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Electrification of Buses and Trucks: Battery and fuel cell powertrains

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Abstract

This paper considerstechnologies and cost assessments of ZEV medium-duty and heavy-duty vehicles. The battery/electric and fuel cell/hydrogen technologies are considered as zero-emission (ZEV) options in buses and MD/HD trucks to reduce greenhouse gas emissions in the transportation sector. The battery and fuel cell technologies are summarized in terms of their present and future status. Detailed simulation results for the energy consumption of various types of buses and MD/HD trucks are presented. The purchase prices/costs of the various types of ZEV vehicles are calculated/projected for the time period 2020-2050 and the economics of each of the vehicle types compared to baseline diesel vehicles. The cost comparisons indicate that the battery- electric transit buses and city delivery trucks are the most economically attractive of the ZEV vehicles based on their breakeven mileage being a small fraction of the expected total mileage by the original owner. The ZEV vehicles using fuel cells were also attractive for a hydrogen cost of $5/kg. The most unattractive from the economic perspective were the long-haul trucks and inter-city buses.

1. Introduction

California has a number of programs and regulations [1-2] intended to result in the introduction of zero- and near-zero emission technologies into the medium/heavy-duty vehicle sector to meet established air quality and climate change (GHG emission reduction) goals. To meet these goals will require the sale of large numbers of electrified transit buses and medium/heavy-duty trucks before 2025 and beyond. This will only occur if the economics and utility of the ZEV vehicles are acceptable to the vehicle users. The intent of this paper is to link together the technology and cost assessments of ZEV medium-duty and heavy-duty vehicles to their marketing and associated policy for mandates and incentives. Both battery and fuel cell powered vehicles were considered in this study.

2. Zero-Emission bus and truck technology Assessments

2.1 Zero-Emission bus and truck characteristics

The simulations of the ZEV MD/HD vehicles were performed using the UC Davis version of the **ADVISOR** vehicle simulation computer program which has been developed over the past 10 years to support studies of vehicles using advanced powertrains and alternative fuels. In recent years, the ADVISOR program has been used to study advanced powertrain and fuel technologies in MD/HD trucks of various types [3-6]. The simulation results for the fuel efficiency (kWh/mi and mi/KgH_2) of the various types of buses and trucks are given in Table 3. The detailed inputs for the simulations are given in [7].

Table 1: Energy use of battery-electric and fuel cell vehicles of various types

Vehicle type	2030	2050
MD delivery truck (city)		
Battery- powered (kWh/100 mi)	85	72
Fuel cell (kgH_2 /100 mi)	5.6	5.2
Diesel mpg	10.5	12.5
Transit bus (city)		
Battery- powered (kWh/100 mi)	230	215
Fuel cell (kgH_2 /100 mi)	9.6	9
Diesel mpg	6.5	7.3
Inter-city bus (highway)		
Battery- powered (kWh/100 mi)	123	95
Fuel cell (kgH_2 /100 mi)	166	130
Diesel mpg	10.1	11.9
HD long-haul truck (highway)		
Battery- powered (kWh/100 mi)	240	200
Fuel cell (kgH_2 /100 mi)	.15	.11
Diesel mpg	8.7	10.1

HD short-haul truck (city)		
Battery- powered (kWh/100 mi)	233	210
Fuel cell (kgH_2 /100 mi)	12.9	11.6
Diesel mpg	8.2	9
HD pick-up truck (city)		
Battery- powered (kWh/100 mi)	53	58
Fuel cell (kgH_2 /100 mi)	2.9	2.6
Diesel mpg	18.6	20.3

3.0 Infrastructure requirements and costs

This section of the paper is concerned with the infrastructure required to support a large volume of highway, heavy-duty bus and truck traffic that utilizes fuel/hydrogen and batteries/electricity. The range (miles) of vehicles using both technologies will be less than the normal distance that those buses and trucks travel daily. Hence it will be necessary for those vehicles to refuel along the highway as they travel to their destinations. The approach taken to analyze the infrastructure requirements and economics will be similar to that used in [21]. In that study, a 500 mile section of highway having refueling stations spaced 50 miles apart was analyzed to determine the refueling requirements for a specified volume of vehicle traffic. In the present study, the refueling areas will provide hydrogen for fuel cell powered heavy-duty vehicles and electricity to fast charge in about 1 hr. the batteries in battery-electric HD vehicles. As in [21], the analysis/calculations will be made for a traffic volume of 5000 HD vehicles per day. That is thought to be a typical volume on a major highway like Rt. 5 from northern California to Los Angeles.

Hydrogen production and storage requirements and economics

The HD vehicles being considered will store on-board hydrogen (70 kg) for a maximum range of about 500 miles and will require refueling to complete their daily trip of up to 800 miles. The refueling time for hydrogen will not be a problem - 10-15 minutes at a rate of 5 kgH_2/minute. It is assumed that each of the stations along the 500 mile section of the highway will service on average 1/10 of the vehicles. This means that each station will need to dispense 35000 kg (500 x 700) of hydrogen per day. It is further assumed that the hydrogen will be produced onsite with an electrolyzer. If the electrolyzer has an efficiency of 65%, the electricity from the grid required by the electrolyzer will be 1.166 $x10^6$ kWh (1166 MWh). If the electrolyzer operates 24 hr., the continuous power would be about 50 MW for each of the 10 stations along the 500 mile section of highway. Continuous operation of the electrolyzer will require storage of about half of the hydrogen produced or about 17500 kg. This storage will be at a relatively low pressure (about 500 -1000 psi). This is a very large station. The costs of the components in the station are summarized in Table 2. The station is sized to refuel trucks requiring 35,000 kgH_2 per day at a pressure of 700 atm. The total cost of the station is estimated to be $75 million, which corresponds to $2127/ kgH_2. The cost of electricity (at $.1/kWh) for the refueling is $360 corresponding to $5.14/ kgH_2.

Table 2: Estimated Cost of a highway hydrogen refueling station for long-haul trucks

Component	**Unit cost**	**Size parameter**	**Cost $million**
Electrolyzer	$800/kW	50 MW	**40**
Low pressure Storage	$725/$kgH_2$	17500 kgH_2	**12.7**
Low pressure compressor	$700/ kgH_2/hr	1500 kgH_2/hr	**1**
High pressure Storage	$1000/ kgH_2	3500 kgH_2	**3.5**
High pressure compressor	$2000/$kgH_2$/hr	3500 kgH_2/hr, 900 atm.	**7**
Dispenser hoses and pre-cooling	$430,000 for 3 hose unit	5 kgH_2/min., -40C 20 hoses	**3**
Total w/o installation	**$1900/$kgH_2$**		**67**
Total with installation	**$2127/ kgH_2**		**75**
Present value (10%, 10 yr)			**177**
Electricity for hydrogen compression (4kWh/ kgH_2)	70 kgH_2	280 kWh	**.4/ kgH_2 ($.10/kWh)**
Electricity for producing hydrogen by electrolyzer	70 kgH_2	3597 kWh	**$5.1/ kgH_2 ($.10/kWh)**

Cost of battery fast charging stations along the highway

The operation and capital cost of the fast charging stations required to service the traffic of 5000 trucks along the 500 mile section of highway is also analyzed. The stations will be spaced at 50 mile intervals along the highway and be able to charge the trucks in 45 minutes. This is assumed to be a reasonable time for a rest period for a truck driver. The battery to be charged in the truck is assumed to store 680 kWh useable energy using the advanced cells having an energy density of 400 Wh/kg. The range of the truck would be about 300 miles. The average power to recharge the battery in 45 minutes would be 900 kW, but the maximum power would be higher because the power to the battery would be tapered somewhat as the charge proceeds. The maximum power required will be at least 1 MW per fast charger.

The results of a recent study of fast charging of battery-electric long-haul trucks in Germany are given in [24]. It will be assumed that each of the 5000 trucks traveling along the highway will stop to have their battery recharged at one of the 10 stations. Hence each station will charge 500 trucks per day or on average about 50 per hour. This would require at least 50 charging connections at each station. For purposes of the cost analysis, it will be assumed that each station has 60 charging connections to meet periods of high demand.

The cost of the various components (including the markup) of the fast charger are shown in Table 3. The total cost per fast charger connection is $404,000 so that the cost of the 60 connections for battery charging at a single station would be $24 million. The maximum total power per station would be 60 MW and the electricity cost at $.10/kWh per charge would be $75. These costs do not include the cost of the substation at the fast charging station to provide the 60MW.

Table 3: Component costs of the fast charger

Component	**Cost/connection K$**
Power electronics	172
Coupling connection to grid	12
Transformer	52
Contribution towards network	70
Installation	98
Total capital cost K$/connection	404
Total capital cost K$/station 60 connections	24,240
Electricity per charge	755 kWh
Cost of electricity/charge	**$75/charge**

($.1 $/kWh, 90% efficient)	

Comparison of the costs of the hydrogen station and fast charger infrastructure

The range of the fuel cell powered trucks is about 500 miles and that of the battery-electric trucks are about 300 miles. The refueling stations are spaced so that either type of truck can be refueled conveniently. Both stations are sized to handle 500 trucks per day accounting for the difference in refueling time – 45 minutes for the battery powered trucks and 10-15 minutes for the fuel cell trucks. The capital cost per station for refueling the fuel cell trucks is estimated to be $75 million and that of the battery-electric trucks to be $24 million. The size (MW) of the substation needed for the hydrogen refueling would be 50 MW and for the fast charger station would be 60 MW. The substation for the hydrogen refueling would operate continuously and that for the battery trucks would be drawing power from the grid only during fast charging events. The fast charger would use 755 kWh for each battery charge and the hydrogen station would use about 3900 kWh per hydrogen refueling. Hence the hydrogen stations are more costly and energy intensive than the battery fast charging stations.

4. ZEV MD/HD Vehicle and fuel costs

Key economic factors in determining the marketability of the battery-electric and fuel cell vehicles are the purchase price of the vehicle and the cost of refueling the vehicles. Lower maintenance costs of the electrified vehicles compared to the conventional vehicles are also a factor to consider. The cost/purchase price of the battery-electric and fuel cell vehicles are presently high primarily, because the technologies are not yet mature and the production volumes are low. It is of interest to estimate the vehicle costs for the time period 2020-2050 during which the technologies will become mature and the production volumes will greatly increase. The vehicle costs were considered in detail in [25]. Those results are reviewed in the following section.

Vehicle costs

The purchase price can be estimated by adding the cost of the powertrain and fuel system components to the cost of the glider for the vehicle of interest. The unit costs of the various powertrain and energy storage components [15, 18, 19, 25-27] are shown in Table 4. A system integration mark-up of 50% is used to calculate the retail price of the component system from the production costs. The battery costs are assumed to decrease rapidly as discussed in [28, 29]. The cost of the gliders [26] for the vehicles are the following: transit bus $360,000, tractor of a long haul truck $90,000, and city delivery truck $36,000. The resultant cost of the baseline vehicles of the various types are given in Table 5.

Table 4: Unit costs (2017$) of the vehicle components to the OEM (2015-2050)

Year	Fuel cell $/kW	Electric drive $/kW	H_2 storage $/$H_2$kg	Power battery $/kWh	Energy battery $/kWh *
2015	200	52	900	600	725
2020	150	45	500	350	405
2030	100	30	250	225	218
2040	80	25	200	175	200
2050	80	20	200	150	150

*retail price [28]

Table 5: Ranges (miles) of ZEV MD/HD vehicles

Vehicle type	Vehicle Weight kg	Battery-electric Range miles	Fuel cell Range miles	Price of base diesel truck
Transit bus	13750	150	300	400,000
Inter-city bus	14850	350	500	400,00
City delivery truck	6900	150	150	55,000
Long-haul truck	29500	300	500	134,000
Short-haul truck	20750	150	150	119,00
HD pickup truck	3950	150	150	42,000

The costs of the buses and trucks using batteries and fuel cells have been projected [25]. The size of the powertrain components for each of the vehicle types is given in Table 2. The range of each vehicle type using batteries and fuel cells is given in Table 5. The results of projected cost calculations are shown in Tables 6-11. Note that in all cases, the cost of the ZEV MD/HD vehicles are expected to decrease significantly between 2020 and 2030 and in some cases approach the cost of the baseline conventional diesel fueled vehicle by 2050.

All the future costs of the vehicles have been given in 2017$ and no attempt has been made to include the effects of inflation which over 20 years at 2% could double the level of costs. It is very difficult to know the relative effect of inflation on the variations in the costs of the various maturing technologies and on the price of electricity, hydrogen, and diesel fuel. It was assumed that the effects of inflation would not significantly influence the relative attractiveness of the various electrification technologies based on current knowledge of those technologies and their future costs.

Table 6: Battery-electric and fuel cell transit bus costs (2017$) in 2015-2050

Year	Battery-electric bus* 325 kWh, 250 kW K$	Fuel cell bus* 200kW, 25kgH_2 K$

2020	509	448
2030	443	418
2040	437	410
2050	429	408

*The OEM component costs have been marked up by 50%

Table 7: Battery-electric and fuel cell inter-city bus costs (2017$) in 2015-2050

Year	Battery-electric inter-city bus 500 kWh, 250 kW., 350 miles K$	Fuel cell inter-city bus 200 kW, 40 kgH_2, 500 miles K$
2020	616	470
2030	489	427
2040	471	415
2050	434	413

*The OEM component costs have been marked up by 50%.

Table 8: Battery-electric and fuel cell tractor costs for a long haul truck (2017$) for 2015-2050

Year	Battery-electric long haul truck 900 kWh, 350 kW., 300 miles K$	Fuel cell long haul truck 350kW, 69kgH_2, 600 miles K$
2015	685	321
2020	389	243
2030	213	183
2040	194	164
2050	169	160

*The OEM component costs have been marked up by 50%.

Table 9: Battery-electric and fuel cell tractor costs for a short haul truck (2017$) for 2020-2050

Year	Battery-electric short haul truck 350 kWh, 300 kW., 150 miles K$	Fuel cell long haul truck 250kW, 20 kgH_2,150 miles K$
2020	261	193
2030	175	151
2040	162	137
2050	140	132

*The OEM component costs have been marked up by 50%.

Table 10: Battery-electric and fuel cell costs for a HD pickup truck (2017$) for 2020-2050

Year	Battery-electric HD pickup truck 80 kWh, 225 kW., 150 miles K$	Fuel cell HD pickup truck 200kW, 6kgH_2, 150 miles K$
2020	99	102
2030	59	77
2040	56	69
2050	50	66

*The OEM component costs have been marked up by 50%.

Table 11: battery-electric and fuel cell city delivery truck costs for 2020-2050l

Year	Battery-electric city delivery 150 kWh, 150 kW., 150 miles K$	Fuel cell city delivery 150kW, 8g H_2, 150 miles K$
2020	113	82
2030	79	66
2040	75	53
2050	66	52

*The OEM component costs have been marked up by 50%.

Energy costs and savings

The energy use and cost for the various vehicle types and powertrains/fuels are shown in Table 18. The energy costs used to relate the energy uses to the related economics are indicated below the table. All the energy costs are in 2017$ for the 2030 vehicle characteristics and costs. The breakeven miles shown correspond to the miles required to recovery the purchase price differential from energy cost savings. The cost of the hydrogen is the most uncertain of the energy costs and has the largest effect on the interpretation of the results. According to results in Table 18, the battery-electric options in city operation are more economically attractive than long distance highway operations using either electrified powertrains. One reason for this is that in 2030 engine-powered diesel trucks will be nearly as efficient as fuel cells for high-speed highway applications. These conclusions, of course, depend on the relative cost of diesel fuel, electricity, and hydrogen. City operation of the delivery truck and transit bus are the most attractive applications for both the battery-electric and the fuel cell powertrains. Buses are a special case because the FTA provides 80% of the cost of buses to cities so that the cities would have to fund only 20% of the cost difference between the base diesel bus and the ZEV bus. This should make the ZEV buses attractive even in the early 2020's. The HD pickup truck does not appear to be attractive in general for either the battery-electric or fuel cell powertrains, but for high mileage applications, the battery-electric truck could be attractive including incentives and savings from reduced maintenance costs.

Table 12: The energy consumption and related economics for the electrified transit bus and long-haul truck in 2030 (2017$)

Vehicle type	Battery –electric*	Fuel cell*	Diesel*

Transit bus			
Fuel use	2.1 kWh/mi	.08 kgH_2/mi	6.5 mpgD
$/mi	.21	.40	.62
Breakeven miles	105K	82K	
Inter-city bus			
Fuel use	1.33 kWh/mi	.07 kgH_2/mi	8.5 mpgD
$/mi	.133	.35	.47
Breakeven miles	264K	225K	
Long-haul truck			
Fuel use	2.4 kWh/mi	.115 kgH_2/mi	8.7 mpgD
$/mi	.24	.575	.46
Breakeven miles	377K	Not possible	
short-haul truck			
Fuel use	1.86	.116 kgH_2/mi	8.2 mpgD
$/mi	.186	.581	.488
Breakeven miles	179K	Not possible	
HD pickup truck			
Fuel use	.43 kWh/mi	.029 kgH_2/mi	18.6
$/mi	.043	.145	.215
Breakeven miles	99K	500K	
City delivery truck			
Fuel use	.83 kWh/mi	.05 kgH_2/mi	10.5 mpgD
$/mi	.083	.25	.62
Breakeven miles	40K	22K	

*Diesel fuel: $4/gal, electricity: $.1/kWh, hydrogen: $5/$kgH_2$

5. Summary and conclusions

This paper considers the technologies and cost assessments of ZEV medium-duty and heavy-duty vehicles. The battery/electric and fuel cell/hydrogen technologies are considered as zero-emission (ZEV) options in buses and MD/HD trucks to reduce greenhouse gas emissions in the transportation sector. The battery and fuel cell technologies are summarized in terms of their present and future status. Detailed simulation results for the energy consumption of various types of buses and MD/HD trucks are presented.

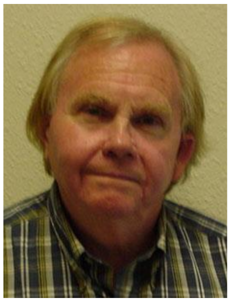
The purchase prices/costs of the various types of ZEV vehicles are calculated/projected for the time period 2020-2050 and the economics of each of the vehicle types compared to baseline diesel vehicles. In most cases, the costs of the fuel ($/mile) used by the ZEV vehicles are significantly less than that of the baseline diesel vehicles. In those cases, the lower cost of the fuel and likely lower maintenance cost could offset the higher initial purchase costs of the ZEV vehicles over their life times. The cost comparisons indicate that the battery- electric transit buses and city delivery trucks are the most economically attractive of the ZEV vehicles based on their breakeven mileage being a small fraction of the expected total mileage by the original owner. These ZEV vehicles using fuel cells were also attractive for a hydrogen cost of $5/kg. The most unattractive from the economic perspective were the long-haul trucks and inter-city buses. This was the case for both the battery-electric and fuel cell options for these vehicles. In the case of the battery-electric vehicles, the cost of the battery pack for a 300 mile range was still too high even for the reduced battery unit costs in 2030 and beyond. In the case of the hydrogen/fuel cell vehicles, the cost of hydrogen at $5/kg resulted in a vehicle fuel cost ($/mile) close to or greater than that of the baseline diesel vehicles.

The cost of the highway infrastructures needed to fast charge battery-electric and refuel hydrogen/fuel cell vehicles was assessed for high concentrations of vehicles on the highway. The analysis of the costs of the infrastructure for refueling battery-electric and fuel cell vehicles indicated that the cost of the infrastructure for fast charging the batteries is much less (about 1/3) than the cost of hydrogen refueling fuel cell vehicles with hydrogen produced onsite with electrolyzers. The battery fast charging stations are less complex than the hydrogen refueling stations because they can use electricity directly on demand from the grid rather than having to store large quantities of hydrogen for later use. Hence, both the vehicle and infrastructure economics of the fuel cell vehicles are less attractive in the short term than for the battery-electric vehicles. In the longer term, the long range capability of the fuel cell/hydrogen ZEV option seems likely to be used for long distance bus and freight applications.

References

1. ZEV Action Plan-2016, issued by Gov. Brown, October 2016
2. California Sustainable Freight Action Plan, July 2016
3. A.F. Burke and H. Zhao, Fuel economy Analysis of Medium/Heavy-duty Trucks- 2015-2050, EVS30, October 2017
4. Zhao, H., Burke, A.F., and Lin, Z., Analysis of Class 8 Hybrid-electric Truck Technologies using Diesel, LNG, Electricity, and Hydrogen as the Fuel for Various Applications, Proceedings of EVS27, Barcelona, Spain, November 2013
5. H. Zhao and A.F. Burke, Modeling and Analysis of Plug-in Series-Parallel Hybrid Medium-Duty Vehicles, paper at the European Electric Vehicle Conference, 2015, Report UCD-ITS-RR-15-19
6. H. Zhao and A.F. Burke, Fuel cell Powered Vehicles using Supercapacitors: Device characteristics, control strategies, and simulation results, Report UCD-ITS-RR-10-01

7. Burke, A.F., Miller, M., and Zhao, H., Fuel Cells and Batteries in Buses and MD/HD Trucks, STEPS Report September 2018
8. Toyota, Nissan, and Honda team up for solid-state battery development to develop batteries with a range of 500 miles, May 7, 2018, available on the internet
9. Ahluwalia, R.K., and etals, Technical assessment of cyro-compressed hydrogen storage tank systems for automotive applications, International journal of hydrogen Energy, 35 (2010) 4171-4184
10. James, B. and Houchins, C., 2017 DOE Hydrogen and Fuel Cell Program Review – Hydrogen Storage Cost Analysis, 8 June 2017
11. James, B., 2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-duty Vehicles, DOE Fuel Cell Technologies office Webinar, April 25, 2018
12. James, B. and etals, Final Report: Mass Production Cost of Direct H_2 PEM Fuel Cell Systems for Transportation Applications (2012-2016), September 2016
13. Zhao, H., Burke, A.F., and etals., Zero-emission Highway Trucking Technolgies, UCD-ITS STEPS report, August 2018
14. Park, G., and etals., Hydrogen Station Compression, Storage, and Dispensing - Technical Status and Costs, Technical Report NREL/BK-6A-10-58564, May 2014
15. Melaina, M. and Penev, M., Hydrogen Station Cost Estimates, Technical Report NREL/TP-5400-56412, September 2013
16. Mareev, I., Becker, J., and Sauer, D.U., Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation, Energies 2018, 11, 55
17. Miller, M., Wang, Q., and Fulton, L., Truck Choice Modeling: Understanding California's Transition to Zero-emission Vehicle trucks taking into account truck technologies, costs, and fleet decision behavior, November 2017
18. Rogers, S. and Boyd, S., Overview of the DOE advanced power electronics and electric motor R&D program, June 17, 2014, available on the internet
19. Public hearing to consider the proposed innovative clean transit regulation – a replacement of the fleet rule for transit agencies, Staff Report: initial statement of reasons, Appendix E: Battery Cost for Heavy-duty Electric Vehicles, August 7, 2018
20. Nykvist, b. and Nilsson, M., Rapidly falling costs of battery packs for electric vehicles, Nature Climate Change 5, 329-332, 2015



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