Title
Zero-Emission Medium- and Heavy-duty Truck Technology, Markets, and Policy Assessments for California

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Publication Date
2020

DOI
10.7922/G23776ZB

UNIVERSITY OF CALIFORNIA

Zero-Emission Medium- and Heavy-duty Truck Technology, Markets, and Policy Assessments for California

A Research Report from the University of California Institute of Transportation Studies

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January 2020

REPORT No.: UC-ITS-2018-30 | DOI:10.7922/G23776ZB

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UC-ITS-2018-30	N/A	N/A

4. Title and Subtitle Zero-Emission Medium- and Heavy-duty Truck Technology, Markets, and Policy Assessments for California	**5. Report Date** January 2020 **6. Performing Organization Code** ITS-Davis
7. Author(s) Andrew Burke, PhD https://orcid.org/0000-0002-4245-0056 Marshall Miller, PhD https://orcid.org/0000-0002-9105-3188	**8. Performing Organization Report No.** UCD-ITS-RR-20-07
9. Performing Organization Name and Address Institute of Transportation Studies, Davis 1605 Tilia Street Davis, CA 95616	**10. Work Unit No.** N/A **11. Contract or Grant No.** UC-ITS-2018-30
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org	**13. Type of Report and Period Covered** Final Report (January 2018 – December 2018) **14. Sponsoring Agency Code** UC ITS

15. Supplementary Notes

DOI:10.7922/G23776ZB

16. Abstract

This report assesses zero emissions medium- and heavy-duty vehicle technologies, their associated costs, projected market share, and possible policy mandates and incentives to support their adoption. Cost comparisons indicate that battery-electric transit buses and city delivery trucks are the most economically attractive of the zero-emission vehicles (ZEVs) based on their break-even mileage being a small fraction of the expected total mileage. These ZEVs using fuel cells are also attractive for a hydrogen cost of $5/kg. The most economically unattractive vehicle types for ZEV adoption are long-haul trucks and inter-city buses. Developing mandates for buses and trucks will be more difficult than for passenger cars for several reasons, including the large differences in the size and cost of the vehicles and the ways they are used in commercial, profit-oriented fleets. The best approach will be to develop separate mandates for classes of vehicles that have similar sizes, cost characteristics, use patterns, and ownership/business models. These mandates should be coupled to incentives that vary by vehicle type/class and by year or accumulated sales volume, to account for the effects of expected price reductions with time.

17. Key Words	18. Distribution Statement
Zero emission vehicles, electric vehicles, fuel cell vehicles, heavy duty vehicles, medium trucks, buses, operating costs, incentives, policy analysis	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	42	N/A

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Acknowledgements

This study was made possible through funding received by the University of California Institute of Transportation Studies from the State of California via the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project.

Disclaimer

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UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES

January 2020

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Executive Summary

This report assesses zero emissions medium- and heavy-duty vehicle technologies, their associated costs, projected market share, and possible policy mandates and incentives to support their adoption. Battery/electric and fuel cell/hydrogen technologies are considered zero-emission options in buses and medium- and heavy-duty. These powertrain and fuel options are evaluated from a number of points-of-view: design, energy consumption, battery capacity (kWh) and hydrogen storage (kg), infrastructure, and economics. 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 and costs of the various types of zero-emission vehicles (ZEVs) are projected for 2020-2050 and the economics of each of the vehicle types are 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 ZEVs based on their break-even mileage being a small fraction of the expected total mileage by the original owner. These ZEVs using fuel cells were also attractive for a hydrogen cost of $5/kg. The most economically unattractive vehicle types were long-haul trucks and inter-city buses.

The questions of mandates and incentives for the MD/HD ZEVs are also addressed. Developing mandates for buses and trucks will be more difficult than for passenger cars for several reasons, including the large differences in the size and cost of the vehicles and the ways they are used in commercial, profit-oriented fleets. These factors will make it difficult to develop a mandate or series of mandates for the MD/HD vehicles that will be workable and acceptable by the trucking industry. The best approach will be to develop separate mandates for classes of vehicles that have similar size and cost characteristics, use patterns, and ownership/business models. These mandates should be coupled to incentives that vary by vehicle type/class and by year or accumulated sales volume, to account for the effects of expected price reductions with time in the future.

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-duty (MD) and heavy-duty (HD) vehicle sector to meet established goals for air quality and reduced greenhouse gas (GHG) emissions. Meeting these goals will require the sale of large numbers of advanced technology 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. This report assesses zero emissions medium- and heavy-duty vehicle technologies, their associated costs, projected market share, and possible policy mandates and incentives to support their adoption.

In the past 4 years, we evaluated the ZEV emission technologies for various MD/HD vehicle sectors [3-7]. We considered vehicles in terms of their weight and road-load characteristics. The powertrains were specified in terms of their configuration, component power/energy storage and efficiency, and operating strategy. Computer simulations of the vehicles were run for appropriate driving cycles. The vehicle definitions and the simulation results permitted the calculation of the initial and operating costs of the vehicles. Projections were made of future changes and improvements in vehicle and component characteristics, and the resultant changes in performance and cost were projected out to 2050. As discussed in the corresponding reports [3-7], there is considerable uncertainty in some of the component performance and cost inputs, especially those for batteries and fuel cells for HD applications.

The second major element in evaluating the advanced technologies is the availability of the required fuel or energy, onboard storage of fuel, and the refueling infrastructure. This is especially important for fuel cell electric vehicles (FCEVs). For these vehicles, considerable uncertainty remains regarding both the technology and cost of storing hydrogen onboard the vehicle and providing the infrastructure for dispensing the hydrogen at highway refueling stations. For the battery-powered vehicles, the largest uncertainties are the cost of the batteries, the time required to recharge the batteries, and the improvements in the energy density (Wh/kg, Wh/L) of the batteries that can be expected by 2025 and beyond. Here we review the present status and projected improvements in ZEV technologies. The influence of the present and future technologies on the marketability of the ZEV medium- and heavy-duty vehicles is assessed in terms of the likely response of the bus and truck communities to various state regulations and policies for 2020-2040.

Zero-Emission Bus and Truck Technology Assessments

Zero-Emission Bus and Truck Characteristics

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 vehicle road-load and powertrain inputs for each bus and truck type are given in Tables 1 and 2. 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. Table 3 also shows whether the vehicle types are used primarily in the city or on the highway. In the case of the highway vehicles, the speed assumed is 55-65 mph. For each vehicle type, the fuel efficiency results can be used to calculate the energy storage requirements for electricity or hydrogen to reach any specified vehicle range. For city use, the fuel efficiency depends mostly on the transient nature of the driving cycle and the vehicle weight. For highway use, the fuel efficiency depends primarily on the vehicle speed and drag coefficient (C_DA). The fuel efficiency for all vehicles is projected to improve between 2030 and 2050.

Table 1. Road load characteristics of MD/HD buses and trucks

Vehicle type	Electric motor kW	C_DA m^2	f_r	W_V Kg	Accessories kW
City Delivery					
2030	125	5.85	.007	6900	1.5
2050	125	3.15	.006	6750	1.5
City transit bus					
2030	250	2.65	.0075	15000	6
2050	250	2.25	.005	14000	6
Inter-city bus					
2030	250	2.65	.0075	15000	6
2050	250	2.25	.005	14000	6
HD truck (long- and short-haul)					
2030	300	5.25	.0055	29500	1.5
2050	300	4.28	.005	29000	1.5
HD pick-up truck					
2030	250	1.27	.0075	3950	.8
2050	250	1.20	.006	3875	.8

HD, heavy duty; C_DA, drag coefficient; f_r, rolling resistance coefficient; W_v, vehicle weight.

Table 2. Powertrain characteristics for various types of vehicles

Vehicle	Battery kWh	Electric drive kW	Fuel cell kW	H_2 stored Kg	Diesel engine kW
Transit bus					
Diesel					300
Battery-electric	400	250			
Fuel cell		250	200	35	
Inter-city bus					
Diesel					300
Battery-electric	500	250			
Fuel cell	15	250	200	40	
Long-haul truck					
Diesel					350
Battery-electric	900	350			
Fuel cell	40	350	250	62	
Short-haul truck					
Diesel					320
Battery-electric	350	300			
Fuel cell	20	300	250	25	
City delivery truck					
Diesel					150
Battery-electric	150	150			
Fuel cell	6	150	125	8.5	
HD Pickup truck					
Diesel					320
Battery-electric	80	225			
Fuel cell	3	225	200	7	

Table 3. 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 (kgH2 /100 mi)	9.6	9
Diesel mpg	6.5	7.3
Inter-city bus (highway)		
Battery-powered (kWh/100 mi)	123	95
Fuel cell (kgH2/100 mi)	166	130
Diesel mpg	10.1	11.9
HD long-haul truck (highway)		
Battery-powered (kWh/100 mi)	240	200
Fuel cell (kgH2/100 mi)	.15	.11
Diesel (mpg)	8.7	10.1
HD short-haul truck (city)		
Battery-powered (kWh/100 mi)	233	210
Fuel cell (kgH2/100 mi)	12.9	11.6
Diesel (mpg)	8.2	9
HD pick-up truck (city)		
Battery-powered (kWh/100 mi)	53	58
Fuel cell (kgH2/100 mi)	2.9	2.6
Diesel (mpg)	18.6	20.3

Characteristics of Battery and Hydrogen Storage Systems

Battery systems

In the battery-electric vehicles, all the energy to operate the vehicle is stored in the battery pack and the pack is charged from the grid. Lithium-ion batteries of several chemistries have been developed. The general characteristics of these batteries are given in Table 4. The technologies for all the lithium battery chemistries are relatively mature and present development is directed primarily to more efficient packaging of the cells into modules and reducing the cost ($/kWh) of the batteries. A large R&D effort is underway world-wide to increase the energy density (Wh/L, Wh/kg) of the NCM (nickel-cobalt-manganese) batteries from the present energy density of about 200 Wh/kg to 350-400 Wh/kg. Most of the battery development is intended for light-duty (automotive) applications [7-9], but some [10] is intended specifically for heavy-duty applications. In some cases, the developments are being done in partnership with a bus manufacturer.

Table 4. Characteristics of lithium batteries of various chemistries

Lithium battery type	Wh/kg	Wh/L	Cycle life	Cost $/kWh	Power capability	Fast charge capability
NiCoMn (NCM)	200-250	420-525	1000-2000	200-300	Moderate	Fair
$LiFePO_4$ (LFP)	100-140	220-310	2000-3000	200-300	Low	Good
LiTiOxide (LTO)	45-100	85-190	10000-20000	400-500	High	Excellent

An example of a battery developed for automotive applications that is now being used in heavy-duty truck applications is the AESC NCM cell and module (Figure 1) used in the Nissan Leaf. Transpower, San Diego, has configured battery packs of the AESC modules for their heavy-duty vehicle projects. The characteristics of the cell, module, and standard “battery box” are given in Table 5. The voltage of the box is 400V and it stores 45 kWh. The battery pack on the vehicles is configured by placing a number of the boxes in parallel. Eight of the boxes can be placed along the sides of the tractor of a long-haul truck, storing 360 kWh. Additional energy can be stored by placing boxes behind or under the cab of the tractor. The weight of the 8-box configuration is about 2000 kg. The AESC cells are state-of-the-art with energy densities of 224 Wh/kg, 460 Wh/L. If the energy density of the cells can be increased to 350 Wh/kg, the same battery pack (2000 kg) could store about 500 kWh. The cost of lithium-ion cells/modules to OEMs has been decreasing rapidly in recent years [7]. It seems possible that the retail cost of a module like that shown in Figure 1 could be less than $200/kWh for large volume sales in the near future.

Figure 1. The AESC 55 Ah cell and module [11]

Table 5. Characteristics of the AESC cell, module, and battery box [11]

Parameter	Cell	Module	Battery Box*
Ah	56	112	112
voltage	4.1	15	405
Wh	205	1.65 kWh	45 kWh
Weight kg	.914	8.7	260
Volume L	.45	4.6	238*
Wh/kg	224	188	155
Wh/L	460	360	189*

*Transpower packaging in the "battery box"

Hydrogen storage systems

Sufficient hydrogen must be stored onboard the vehicle to meet the range requirement of the vehicle. At present, nearly all fuel cell vehicles store the hydrogen as a compressed gas at either 350 atm. (5000 psi) or 700 atm. (10000 psi). There has been consideration of storing the hydrogen as a liquid at near 30 deg K at low pressure (<10 atm.) or as a liquid at about 50 deg K at high pressure (200-300 atm.). This later system is referred to as cryo-compressed hydrogen storage (see Fig 2) and it has been studied/developed by BMW and the Department of Energy (DOE)/Argonne National Laboratory (ANL) [12, 14]. The present status of the various approaches to storing hydrogen are summarized in Table 6. Note in Table 6 that the Toyota hydrogen storage system (see Fig. 3) meets the DOE targets for hydrogen storage in 2020. The cryo-compressed gas system seems to have a significant advantage in weight compared to hydrogen storage at 700 atm, but not in volume.

Table 6. Hydrogen storage characteristics using several technologies

Storage of 25kgH_2 useable	Compressed gas (350 atm.) BMW	Toyota (700 atm.)	Cryo-compressed (350 atm) BMW	DOE Goals	
Weight (kg)	430	439	250		
Volume (L)	1420	678	607		
				2020	**Ultimate**
kgH_2/kg syst.	.058	.057	.100	.055	.075
kgH_2/L syst.	.018	.037	.041	.04	.07

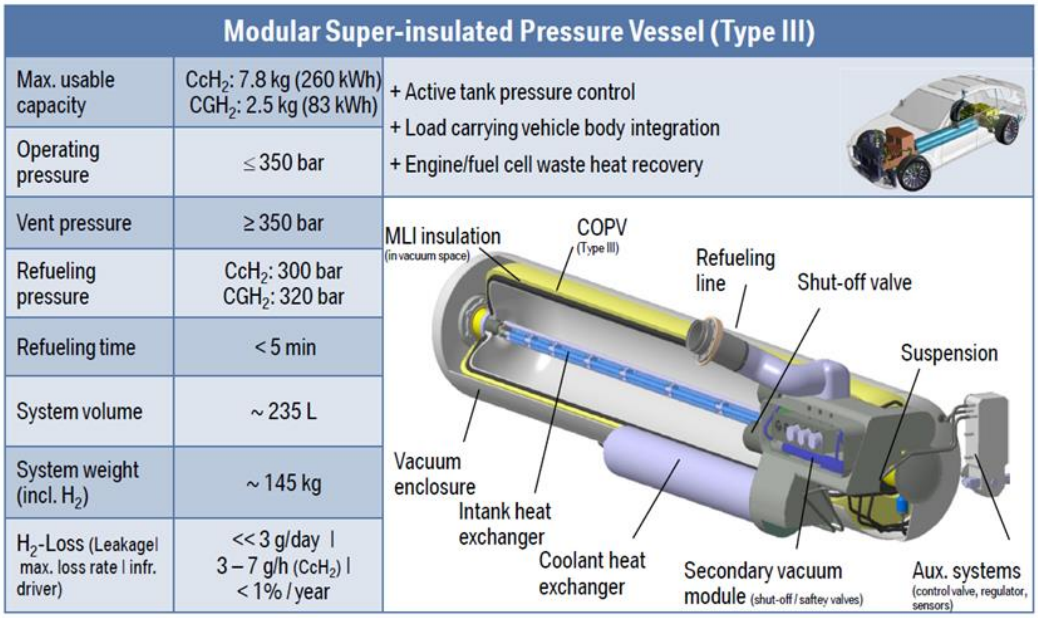


Figure 2. The cryo-compressed gas storage unit being developed by BMW [12]

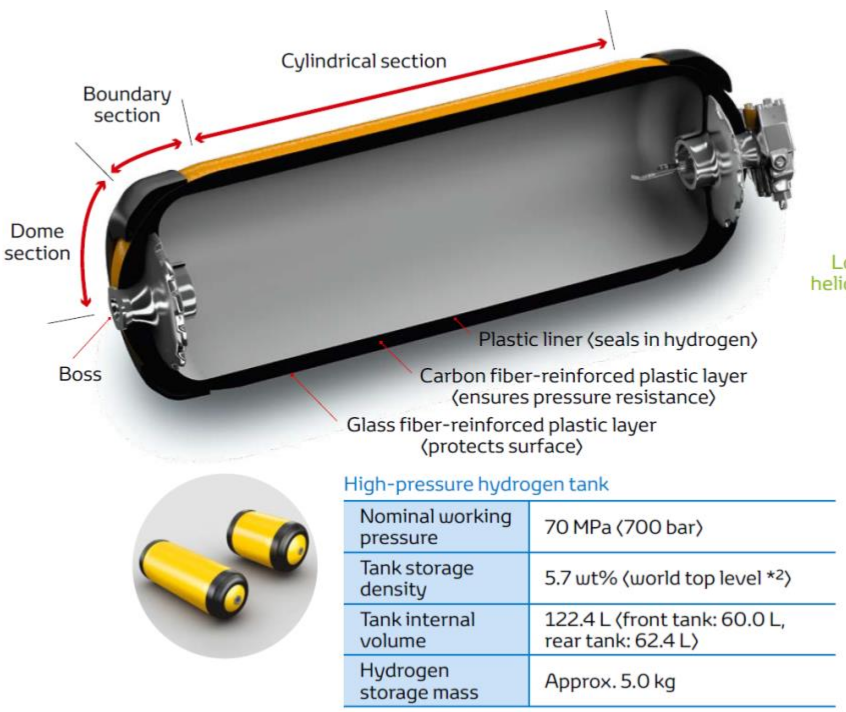


Figure 3. The Toyota Mirai hydrogen storage unit [14]

The cost of hydrogen storage is given as \$/kWh or \$/kgH_2 (1kgH_2 =33.4 kWh). Recent results of DOE studies of the costs of hydrogen storage are given in [15]. A result from that study is shown in Figure 4 for a 40 kg storage unit. The unit costs for that system are \$1137/kgH_2, \$28.4/kWh for 200 units/yr. and \$498/kgH_2, \$14.6/kWh f0r 5000 units/yr. Hence the cost of hydrogen storage can be expected to be relatively expensive in the near future.

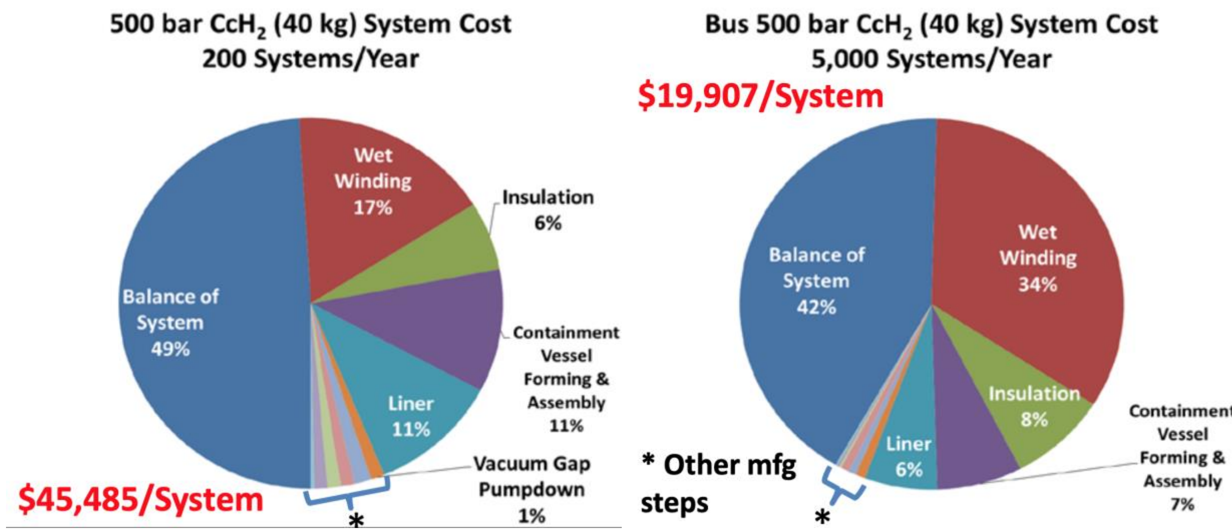
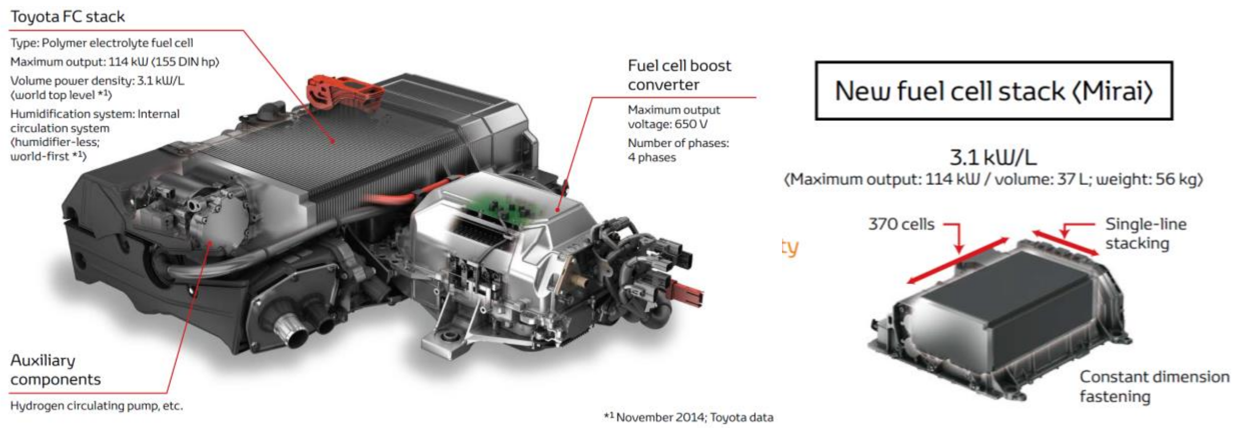


Figure 4. Hydrogen storage cost results [15]

Fuel Cell Characteristics

Most of the fuel cell systems available have been developed for light-duty automotive applications. The 100 kW systems developed and presently being marketed in passenger cars by Toyota and Honda are shown in Figures 5 and 6. The characteristics of the systems are shown in the figures. Both stacks have high specific power (2 kW/kg, 3 kW/L). As indicated in the figures, the balance of plant for the fuel cell systems are much larger than the stacks resulting in much lower specific power for the system than for the stack alone. In the case of the Honda fuel cell, the system volume is about 360L resulting in system specific power of .286 kW/L. It appears from Figure 5 that the specific power of the Toyota fuel cell unit is considerably higher than the Honda fuel cell unit—maybe by a factor of at least 2. However, in both cases there has been steady progress [14, 16] in reducing the weight and volume of both the stack and balance of plant.

A



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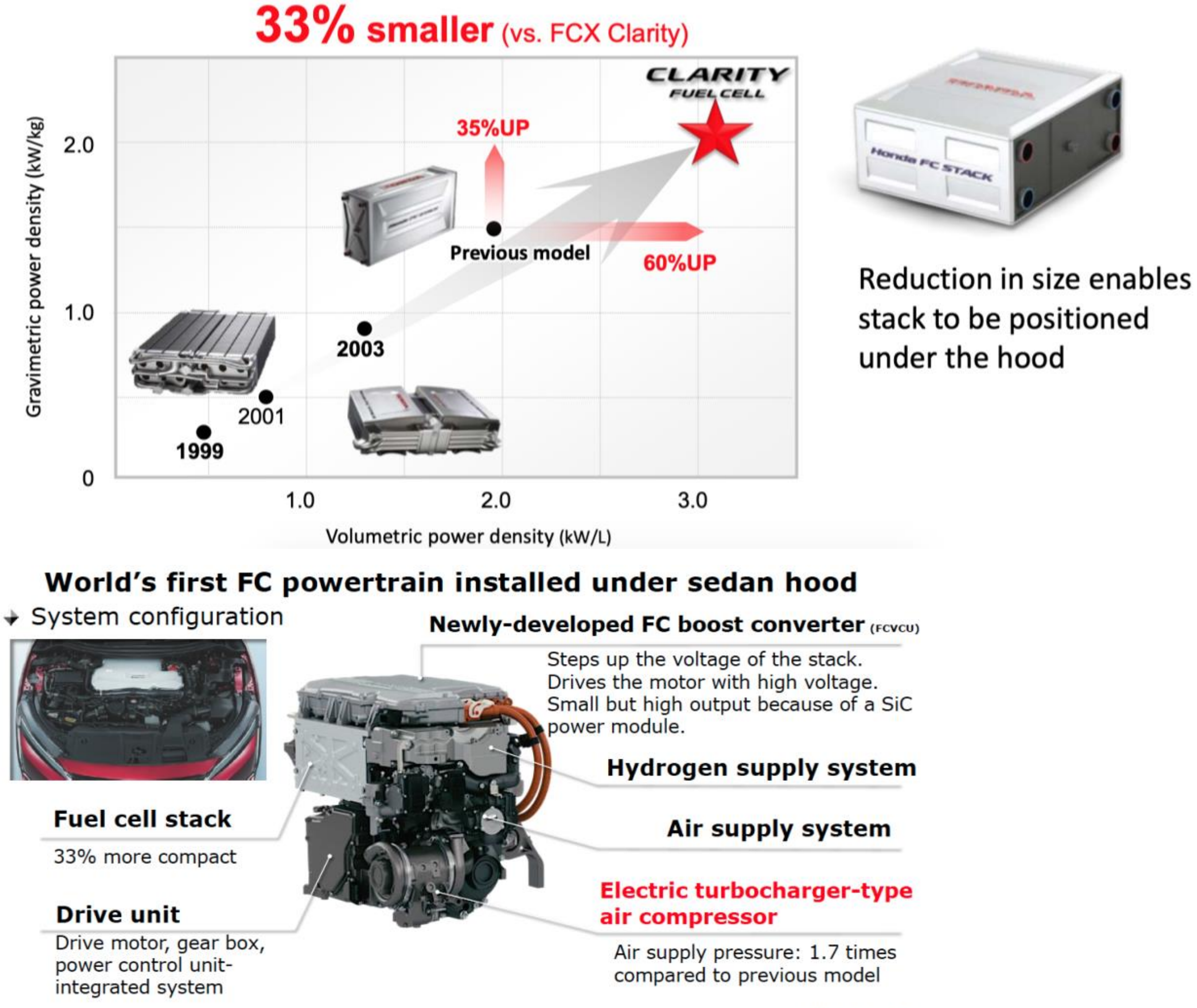

Figure 5. (A) Characteristics of the Toyota fuel cell in the 2018 Mirai [14]. (B) Characteristics of the Honda fuel cell in the 2018 Clarity [16]. *Honda fuel cell stack: 103 kW, 346V, 51 kg (2.02 kW/kg), 33L (3.12 kW/L); System 374 L (.275 kW/L).*

The characteristics of the Ballard 100 kW fuel cell system are shown in Figure 6 and summarized in Table 7. The Ballard fuel cell has been developed for heavy-duty applications and is heavier and larger than the Toyota and Honda fuel cell systems, which were developed for light-duty vehicle applications. The durability of the Ballard system is 25,000 hours, which is much greater than required in light-duty applications.

Figure 6. The Ballard 100 kW heavy-duty fuel cell system [17]

Table 7. Characteristics of the Ballard 100 kW heavy-duty fuel cell system [17]

Component	Weight, kg	Volume, L	kW/kg	kW/L
Fuel cell module	285	528		
Coolant system	44	148		
Air subsystem	61	99		
Total	390	775	.256	.129

It is of interest to compare the specific power of the fuel cell systems with that of the diesel engine in a heavy-duty truck. Based on the weight and volume data for a Detroit Diesel engine available in the literature [18], the weight and volume of a 320kW engine are 1200 kg and 1584 L, resulting in specific powers of .27 kW/kg and .2 kW/L, respectively. At their present status of development, the light-duty fuel cell units are significantly smaller than the diesel engine.

However, the Ballard fuel cell system is larger than the diesel engine it would replace in the heavy-duty vehicles.

The US DOE has performed cost studies of fuel cells for light-duty and medium-duty vehicle applications for a number of years [19, 20]. The results of the most recent studies are given in Figure 7. The cost projections are given as a function of annual production rate. The DOE studies project a present cost of $180/kW and $320/kW in 2018 for fuel cell units for light-duty and MD applications, respectively. For light-duty vehicles, it is projected that the costs will decrease to about $50/kW by 2025 for an annual production of 100, 000 units/yr. For the MD/HD applications, the costs are projected to decrease to about $100/kW by 2025 for an annual production of 20,000 units/yr.

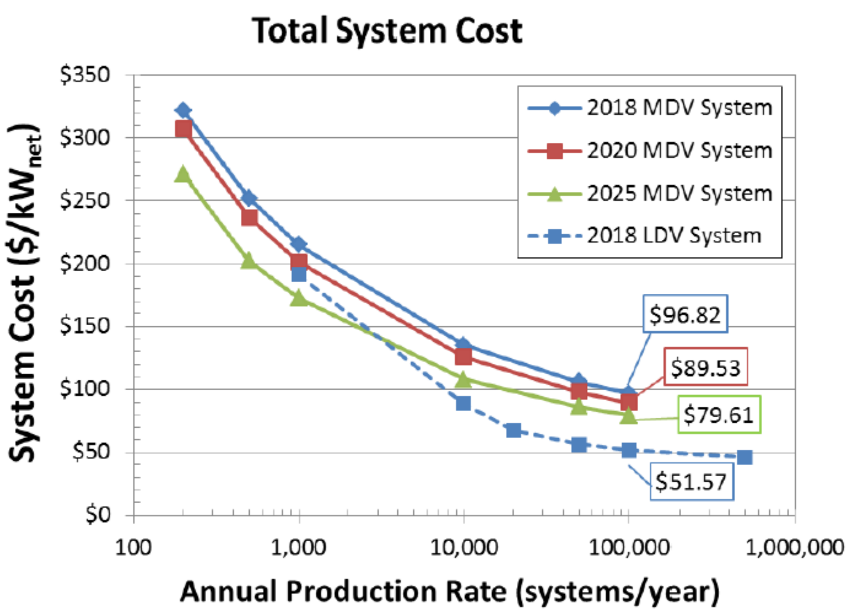

Figure 7. Costs of 160 kW MDV fuel cells projected by US DOE [19]

Infrastructure Requirements and Costs

This section of the report is concerned with the infrastructure required to support a large volume of highway, heavy-duty bus and truck traffic powered by hydrogen and electricity. The range 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 the vehicles to refuel along the highway as they travel to their destinations. We analyzed the infrastructure requirements and economics using a method similar to that used in Zhao et al. [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 battery-electric HD vehicles. As in the previous study, the analysis was performed for a traffic volume of 5000 HD vehicles per day. That is thought to be a typical volume on a major highway like Interstate 5 from northern California to Los Angeles.

Hydrogen Production and Storage: Requirements and Economics

The HD vehicles considered would 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 35,000 kg (500 x 70) 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 1.776 $x10^6$ kWh (1776 MWh). If the electrolyzer operates 24 hours a day, the continuous power would be about 75 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 17,500 kg. This storage will be at a relatively low pressure (about 500–1000 psi).

This is a very large station. For the large amount of hydrogen required by this station, production of hydrogen on-site is the most economical approach. Large stations using electrolyzers have been analyzed by NREL [22, 23]. The components needed to control the flow of the hydrogen from production to dispensing have also been analyzed in the NREL reports. However, the magnitude of the daily hydrogen dispensed in the station being evaluated is more than an order of magnitude greater than treated in the NREL studies. Hence estimates of the costs resulting from extrapolating from the NREL results will be uncertain, but should be enlightening for comparison with economic estimates for fast charging stations for battery-electric heavy-duty trucks.

A schematic of the station is shown in Figure 8. The electrolyzer produces 1458 kgH_2/hr. For purposes of the analysis, it is assumed that the hydrogen is dispensed to trucks during a 12-hour period. During the remainder of the day, the hydrogen is put into low pressure storage. It is further assumed that the hydrogen needed to refuel the average number of trucks per hour (50 trucks–3500 kgH_2) will be maintained in high pressure storage at 800 atm in order to fuel trucks at 700 atm. As shown in Figure 8, the station will have both low- and high-pressure compressor systems. To service 50 trucks per hour, on average, the station will need at least 15 dispensing hoses; however, 20 hoses would be better to handle periods of high demand. The hose systems would be designed to provide fueling at 5kgH_2/minute and have pre-cooling of -40 °C. As indicated in Melaina et al. [23], the components to construct the hydrogen station outlined above are not currently (2018) commercially available in the sizes needed. The cost data from previous studies [22, 23] were extrapolated to estimate the cost of the components needed in this station. For most of the components, the costs used from [23] were those labeled “future” for 2025.

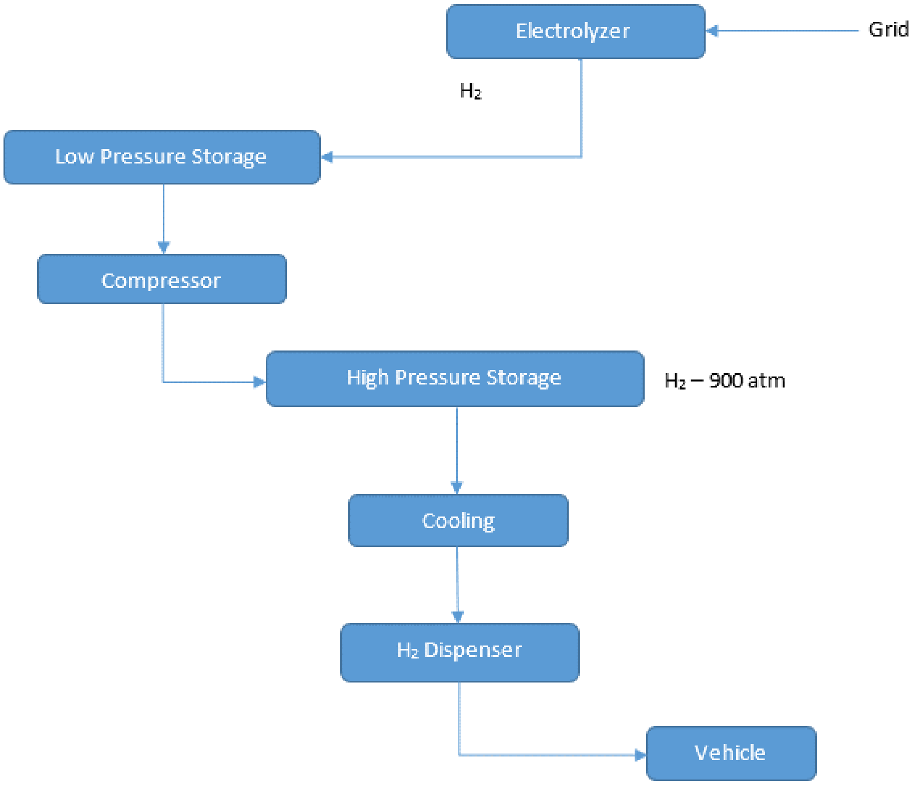

Figure 8. Schematic of a hydrogen refueling station

The costs of the components in the station are summarized in Table 8. 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. As shown in Figure 9, this unit cost is consistent with the results shown in Park et al. [22]. The cost of electricity (at \$.1/kWh) for the refueling is \$360 corresponding to \$5.14/kgH_2. As indicated in Figure 10, the effect of the fixed operating costs on the cost of the hydrogen will be small compared to the electricity costs.

Table 8. Estimated Cost of a highway hydrogen refueling station for long-haul trucks

Component	Unit cost	Size parameter	Cost (millions of $)
Electrolyzer	$800/kW	50 MW	**40**
Low pressure Storage	$725/kg$H_2$	17500 kgH_2	**12.7**
Low pressure compressor	$700/kg$H_2$/hr	1500 kgH_2/hr	**1**
High pressure Storage	$1000/kg$H_2$	3500 kgH_2	**3.5**
High pressure compressor	$2000/kg$H_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	**$1900/kg$H_2$**		**67**
Total with installation	**$2127/kg$H_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	**$5.1/kg$H_2$ ($.10/kWh)**

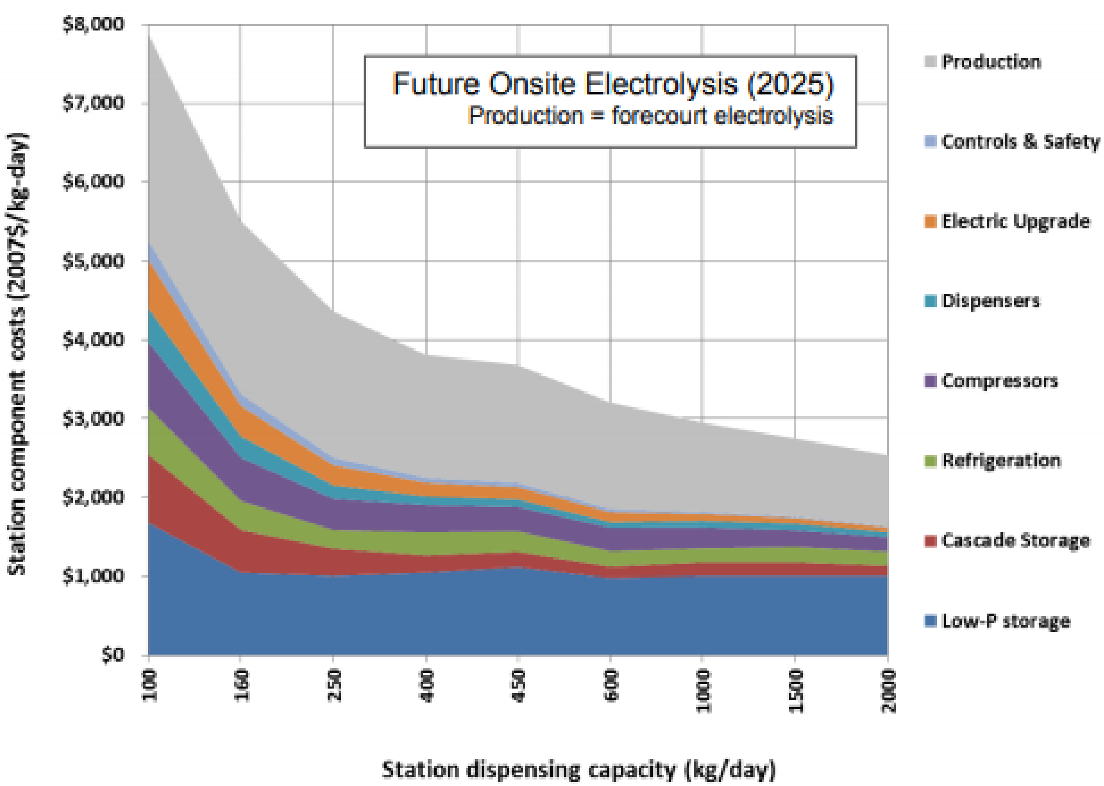

Figure 9. Capital costs for the hydrogen refueling station [22]

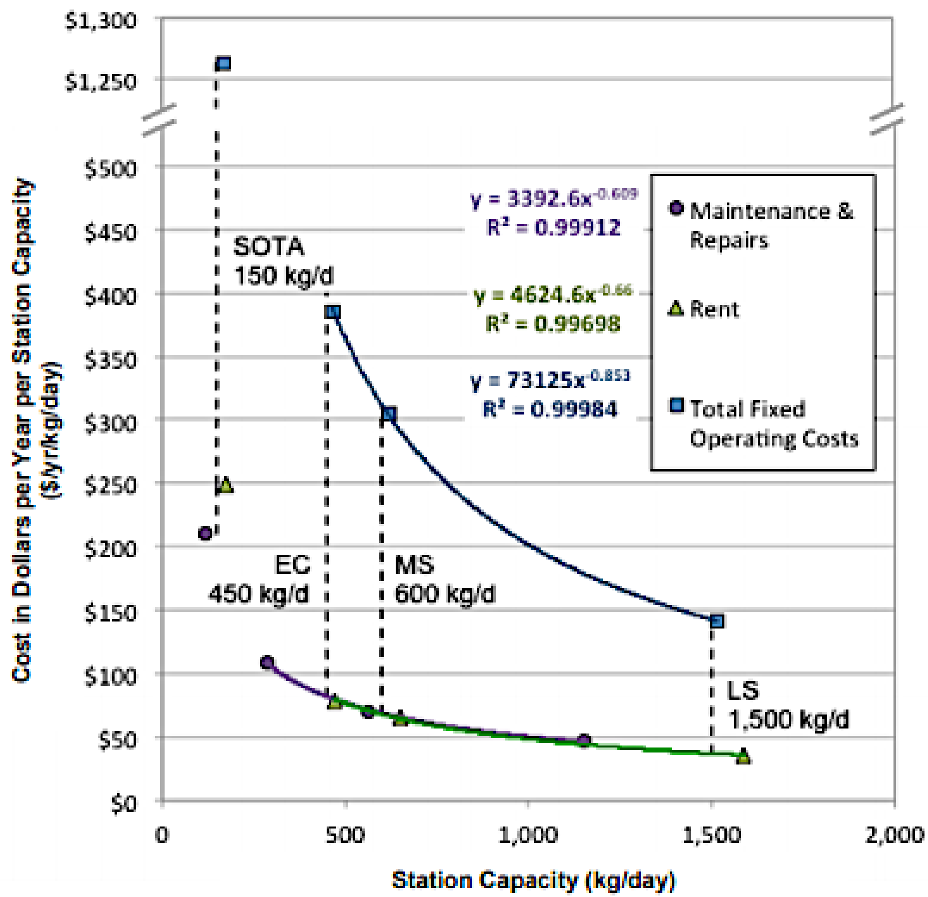

Figure 10. Fixed operating costs of the hydrogen refueling station [23]

Cost of Fast Charging Stations Along the Highway

We analyzed the operation and capital costs of the fast charging stations required to service the traffic of 5000 trucks along the 500 mile section of highway. 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 about 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 Mareev et al [24]. The characteristics of the trucks and chargers considered in that study are close to those of this study, thus the results in that study were used in the present cost analysis. We 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, we assumed that each station has 60 charging connections to meet periods of high demand. The fast charging capability will permit the battery-electric buses and trucks to travel at least 500 miles per day. The trucks could use slow chargers of much lower power (75-100 kW) for overnight charging along the highway or at home base to prepare for travel the next day.

The cost of the various components (including the markup) of the fast charger are shown in Table 9. 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 cost would be $75 per charging event if electricity costs $.10/kWh. These costs do not include the cost of the substation at the fast charging station to provide the 60 MW.

Table 9. Component costs of the fast charger [24]

Component	Cost/connection, × $100,000
Power electronics	172
Coupling connection to grid	12
Transformer	52
Contribution towards network	70
Installation	98
Total capital cost	404
Total capital cost/station of 60 connections (× $100,000)	24,240
Electricity per charge	755 kWh
Cost of electricity/charge ($.1 $/kWh)	**$75/charge**

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 is about 300 miles. The refueling stations are spaced so that either type of truck can be refueled conveniently. Both types of stations are sized to handle 500 trucks per day, based on refueling times of 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 75 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 3600 kWh per hydrogen refueling. Hence the hydrogen stations are more costly and energy intensive than the battery fast charging stations.

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 vehicles and the cost of refueling. Lower maintenance costs of the electrified vehicles compared to the conventional vehicles are also a factor to consider. The cost and purchase prices 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 Burke, et al [25]. Those results are reviewed in the following section.

Vehicle Costs

The purchase price can be estimated based on 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, 19, 20, 27] are shown in Table 10. A mark-up of 50% is used to calculate the retail price from the production costs. The battery costs are assumed to decrease rapidly as discussed by Rogers & Boyd and the California Air Resources. Board (CARB) [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 11.

Table 10. 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 [27]

Table 11. 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	13,750	150	300	400,000
Inter-city bus	14,850	350	500	400,000
City delivery truck	6900	150	150	55,000
Long-haul truck	29,500	300	500	134,000
Short-haul truck	20,750	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 11. The results of projected cost calculations are shown in Tables 12-17. In all cases, the cost of the MD/HD ZEVs 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 12. 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 13. 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 14. 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 15. 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$)	Fuel cell short-haul truck 250kW, 20 kgH_2, 150 miles (K$)
2020	261	193
2030	175	151
2040	162	137
2050	140	132

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

Table 16. 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 17. Battery-electric and fuel cell city delivery truck costs for 2020-2050

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 are shown in Table 18. The energy costs used to relate the energy uses to the relevant economics are indicated below the table. All the energy costs are in 2017$ for the 2030 vehicle characteristics and costs. The break-even miles shown correspond to the miles required to recover the purchase price differential from energy cost savings. The cost of hydrogen is the most uncertain of the energy costs and has the largest effect on the interpretation of the results. According to the 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 Federal Transit Administration 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 2020s. 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, especially with additional savings from incentives and reduced maintenance costs.

Table 18. 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
Break-even miles	105K	82K	
Inter-city bus			
Fuel use	1.33 kWh/mi	.07 kgH_2/mi	8.5 mpgD
$/mi	.133	.35	.47
Break-even miles	264K	225K	
Long-haul truck			
Fuel use	2.4 kWh/mi	.115 kgH_2/mi	8.7 mpgD
$/mi	.24	.575	.46
Break-even miles	377K	Not possible	
Short-haul truck			
Fuel use	1.86	.116 kgH_2/mi	8.2 mpgD
$/mi	.186	.581	.488
Break-even miles	179K	Not possible	
HD pickup truck			
Fuel use	.43 kWh/mi	.029 kgH_2/mi	18.6
$/mi	.043	.145	.215
Break-even miles	99K	500K	
City delivery truck			
Fuel use	.83 kWh/mi	.05 kgH_2/mi	10.5 mpgD
$/mi	.083	.25	.62
Break-even miles	40K	22K	

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

Market Considerations

ZEV Truck and Bus Decisions

The factors that will affect the future market of the battery-electric and fuel cell buses and trucks are their purchase price, the cost of energy to operate them, their utility to truck operators relative to the diesel vehicles they would replace, their durability and resultant reliability, and the cost and availability of the refueling infrastructure needed to support their on-road operation. For short range applications, the vehicles can be fueled at their home base and on-road refueling will not be needed. In those cases, the vehicle fleet owner will provide the fueling capability. This is likely to be the case for transit buses and city delivery trucks. Charging batteries at a home-base is more straight-forward than providing relatively large quantities of hydrogen at multiple home-bases. The following discussion addresses refueling on the road, not at home-bases.

The impact of various factors on the market share of MD/HD ZEV vehicles have been studied in detail using a Truck Decision Choice Model [26]. The truck and bus choice model includes all of the factors cited above and simulates market development from early adopters, in-between, and late adopters as the technologies mature. The model calculates a **total generalized cost** which is the numerical summation of both monetary and non-monetary factors: capital cost, fuel cost, green public relations, uncertainty, incentives, refueling inconvenience, maintenance cost, carbon tax, and model availability cost. For monetary factors, the cost in US dollars is calculated. Non-monetary factors are quantified by certain functions and subsequently expressed in US dollars. For each truck type (e.g. long-haul, short-haul, medium-duty urban, transit bus, etc.) the **generalized cost** is calculated for each technology type (e.g. diesel, natural gas, hybrid, fuel cell, battery electric, gasoline). The contributions of each of the factors to the total generalized cost are described in detail in Miller et al. [26]. In calculating the market share of each of the advanced technologies, the effects of incentives and a carbon tax are included. The general approach taken is to determine the incentive needed for each type of ZEV bus and truck to meet a specified market share set by different scenarios. The ZEV scenarios considered in the truck choice study [26] are given in Table 19. The ZEVs included were battery-electric and hydrogen fuel cell vehicles. Two cases for Scenario 1 were considered. Scenario 1a had some limits on the refueling availability for the ZEV trucks and buses and Scenario 1b had the same availability for refueling as for diesel buses and trucks. We inferred the magnitude of the incentives needed to meet the ZEV market share in the various years. Selected results for Scenarios 1a, 1b, and 2, taken from Miller et al. [26], are shown in Tables 20-23. In the tables, the maximum incentives correspond to those needed in the early years near 2030 and those needed in the later years near 2050. The total investments are the projected sum of the incentives needed for 2030-2050 to meet the ZEV market targets for the scenarios. The total investment in incentives to meet Scenario 2 is projected to be much higher than for Scenario 1, which targets 25% ZEVs by 2050.

Table 19. Market share of ZEV MD/HD vehicles by year for the two ZEV scenarios

Year	Scenario 1 ZEV Market Share	Scenario 2 ZEV Market Share	CARB Proposed ZEV Mandate (Classes 2b-7)
2025	0.0%	3.0%	7.0%
2026	0.0%	4.4%	8.5%
2027	0.0%	5.8%	10.0%
2028	0.0%	7.2%	10.0%
2029	0.0%	8.6%	13.0%
2030	1.0%	10.0%	15.0%
2031	1.8%	12.0%	
2032	2.6%	14.0%	
2033	3.4%	16.0%	
2034	4.2%	18.0%	
2035	5.0%	20.0%	
2036	6.2%	22.6%	
2037	7.4%	25.2%	
2038	8.6%	27.8%	
2039	9.8%	30.4%	
2040	11.0%	33.0%	
2041	12.4%	35.0%	
2042	13.8%	37.0%	
2043	15.2%	39.0%	
2044	16.6%	41.0%	
2045	18.0%	43.0%	
2046	19.4%	44.4%	
2047	20.8%	45.8%	
2048	22.2%	47.2%	
2049	23.6%	48.6%	
2050	25.0%	50.0%	

Table 20. Incentives per long haul vehicle necessary to meet the ZEV mandate for scenarios 1a and 1b (limited refueling ability vs. refueling ability similar to diesel vehicles).

Year	Scenario 1a	Scenario 1b
2030	$287,100	$227,500
2031	$275,000	$219,100
2032	$255,200	$202,750
2033	$233,750	$184,650
2034	$213,700	$167,900
2035	$196,400	$153,850
2036	$184,800	$145,380
2037	$173,720	$137,320
2038	$162,900	$129,450
2039	$152,580	$121,990
2040	$143,140	$115,300
2041	$136,420	$111,270
2042	$130,370	$107,800
2043	$124,780	$104,700
2044	$119,500	$101,810
2045	$114,420	$99,040
2046	$109,850	$96,700
2047	$105,420	$94,400
2048	$101,130	$92,150
2049	$96,980	$89,950
2050	$92,970	$87,800

Table 21. Value of incentives to meet ZEV mandate scenario 1a for each truck type.

Truck Type	Maximum yearly incentive ($)	Minimum yearly incentive ($)	Total investment from 2030-2050 (million$)
Long-haul	287,100	92,970	3,689
Short-haul	149,900	1,390	303
Heavy-duty vocational	125,500	12,850	364
Medium-duty vocational	99,100	24,780	177
Medium-duty urban	46,530	11,050	1,218
Urban buses	148,000	0	62
Other buses	56,800	3,580	63
Heavy-duty pickups and vans	35,350	7,260	3,046

Table 22. Value of incentives to meet ZEV mandate scenario 1b for each truck type.

Truck Type	Maximum yearly incentive ($)	Minimum yearly incentive ($)	Total investment from 2030-2050 (million$)
Long-haul	227,500	87,800	3,143
Short-haul	86,800	0	116
Heavy-duty vocational	121,500	11,570	334
Medium-duty vocational	94,800	23,480	165
Medium-duty urban	41,500	7,020	834
Urban buses	142,500	0	53
Other buses	51,100	2,340	48
Heavy-duty pickups and vans	23,750	6,200	2,202

Table 23. Value of incentives to meet ZEV mandate scenario 2 for each truck type.

Truck Type	Maximum yearly incentive ($)	Minimum yearly incentive ($)	Total investment from 2025-2050 (million$)
Long-haul	312,950	110,980	11,163
Short-haul	169,570	12,520	880
Heavy-duty vocational	202,800	34,790	2,115
Medium-duty vocational	157,550	41,030	813
Medium-duty urban	100,100	29,805	7,278
Urban buses	257,500	20,220	577
Other buses	105,600	23,130	500
Heavy-duty pickups and vans	65,800	27,355	19,577

Projected Markets 2020-2050

The cost results in Table 18 give an assessment of the relative economic attractiveness of the various ZEV bus and truck options and the baseline diesel vehicles. The cost results in Table 18 and the truck choice results (Tables 20-23) indicate that the urban bus and medium-duty truck markets are the most attractive and that the long-haul HD truck market will be the least attractive for ZEVs. However, it will be late in the time period before any of the projected incentives will be relatively small.

The truck choice model results do not differentiate between the incentives between battery-electric and fuel cell options for ZEVs. However, the cost results in Table 23 show consistently that the incentives for urban applications of buses and trucks are the lowest. These applications would be expected to use the battery-electric option. These considerations will be dependent on the relative ranges of the battery and fuel cell vehicles and the price of electricity and hydrogen. A hydrogen cost of less than $5/kg seems to be needed to make the fuel cell option favorable in most cases. The results in Table 18 indicate that the battery-electric option is more cost effective than the fuel cell option if the range requirement needed can be met using batteries. In applications in which a range of over 300 miles is needed, the fuel cell option is likely to be the only economically feasible one.

Policy Considerations, Mandates, and Incentives

ZEV Mandates for Light-Duty Vehicles

The first ZEV mandates in California were set in 1990 as part of the LEV 1 regulation. It required 2% of all passenger cars sold by large manufacturers in 1998-2000 to be ZEVs, 5% for 2001-2002, and 10% for the 2003 model year. The ZEV regulations have been modified many times since 1998 because the electric vehicle/battery technologies and the market response did not support the mandate.

The present light-duty ZEV requirements for 2018 and beyond [29] are given in Table 24. In 2016, plug-in vehicle (EV + PHEV) sales in California accounted for 3.5% of the total car sales. ZEV sales have been increasing significantly (15-20 % per year) in recent years, but this increase will need to continue between 2018 and 2025 to reach the requirements set by CARB. It seems clear at the present time that the electric vehicle/battery technology is sufficiently advanced to support an expanding ZEV market if auto companies offer a wide range of model types at prices that car buyers find attractive including Federal and State incentives in the near term as the volume of production increases.

Table 24. The Light-duty ZEV requirements for 2018 and beyond

Model Year	Credit Percentage Requirement
2018	4.5%
2019	7.0%
2020	9.5%
2021	12.0%
2022	14.5%
2023	17.0%
2024	19.5%
2025 and subsequent	22.0%

Possible Mandates for Medium-Duty and Heavy-Duty Vehicles

As discussed above in ZEV Mandates for Light-Duty Vehicles, the California Air Resources Board has had extensive experience with mandates for light-duty vehicles and they are apparently [31, 32] planning to follow a similar path for MD/HD ZEVs. As noted previously, developing mandates for buses and trucks will be more difficult than for passenger cars for several reasons. The best approach will likely be to develop specific mandates for classes of vehicles that have similar physical characteristics, use patterns, and ownership/business models. As indicated in Figure 11, this seems to be the approach currently being considered by CARB. The ZEV economic and fueling assessments, discussed in the section ZEV MD/HD Vehicle and Fuel Costs, indicated that separate mandates for transit buses (see Table 25 for proposed CARB mandate for buses [32]) and city delivery trucks could be developed and have a good chance of success in the near-term with a limited need for incentives by 2025.

Figure 11. Proposed HD ZEV rules by CARB [31]

Table 25. CARB mandate for ZEV transit buses [32]

Calendar Year	Credit Percentage Requirement	
	Large Transit Agency	Small Transit Agency
2023	25%	-
2024	25%	-
2025	25%	-
2026	50%	25%
2027	50%	25%
2028	50%	25%
2029 and after	100%	100%

Incentives for ZEV MD/HD Vehicles

The Federal government has been providing incentives for buyers of alternative fuel vehicles since 2005 and for plug-in electric vehicles since 2007. The State of California has been providing incentives for buyers of ZEVs since 2005. Presently the federal tax credit for plug-in hybrid electric vehicles is $7500 and the rebate in California is $2500. These incentives are presently independent of the car size and price.

As discussed in the previous section, it seems necessary to couple incentives with a mandate at least initially for the mandate to succeed. The ZEV cost assessments (ZEV MD/HD Vehicle and Fuel Costs showed that in most cases, the cost of the ZEV was significantly higher than that of the baseline diesel vehicle. The cost differences varied with vehicle type and year and decreased with time as the technologies matured and volumes of production increased. The magnitude of the cost differences varied greatly with vehicle type for a given year. These cost results indicate that the incentives should vary with vehicle type and year. This is consistent with the results given in Tables 20-23 from the Truck Choice model that show the incentives for the various types of vehicles needed to meet the specific mandates listed in Table 19. The individual and total investments in incentives vary greatly between vehicle types. The incentives shown in Tables 20-23 are significantly larger than the cost differences given in Tables 12-17 because the incentives in Tables 20-23 are intended to compensate the vehicle purchasers for non-monetary factors and uncertainties in addition to differences in the purchase price of the vehicles.

Proposed incentives [32] by CARB for MD/HD ZEVs are shown in Figure 12. The incentives vary markedly by vehicle weight. It seems appropriate to vary the incentives with vehicle type/class and by year or accumulated sales volume to include the effects of expected price reductions with time. The approach of developing a series of mandates and associated incentives for various vehicle types/classes that reflect advances in battery, fuel cell, and hydrogen/infrastructure technologies seems to be appropriate for the MD/HD ZEV sector.

- Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)
  - Point-of-sale voucher
  - Zero-emission & advanced technology
  - Offset incremental cost
  - Varies by technology/vehicle type
  - Higher for operating within a disadvantaged community (DAC)

Funding Table for Zero-Emission Trucks

GVWR (lbs)	Base Voucher Incentive	
	1-100 vehicles	
	Outside DAC	Inside DAC
5,001-8,500	$20,000	$25,000
8,501-10,000	$25,000	$30,000
10,001-14,000	$50,000	$55,000
14,001-19,500	$80,000	$90,000
19,501-26,000	$90,000	$100,000
26,001-33,000	$95,000	$110,000
>33,001	$150,000	$165,000
Hydrogen FC	$300,000	$315,000

Figure 12. Proposed incentives by vehicle weight class [31]

Summary and Conclusions

This report assesses zero emissions medium- and heavy-duty vehicle technologies, their associated costs, projected market share, and possible policy mandates and incentives to support their adoption. The battery/electric and fuel cell/hydrogen technologies are considered zero-emission (ZEV) options in buses and MD/HD trucks to reduce greenhouse gas emissions in the transportation sector [30]. These powertrain/fuel options were evaluated from a number of points-of-view—design, energy consumption, batteries and hydrogen storage, infrastructure, and economics. 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 and costs of the various types of ZEVs were projected for the time period 2020-2050, and the economics of each of the vehicle types were compared to baseline diesel vehicles. In most cases, the costs of the fuel ($/mile) used by the ZEVs 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 ZEVs over their lifetimes. The cost comparisons indicate that the battery- electric transit buses and city delivery trucks are the most economically attractive of the ZEVs based on their break-even mileage being a small fraction of the expected total mileage by the original owner. These ZEVs using fuel cells were also attractive for a hydrogen cost of $5/kg. The most economically unattractive ZEVs 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 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 infrastructure needed to fast charge battery-electric and refuel fuel cell vehicles was assessed for high concentrations of vehicles on the highway. The cost of the infrastructure for fast charging 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 are less attractive in the short-term for fuel cell vehicles than for battery-electric vehicles. In the longer-term, the long range capability of the fuel cell ZEV option seems likely to be used for long distance bus and freight applications.

The questions of mandates and incentives for the MD/HD ZEVs were also considered in this report. CARB has had extensive experience with mandates and incentives for light-duty ZEVs, and they are apparently planning to follow a similar path for MD/HD vehicles. Developing mandates for buses and trucks will be more difficult than for passenger cars for several reasons including large differences in the size and cost of the various types of vehicles and the way in which the vehicles are used in commercial, profit-oriented fleets that are refueled at a central location. These factors will make it difficult to develop a mandate or series of mandates for the MD/HD vehicles that will be workable and acceptable by the trucking industry. It seems that the best approach will be to develop separate mandates for different classes of vehicles that have similar size and cost characteristics, use patterns, and ownership/business models. A recent CARB workshop seems to indicate this is the approach currently being considered.

It seems necessary to couple incentives with a mandate at least initially for the mandate to succeed. Our ZEV cost assessments indicate that, in most cases, the cost of the ZEV was significantly higher than the baseline diesel vehicle. The cost differences varied with vehicle type and year and decreased with time as the technologies matured and volumes of production increased. Hence, it would seem appropriate to vary the incentives also with vehicle type/class and by year or accumulated sales volume to include the effects of expected price reductions with time/year. This approach of developing a series of mandates and associated incentives for various vehicle types/classes that reflect advances in battery, fuel cell, and hydrogen/ infrastructure technologies seems a good approach for the MD/HD ZEV sector.

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