electricity and hydrogen can be produced by different approaches. In the case of electricity, it can be produced using fossil fuels or solar/wind energy. In the case of hydrogen, it can be produced from natural gas (SMR) or from electrolyzing water using electricity. Clearly, from the CO_2 emissions point-of-view, it is advantageous to produce the electricity from the renewable sources, but in this study, it is assumed the electricity is produced from natural gas as will be the case in the near-term.

The fuel economy and energy consumption of the various vehicles using different powertrains have been discussed in previous sections. In this section, the CO_2 emissions will be considered. These emissions depend not only on the fuel economy of the vehicle, but also on how the fuel used is produced. This is particularly true of electricity and hydrogen. The CO_2 emissions, $kgCO_2/mi$, for the various fuels can be expressed as follows:

Diesel: $kgCO_2/mi = kgCO_2/galD/(mi/galD)$, $kgCO_2/galD = 10.1$
Electricity: $kgCO_2/mi = kgCO_2/kWh/(mi/kWh)$
Hydrogen: $kgCO_2/mi = kgCO_2/kgH_2/(mi/ kgH_2)$

Both electricity and hydrogen can be produced by several different approaches. In the case of electricity, it can be produced using fossil fuels or solar/wind energy. In the case of hydrogen, it can be produced from natural gas (SMR) or from electrolyzing water using electricity. Clearly, from the CO_2 emissions point-of-view, it is advantageous to produce the electricity from the renewable sources, but in this study, it is assumed the electricity is produced from natural gas as will be the case in the near-term.

Information for the production of grid electricity in the United States is given in [x]. According to the EIA, the average heat rate for generating electricity from natural gas in the United States in 2015 was 7878 Btu/kWh and the CO_2 emissions factor was 53.07 $kgCO_2/10^6$ Btu. These values correspond to an efficiency of 43.3% and CO_2 emissions of .418 $kgCO_2/kWh_{elec.}$ From [x], the distribution loss in the US grid is about 6%.

The chemistry of the steam reforming process using natural gas (SMR) can be expressed as

$$CH_4 + ½\, O_2 + H_2O \rightarrow CO_2 + 3\, H_2$$

Hence 1 kg CH_4 yields 3/8 kgH_2 and 44/16 $kgCO_2$ or 1 kgH_2 results in 7.3 $kgCO_2$. Assuming an efficiency of 70% for the SMR process, the resulting CO_2 emission factor is 10.4 $kgCO_2/ kgH_2$.

If the hydrogen is produced using electrolysis with grid electricity, the CO_2 emissions would result from the generation of the electricity required in the electrolysis. Hence assuming 60% efficiency for the electrolysis process, the total efficiency of producing the hydrogen is

$$\text{Effic. (H2/nat.gas)} = .433 \times .94 \times .6 = .244$$

The electricity to generate the hydrogen is 33.3 kWh/kgH2/.6 = 55.5 kWh/kgH2. The CO_2 emissions would be 55.5 x .444 $kgCO_2/kWh$ = 24.6 kg CO_2/ kgH2.

Using the CO_2 emission factors discussed in the previous paragraphs, the CO_2 emissions using the various fuels become the following:

Diesel: $kgCO_2/mi = 10.1/(mi/galD)$
Electricity: $kgCO_2/mi = .444/(mi/kWh)$
Hydrogen: $kgCO_2/mi = 10.4 \text{ or } 24.6/(mi/ kgH_2)$

These relationships were used to calculate the CO_2 emissions for the various vehicles and powertrains/fuels shown in Table 10. As indicated in the table, the hydrogen for the fuel cell vehicles was produced using the SMR process. If the hydrogen were produced using electrolysis, the CO_2 emissions would be much higher unless the electricity was produced primarily from renewable solar/wind energy.

Table 10: Summary of the fuel economy and CO$_2$ characteristics of various trucks using different drivelines and fuels

Heavy-duty truck	fuel	Power-train	2017		2030		2050	
			Fuel economy	kgCO$_2$/mi	Fuel economy	kgCO$_2$/mi	Fuel economy	kgCO$_2$/mi
GM65 cycle	diesel	engine	6.1 mi/galD	1.66	8.2	1.23	9.5	1.06
	Hydrogen*	Fuel cell			8.5 mi/kg	1.22	8.8	1.18
Medium-duty truck	diesel	engine	9.6	1.05	11.0	.92	12.1	.84
Delivery cycle	diesel	hybrid	13.6	.74	17.6	.57	20.0	.51
	electricity	bat-EV			.83 kWh/mi	.37	.70	.31
	Hydrogen*	Fuel cell			19.9 mi/kg	.52	21.4	.49
Transit bus	diesel	engine	6.1	1.66	7.6	1.33	8.5	1.19
ARB-Trans cycle	diesel	hybrid	9.0	1.12	12.0	.84	14.0	.72
	electricity	bat-EV			1.43 kWh/mi	.63	1.1	.49
	Hydrogen*	Fuel cell			13.9 mi/kg	.75	14.9	.70
Highway cruise	diesel	engine	7.8	1.3	11.3	.89	13.8	.73
	hydrogen	Fuel cell			17.3 mi/kg	.60	20.1	.52

*hydrogen produced from the SMR process

The results in Table 10 indicate that the CO$_2$ emissions for medium and heavy-duty trucks and buses can be reduced significantly using advanced powertrain technologies and electricity and hydrogen as fuels. The largest reductions of 50-60% are in urban stop-go driving for battery-powered delivery trucks and transit buses. The reductions are somewhat smaller using fuel cells and hydrogen produced by SMR in the urban vehicles. Fuel cell vehicles using hydrogen from renewable sources would result in very low CO$_2$ emissions. Hydrogen from electrolysis is attractive from the CO$_2$ emissions point-of view only using electricity from renewable sources [19]. In the case of heavy-duty long haul trucks, expected improvements in diesel engine efficiency will result in large reductions in CO$_2$ emissions that can match the upstream emissions from hydrogen fuel cell trucks unless the hydrogen is produced using renewable sources. However, the CO$_2$ emissions for fuel cell inter-city buses appear to be significantly lower than diesel buses even with SMR hydrogen.

7 NO$_x$ emissions of advanced diesel and natural gas engines

It is well accepted that the reductions in CO$_2$ emissions must be attained without increasing criteria pollutant emissions. Of particular concern in this regard are the NO$_x$ emissions. The present emission standards for heavy-duty engines were set in 2010: .2 g/bhp-hr for NO$_x$ and .01 g/bhp-hr for PM. These criteria emission standards were maintained when the Phase I and II engine and vehicle CO$_2$ standards were set by EPA/NHTSA. As discussed in recent CARB reports on diesel and natural gas engines for HD trucks [20, 21], the exhaust after-treatment technologies currently being used with those engines can be refined to reduce the NO_x emissions to .02 g/bhp-hr leading to vehicles with "ultra-low" NO_x emissions.

In the case of the diesel engines, the SCR system developments to further reduce the NO_x emissions have not been completed, but are expected to be completed in the relatively near future [22, 23]. In the case of the spark-ignition (SI) natural gas engines, "ultra-low" NO_x emissions can be achieved using a three-way catalyst and stiochiometric engine operation. Engines suitable for use in HD trucks have already been demonstrated [24, 25]. The SI natural gas engines have a 10-15% fuel economy (energy) penalty compared to the standard diesel engine. Cummins-Westport is developing a dual-fuel natural gas engine [26. 27], which operates much like a diesel engine and essentially negates the efficiency penalty of SI engine. The dual-fuel engine can utilize the advanced SCR systems being developed for the diesel engine. Both the SI and dual-fuel natural gas engine benefit from the lower carbon content of their fuel relative to the diesel engine and hence, have lower GHG emissions.

In light of the good prospects for "ultra-low" NO_x emission engines, CARB and other Air Quality Management Districts around the United States have petitioned the EPA [28] to begin rule-making soon to reduce the engine NO_x standard to .02 g/bhp-hr by 2022 or 2024. The EPA rejected the requests for the fast timeframe for new rule-making, but proposed a rule-making timeline consistent with the Phase II fuel economy standards set for 2027 [29-31].

8 Summary and conclusions

This paper is concerned with projecting the fuel economy of various classes/types of medium- and heavy-duty trucks and buses that use the conventional engine/transmission and advanced alternative energy technologies from the present to 2050. The alternative truck technologies including hybrid-electric, battery-electric, and fuel cells were simulated over driving cycles appropriate for the applications of each vehicle class and type. Annual fuel and energy savings and reductions in greenhouse gas emissions between the conventional and alternative fuels/technologies were calculated. The results indicate that the CO_2 emissions for medium and heavy-duty trucks and buses can be reduced significantly using advanced powertrain technologies and electricity and hydrogen as fuels. The largest reductions of 50-60% are in urban stop-go driving for battery-powered delivery trucks and transit buses. Both medium- and heavy-duty vehicles using hybrid-electric powertrains with diesel engines can also result in significantly reduced CO_2 emissions (25-30%) in urban use. The reductions are somewhat smaller using fuel cells and hydrogen produced by SMR in the urban vehicles. Hydrogen from electrolysis is attractive from the CO_2 emissions point-of view only using electricity from renewable sources [19].

In the case of heavy-duty long haul trucks, expected improvements in diesel engine efficiency will result in large reductions in CO_2 emissions that match the upstream emissions from hydrogen fuel cell trucks unless the hydrogen is produced using renewable sources. However, the CO_2 emissions for fuel cell inter-city buses appear to be significantly lower than diesel buses even with SMR hydrogen. Hydrogen fuel cell vehicles have zero NO_x emissions and this will remain a large advantage for them even when ultra-low NO_x emission engines are developed for heavy-duty vehicles.

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