Title

Developing Markets for Zero-Emission Vehicles in Goods Movement

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A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

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Developing Markets for Zero-Emission Vehicles in Goods Movement

A National Center for Sustainable Transportation Research Report

March 2018

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TABLE OF CONTENTS

Developing Markets for Zero-Emission Vehicles in Goods Movement

EXECUTIVE SUMMARY

This report evaluates the market status and potential freight market penetration of zero emission vehicles (ZEVs) and near ZEVs in the medium and heavy duty class within the California market. It evaluates alternative technologies, primarily battery electric, fuel cell, and hybrid technologies, and compares them to existing gasoline, diesel, and natural gas vehicles used in comparable applications. Refueling infrastructure requirements and logistics planning are considered along with vehicle technology.

The report's primary focus is on intra-urban, as opposed to long haul, deployment scenarios. Intra-urban scenarios produce the greatest potential for reduction of pollutant exposure while minimizing problems associated with the reduced range of some developing vehicle technologies. In California, there are currently 2080 hybrid, 300 medium duty and 40 heavy duty electric vehicles in demonstration or revenue service. There are currently plans to deploy several dozen heavy duty fuel cell vehicles in the near future.

The literature review finds that while there are substantial existing studies providing direct comparisons between light-duty electric and fossil-fueled vehicles during actual operation, heavy-duty electric vehicles (e.g., class 8) have been less well studied. Fuel cell vehicle studies are also very sparse, and are primarily available in the public transit sector for buses. ZEV vehicles are still comparatively more expensive to purchase (see section 5.6), though they have much higher fuel efficiency when compared with traditional diesel technology (see section 5.4.1). Due to range restrictions, these vehicles would also require additional attention to routing and refueling, which at present is considered on a case-by-case basis by each company conducting demonstration projects thus has limited comparability (see sections 5.4.2 and 5.5).

Findings from Demonstration Projects

Demonstration projects show a wide variety of performance characteristics such as fuel economy. Battery electric demonstration projects tend to outperform fuel cell technologies in terms of fuel efficiency when measured on a diesel gallon equivalent basis.

Operating range was also found to vary significantly based on payload and operating conditions. For battery electric freight trucks, demonstration projects showed operating ranges of between 70-100 miles per charge. Reliability and durability of battery-based systems was found to have steadily improved in recent years.

Battery electric recharging stations for trucks are sparse but deployment is relatively straightforward given the extensive network of light duty recharging stations already in place. Another concern is the draw on the power grid from trucks, particularly if they are required to refuel during the day. Commercial refueling infrastructure for fuel cell trucks does not yet exist.

Demonstration projects therefore rely on non-commercial hydrogen sources. Given the volatility of hydrogen, operators would require substantial safety training to refuel on their own. The paucity of fuel cell truck demonstrations means that some information on battery life and performance has been gleaned from transit bus demonstrations.

Overall, the demonstration projects show that ZEV and near-ZEV heavy-duty vehicles are able to operate along selected routes during pilot projects, but have also revealed areas for improvement and highlighted the importance of operational characteristics. Maintenance costs for battery electric vehicles were found to be roughly in line with diesel and CNG technologies. The operational compromises necessary for heavy haul operation of battery electric and fuel cell trucks are generally higher than for medium duty trucks due to the less predictable pattern or origins and destinations.

Economics

The economic estimates of purchase cost of freight ZEVs are highly speculative due to lower production volumes. The cost of battery electric trucks for drayage operation is estimated at approximately three times that of diesel alternatives. While battery electric trucks would have lower per mile refueling costs, their limited range means that the amortization costs would be spread over fewer productive miles driven per day. The cost of the battery system can be over 50% of the cost of the truck. Fuel cell vehicles offer a range closer to that of diesel equivalents, but have even higher upfront capital costs given current production volumes.

Future Market Penetration

Even if the economics of ZEVs become more favorable due to technological improvements, subsidies, or scale economies, the long operating life of diesel trucks will slow the adoption of ZEVs. In addition, California's diesel fleet is relatively young due to strict air quality requirements prompting upgrades in recent years, which means that most diesel trucks will stay on the road for many years into the future. The medium projection for market penetration for trucks class 3-8 by the California Electricity Commission estimates that diesel electric hybrid, electric, and natural gas trucks would have equivalent market share in 2030. If combined, these three technologies would be about 7 percent of the 2030 California truck fleet.

Introduction

This report seeks to establish the market status of zero-emission vehicles (ZEVs) and near-ZEVs, with a focus on medium- and heavy-duty vehicles in the freight sector. Although light-duty electric vehicles are beginning to gain market traction, medium- and heavy-duty electric vehicles intended for hauling loads still face logistic, range, charging, and weight limitations. Existing demonstration projects, reviewed in the following sections, provide insights as to the current extent of these limitations and recent developments in this area, as well as strategies employed in some demonstration projects to make use of these vehicles feasible. In addition to electric vehicles, demonstrations on fuel cell vehicles are also reviewed. Further, hybrid vehicles and low NOx vehicles are included in the review to examine status of near-zero emission technologies that may be more usable in the short-term due to their more familiar fuel and range requirements.

The literature review overall emphasizes that heavy-duty electric vehicles are only just beginning to undergo extensive demonstration projects, while medium-duty electric vehicles have been used successfully in quite wide-spread demonstrations yet are still only suitable for limited applications where ranges are fairly short and vehicles return to a home-base to re-charge regularly. Fuel cell vehicle demonstrations outside the public transit sector are scarce, and this technology is still extremely expensive with fuel cell buses costing upwards of $1,000,000 for recent demonstration projects. Hybrid vehicles have no range or reliability issues, but like electric vehicles they suffer from a loss of payload capacity due to the weight of battery systems and other electric/hybrid components. Ultra-low NOx vehicles are still highly experimental at present, and vehicles are not currently on the market that could meet the 90% California Air Resources Board (CARB) standards of 0.02 g/bhp-hr for NOx emissions.

Summary of Findings

The literature review finds that while there are substantial existing studies of direct comparisons between light-duty electric and fossil-fueled vehicles during actual operation, heavy-duty electric vehicles (e.g., class 8) have been less well studied. Fuel cell vehicles studies are also very sparse, and are only available in the public transit sector for buses. ZEV vehicles are still comparatively very expensive to purchase (see section 5.6), though they have much higher fuel efficiency (see section 5.4.1). These vehicles would also require additional attention to routing and refueling, which at present is considered on a case-by-case basis by each company conducting demonstration projects thus has limited comparability (see sections 5.4.2 and 5.5). Models to evaluate trucking purchase cost decisions are still in the process of being appropriately adapted to electric and fuel-cell vehicles, though many existing purchase cost frameworks provide a starting point. Developing markets are evident both in the current push to support demonstration projects for heavy-duty EVs, particularly at ports (see section 2.5 and 6.1) and in the projected decline of battery costs expected to make both electric and fuel cell vehicles more competitive (see section 7.4).

1. Size and Characteristics of Short-haul Markets, Truckload (TL), and Less-than-truckload (LTL)

It is anticipated that the initial markets for ZEVS will be short-haul due to their limited range and lack of refueling facilities. Table 1.1 gives the definitions of short, medium and long haul from the Motor Carrier Safety Administration, as well as the types of freight operations that are included in each category. There are many types of short-haul deliveries, and they likely make up a substantial share of urban truck traffic.

Table 1.2 links truck classes with type of operation. Light commercial vehicles are used mostly for local pickups and deliveries, and as repair or service trucks and vans. Medium commercial vehicles are also used for local pickups and deliveries, but for higher volume applications, such as UPS or FedEx deliveries. This size category may also serve perishables, particularly to smaller businesses. Heavy commercial vehicles operate in short, medium and long-haul operations. Table 1.3 is a continuation of table 1.2 showing weight and powertrains available today by class. For this paper, we consider class 9 and higher out of scope for ZEV technologies at this time.

Table 1.4 describes shipping methods and is defined by truck cargo. Both less-than-truckload and truckload shipments can be either short, medium, or long-haul depending on distance. For example, a cargo container arriving at the port will be drayed directly to an inland terminal or local distribution facility. This is an example of a short-haul truckload. In addition, this table addresses the ownership model. Owner operators are individuals who own or lease their own trucks; they are contracted by businesses to haul cargo and are responsible for all costs associated with their equipment (purchase and maintenance). Owner operators haul the majority of full truckloads regardless of distance. The truck ownership model is important to understand when discussing new and potentially costly technologies since owner operators typically work on slim margins and cannot easily raise capital for replacement equipment.

Table 1.1. Haul type characteristics

Haul Type	Miles/trip*	Description
Short-haul	100 or less*	Daily routes returning to home base at least daily. Includes package deliveries as well as truckload container shipments. Examples: port to rail terminal drayage, perishable deliveries.
Intermediate	101-500	Regional deliveries (1-day service). Example: shipments to distribution centers.
Long-haul	501+	+1-day trips, typically between major cities/states.

**(Motor Carrier Safety Administration, 2015)*

Table 1.2. Truck classes and applications

Truck Type	Class	Description	Example	Applications
Light Commercial Vehicles (LCV)	3	One- and two-axle, four-tire trucks	heavy duty pick-up, walk-in van, minibus, box truck	local pick-up and delivery; heavy duty pickup truck, vans, minibuses
Medium Commercial Vehicles (MCV)	4	Two- and three-axle buses	large walk-in van, city delivery truck	parcel delivery, short distance
	5	Two-axle, six-tire, single-unit trucks	bucket truck, large walk-in van, city delivery truck	
	6	Three-axle single-unit trucks	beverage truck, school bus, rack truck	
Heavy Commercial Vehicles (HCV)	7	Four or more axles single-unit trucks	refuse, city transit bus, medium semi-tractor, tow truck	long haul truckload or less than truckload cargo (containers)
	8	Four or fewer axle single-trailer trucks	cement mixer, heavy semi-tractor, dump truck, sleeper cab, firetruck, refrigerator van, tour bus	
	9	Five-axle single-trailer trucks	2 units: heavy semi-tractor with trailer	
	10	Six or more axle single-trailer trucks	2 units: heavy semi-tractor with trailer	
	11	Five or fewer axle multi-trailer Trucks	3 units: heavy semi-tractor with 2 trailers	
	12	Six-axle multi-trailer trucks	3 units: heavy semi-tractor with 2 trailers	
	13	Seven or more axle multi-trailer trucks	3 units: heavy semi-tractor with 2 trailers	

("Compilation of Existing State Truck Size and Weight Limit Laws - FHWA Freight Management and Operations," n.d., "Light-Duty Vehicles Heavy-Duty Vehicles," n.d., "MAG Internal Truck Travel Survey and Truck Model Development Study Appendix," n.d.)

Table 1.3. Truck classes and sizes

Class	Weight incl. equipment/cargo lbs.	Axles	Powertrain†
3	10,001-14,000	2, 3, or 4	G, D, CNG, HYB D
4	14,001-16,000	2 or 3	G, D, CNG, HYB D
5	16,001 - 19,500	2	
6	19,501 - 26,000	3	
7	26,001-33,000	4 or more	D, CNG, HYB D
8	33,001-80,000*	3 or 4	
9	33,001-80,000*	5	
10	33,001-80,000*	6 or more	
11	33,001-80,000*	5 or less	
12	33,001-80,000*	6	
13	33,001-80,000*	7 or more	

*Classes 9-13 are not current candidates for ZEV technology; *Heavier loads can be hauled but only with special permit; †G: Gasoline, D: Diesel, CNG: Compressed Natural Gas, HYB D: Hybrid Diesel (“Compilation of Existing State Truck Size and Weight Limit Laws - FHWA Freight Management and Operations,” n.d., “Light-Duty Vehicles Heavy-Duty Vehicles,” n.d., “MAG Internal Truck Travel Survey and Truck Model Development Study Appendix,” n.d.)*

Table 1.4. Shipping methods and ownership

Shipping methods	Usage	Cargo weight lbs.	Ownership
Less-than-truckload (LTL)	Single origin, multiple destination cargo OR multiple origin, multiple destination cargo. To reduce transportation costs, multiple shippers share space on the same truck.	< 15,000	For local deliveries: company owned (fleet) with an exception of FedEx parcel delivery which is owner operator. Typically due to coordination aspects, fleets use employees.
Truckload (TL)	Single origin, single destination cargo; takes up space or weight of entire trailer	< 46,000 (max weight 80k with equipment)	Predominately owner operators

(“FedEx Custom Critical | Owner Operators | FAQs,” n.d., “Owner-Operator and Independent Driver Facts | Recent Research | OOIDA Foundation,” n.d.; HAN et al., 2008)

2. Broad Status of ZEV and near-ZEV Vehicle Types

Technologies suitable for zero-emission drayage trucks include electric and hydrogen fuel-cell vehicles (Port of Long Beach & Port of Los Angeles, 2016). These electric vehicles may use batteries, inductive charging, or overhead catenary lines, while fuel cell vehicles can be constructed with either a battery-dominant or fuel-cell dominant configuration. Near-zero-emission trucks include those making use of hybrid technologies, with the electric charging capabilities paired with an ICE engine fueled by either conventional or alternative fuels. Alternative fuels in these hybrid arrangements may include CNG, LNG, LPG, biomethane, ethanol, methanol, hydrogen, and others.

2.1 Electric Vehicles

2.1.1 Battery Electric

Battery electric vehicles use electricity from the grid to recharge on-board batteries. This eliminates tailpipe emissions, though there are still remote emissions associated with the electricity generation. The onboard batteries can vary in capacity and weight according to the application. Recharging can take as little as 10 minutes with fast chargers, or may need to occur overnight if only 110 voltage mains power is available. Charging systems are currently not standardized, and can vary between manufacturers (CARB, 2015a). During battery recharging, the grid power needs to be converted from alternative current (AC) to direct current (DC) for storage in the battery. Electric vehicle systems must contain an inverter to convert the DC current back to AC for use in the motor.

As the cost of batteries decreases, large battery electric vehicles will become more commercially competitive. Battery costs are currently in the $500-$700 /kWh range (CARB, 2015a). A number of different battery technologies are available, including lead acid, nickel-metal hydride, lithium-ion, molten salt, and flow batteries. Lithium-ion batteries are most likely to be used in medium- and heavy-duty trucks and buses over the near term (CARB, 2015a). Batteries decline with time, so the capacity/range of battery electric vehicles with decrease as the vehicle's battery ages.

Battery electric vehicles have features not typically found on conventional trucks, including regenerative breaking and high voltage battery systems (CARB, 2015a). A further critical component in battery electric vehicles in the Battery Management System (BMS), which manages charging and battery voltage as well as being involved in battery cell balancing (CARB, 2015a). These systems are still being refined for reliability, which was particularly notable in recent Port of LA trials where the first class 8 demonstration truck was taken completely out of service so that issues with the BMS could be addressed – an entirely new BMS was designed and built by TransPower rather than using that from an external company, and the location of the battery packs was also shifted to increase ease of maintenance (Port of Los Angeles, 2016).

The weight that electric trucks are able to haul or transport can be reduced due to the additional weight of battery systems. In trials at the port of LA, the battery systems weighed

6,000 lbs (Port of Los Angeles, 2016). On-road vehicles in California cannot exceed a combined weight of 80,000 lbs, and when electric vehicles need to add 6,000 lbs of batteries for sufficient range this must result in an equivalent reduction in vehicle payload. This additional weight necessitates either reduced payloads or increased GVWR. If battery energy-to-weight ratios can be improved in future through technological improvements, this problem will be lessened. The location of battery modules on the truck is also important – placing modules in difficult-to-reach locations increases the time and effort associated with maintenance, upgrade, or repair tasks (Port of Los Angeles, 2016).

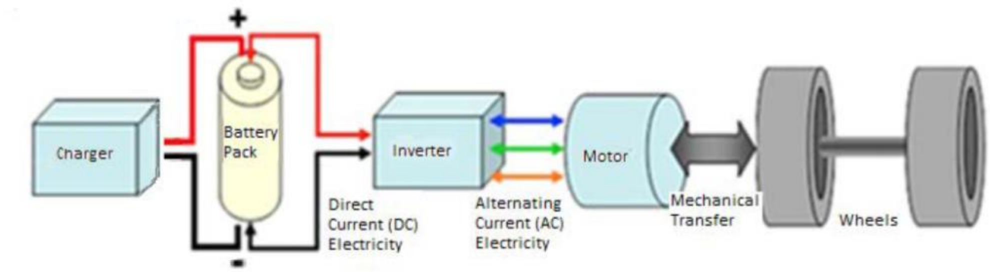


Figure 2.1. Simple overview of battery electric vehicle components, from CARB (CARB, 2015a)

2.1.2 Overhead/Catenary Electric

Although catenary electric vehicles (i.e., those connected to overhead charging lines) are being explored at the Port of LA (Port of Los Angeles, 2016), existing demonstration projects for medium- and heavy-duty short-haul trucks are focused on battery operated vehicles. Buses using overhead electric lines have been in use for decades, and are currently in widespread deployment in San Francisco (described as “trolley buses”) where they have been in use since 2001 (SFMTA, n.d.).

2.2 Fuel Cell Vehicles

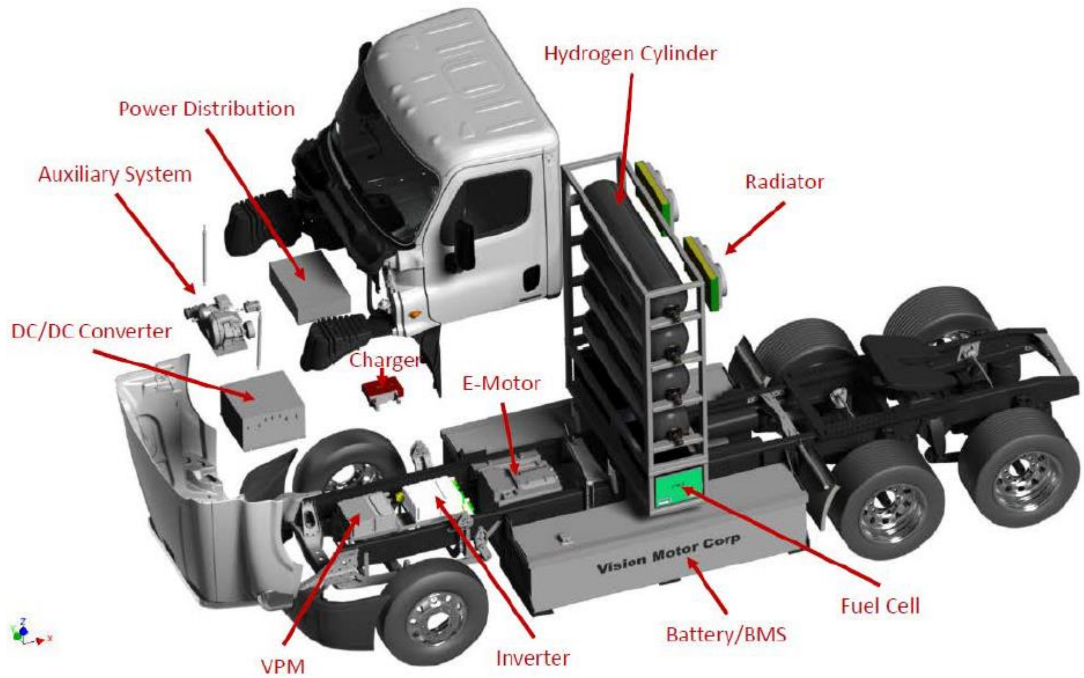


Figure 2.2. Fuel Cell Electric Truck Schematic, taken from CARB who in turn sourced it from Vision Industries Corporation "Building zero-emission hydrogen fuel cell/electric trucks for the 21st century" presentation (CARB, 2015b)

Fuel cell vehicles use a fuel cell stack to convert hydrogen into electricity, which in turn powers the vehicle. The only by-products of the reaction are water vapor and heat, meaning that fuel cell vehicles produce no harmful emissions. In 2010 refueling standards were adopted for hydrogen-fuel vehicles including fuel cell vehicles, specifying that for all vehicles carrying over 10 kg of hydrogen refueling had to occur at a reasonable rate (1.8-7.2 kg per minute) while avoiding exceeding density, pressure, and temperature limits in the storage system (CARB, 2015b). Hydrogen fuel for the fuel cell is stored in cylinders on the truck, sometimes requiring significant additional storage space (see Figure 2.2). These vehicles can use either a fuel-cell dominant or battery dominant configuration, with the fuel-cell dominant configuration requiring a smaller battery.

2.2.1 Fuel-cell Dominant vs. Battery Dominant

In a fuel cell dominant configuration, the majority of power is provided by a fuel cell usually sized 80 kW or over. The battery is used to capture power from regenerative braking, to assist at start-up, and to assist with load following. In a battery dominant configuration, a fuel cell typically sized 30-80 kW is used as a range extender for a vehicle that relies predominantly on battery power. After the battery state-of-charge in a battery dominant system falls to a set level, the fuel cell will begin providing power.

2.2.2 Hydrogen

Fuel cell trucks require hydrogen, which at present is only available in limited locations. Figure 2.3 summarizes hydrogen availability in California.

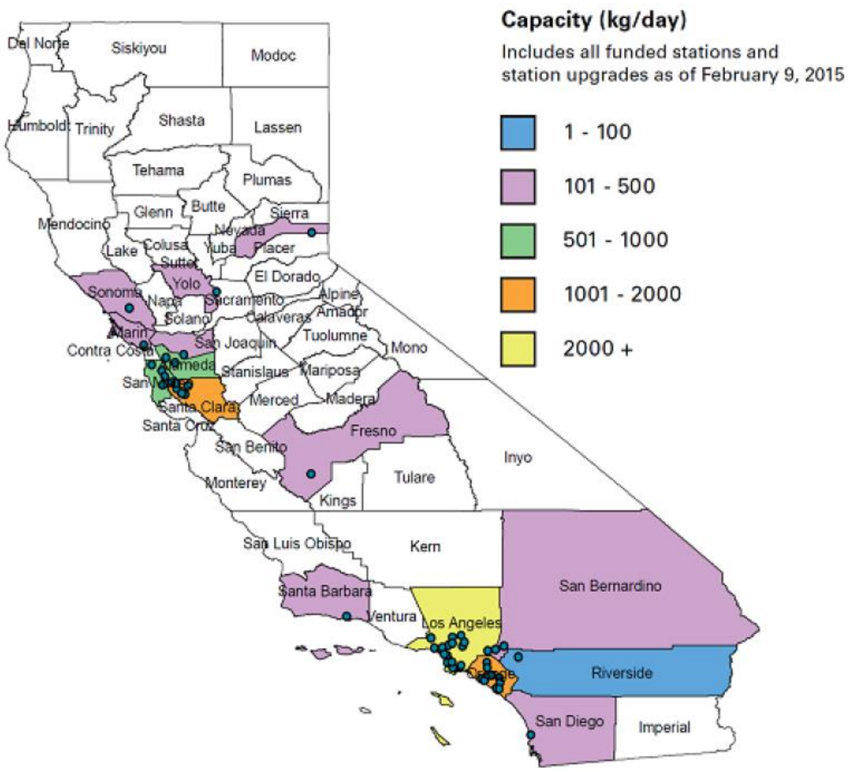


Figure 2.3. Existing and Planned Hydrogen Capacity by County in California, taken from CARB (CARB, 2015b)

2.3 Hybrid Vehicles

Hybrid vehicles typically pair a diesel engine with a battery system, though gasoline hybrids are in demonstration (Barnitt, 2011) and additionally other hybrid configurations could exist using other combinations of fueling types. Hybridization of vehicles by incorporating a battery can improve fuel efficiency through regenerative braking, torque assist, and stop-start coasting (IEA, 2017). Including the battery system in hybrid vehicles can add considerable weight, and hence can reduce vehicle payloads. In a demonstration project of Odyne vehicles, the hybrid system added 1,860 lbs, reducing the payload from 8,960 to 7,100 lbs.

2.4 Low NO_x Diesel

Low NO_x diesel vehicles may provide a way to meet emissions goals while still using combustion engines. These vehicles have the advantage that their fueling methods and operating ranges are already familiar. Current US federal standards require NOx emissions of no more than 0.20 g/bhp-hr. The CARB additionally has optional emissions standards that are 50%, 75%, and 90%

lower than this federal standard (i.e., 0.1, 0.05, and 0.02 g/bph-hr). However, at present there is limited information available about the feasibility of technology to lower emissions below 0.20 g/bhp-hr (Sharp et al., 2017). Some demonstration projects are being supported by CARB, but ultra-low NO_x vehicles with emissions significantly below the 0.20 g/bhp-hr level are not currently on the market.

Vehicles meeting the 0.20 g/bhp-hr NOx emission standard utilize technologies such as cooled gas recirculation, variable geometry turbochargers, high pressure fuel injection, and other associated electronic controls, as well as after treatment controls such as diesel oxidation catalysts, DPF, urea-SCR, and ammonia slip catalysts (CARB, 2015c). Reducing NOx emissions below 0.20 g/bhp-hr will require vehicles to combine after treatment systems with engine management strategies, as opposed to using one approach other the other (CARB, 2015c). Strategies to reduce NO_x emissions often have the side-effect of increasing greenhouse gas emissions, so development of the next generation of low NO_x engines will need to additionally include strategies to keep greenhouse gas emissions low (CARB, 2015c).

2.5 Current Financial Support for ZEV and near-ZEV Vehicles in California and the US

ZEV and near-ZEV technology for heavy-duty transport is still expensive and developing. All of the demonstration projects discussed in this report are financed at least partially by public funds, and in California several organizations are providing extensive funds for development of heavy-duty ZEV technologies.

Since 2009, the CARB in partnership with CALSTART has offered the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), which provides point-of-sale discounts to vehicle purchasers (CA HVIP, 2018). CARB also recently approved a $663 million low-carbon transportation plan to incentivize development of heavy-duty trucks and other ZEV technologies (CARB, 2017a). Since 2007 CARB has supported low carbon transportation investments through proceeds from California's cap-and-trade auction (CARB, 2018), and CARB has funded projects such as the Foothill Transit electric bus trials (Eudy et al., 2014).

The South Coast Air Quality Management District (SCAQMD), and other air quality management boards throughout California, are also supporting development of zero-emission drayage vehicles to reduce pollution near port and other heavy-use areas. SCAQMD has also run goods emission reduction projects under Proposition B since 2006, and currently offers up to $200,000 in funds for replacement of older and polluting engines with newer ZEV or near-ZEV trucks (South Coast AQMD, 2018a, 2018b).

Several of the demonstration projects evaluated by NREL were funded by the American Recovery and Reinvestment Act (ARRA), which covered part of the purchase cost of the vehicles. ARRA appropriates nearly $800 billion towards the creation of jobs, economic growth, tax relief, improvements in education and healthcare, infrastructure modernization, and investments in energy independence and renewable energy technologies, and the U.S. Department of Energy (DOE) some of this funding for supporting heavy-duty ZEV deployment (AFDC, 2018). For example, in dividing ARRA funding Division A, Title VII provides $300 million to retrofit diesel vehicle fleets with cleaner burning engines in support of the Diesel Emission Reduction Act (AFDC, 2018). The DOE also administers funding to support low-emissions transportation technologies such as ZEV buses (U.S. DOE, 2018). Electric vehicle tax credits at the federal level are only offered for vehicles up to 14,000 lbs GVWR.

Table 2.1. Sample of programs offering support for development of heavy-duty ZEV technology

Program	Run by	Start year
HVIP: California-wide point-of-sale voucher for heavy-duty zero emission trucks	CARB and CALSTART	2009
$663 million low-carbon transportation plan to increase the use of clean cars, heavy-duty trucks, buses and freight equipment	CARB	2017
Low Carbon Transportation investments are supported by California Cap-and-Trade auction proceeds projects	CARB	2007
The State of California is awarding $23.6 million to the South Coast Air Quality Management District (SCAQMD) for a statewide zero-emission drayage truck development and demonstration project	SCAQMD	2016
Goods Movement Emission Reduction Funding Program (Proposition 1B) Heavy-Duty Trucks and Transport Refrigeration Units (TRUs)	SCAQMD	2006
American Recovery and Reinvestment Act (ARRA)	U.S. DOE	2009

3. Current Heavy-duty ZEV and near-ZEV Deployment in California

California has been a leader in advancing medium- and heavy-duty electric and fuel-cell vehicle technology (IEA, 2017), but these technologies are still in the early stages of commercialization. In a series of 2015 technical reports, the CARB classifies medium- and heavy-duty hybrids as largely available commercially, while medium- and heavy-duty electric vehicles have limited commercial availability, and medium- and heavy-duty fuel cell vehicles are largely in the demonstration phase (CARB, 2015a, 2015b, 2015d). Numbers of vehicles in service, demonstration, or planned demonstration are shown in Table 3.1; 2,080 hybrid vehicles have been funded by the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and are currently in service, with over 300 medium-duty electric vehicles and about 40 heavy-duty electric vehicles also currently in demonstration or service. Fuel-cell vehicle numbers are much lower, with only 88 vehicles combined in service/demonstration or planned for demonstration. These ZEV and near-ZEV projects are a tiny portion of medium- and heavy-duty vehicles currently on the road.

Table 3.1. ZEV and near-ZEV vehicle deployment is California as of 2015 evaluation by CARB (CARB, 2015a, 2015b, 2015d)

Vehicle fuel	Vehicle type	Number in service/demonstration in CA	Number under construction/planned
Hybrid	Buses (transit, shuttle, school)	20 funded by HVIP, 410 funded through other incentive programs	Not given
	Parcel delivery [a]	830 funded by HVIP	Not given
	Uniform and linen delivery [a]	110 funded by HVIP	Not given
	Beverage delivery [b]	440 funded by HVIP	Not given
	Food distribution and other trucks	680 funded by HVIP	Not given
Electric	Transit bus	~40 [c] (10 HVIP vouchers issued)	
	School bus	4	9
	Medium-duty truck [a]	Over 300 (313 HVIP vouchers issued)	
	Heavy-duty truck [b]	3	13
Fuel Cell	Transit bus	18 [c]	8
	Shuttle bus	Not given	5
	Medium-duty truck [a]	38 planned or active demonstrations	
	Heavy-duty truck [b]	8 planned or active demonstrations	

[a] 8,501 to 14,000 lbs Gross Vehicle Weight Rating (GVWR), [b] >14,000 lbs GVWR, [c] National Transit Database reporting in 2015 recorded exactly 40 battery electric buses in California ranging from 22-40 feet in length (in contrast, CARB recorded only approximately 40). Both organizations record 18 fuel cell buses operating in California.

4. Manufacturer and Fleet Owner Trends to Note

At present, many companies providing electric freight vehicles are focused on manufacturing of electric components and produce electric vehicles through retrofits to combustion engine vehicles. Such companies include TransPower, which retrofitted class 8 trucks to be fully electric for trials at the Port of Los Angeles (Port of Los Angeles, 2016). This may create issues for large fleet operators, as these operators prefer to purchase fleets from OEM's that they trust to provide warranty and repair options throughout the vehicles' lifetimes (Marshall Miller pers. comm., 2017; pers. comm., 2017). However, some manufacturers, such as BYD, are producing the whole vehicle and will have a warranty and repair structure more familiar to fleet operators. Costs are also expected to decrease for electric freight vehicles as economies of scale come into play when larger orders are placed. Fully electric buses are expected to continue to gain traction, potentially to the point where diesel buses may no longer be manufactured by 2030 (Marshall Miller pers. comm., 2017). However, these buses at present still face range, cost, and repair issues (Eudy et al., 2014).

5. Demonstration Projects

Existing demonstration projects in the US and EU have focused heavily on electric and hybrid-electric vehicles, with far fewer publicly documented pilot projects evaluating the feasibility of large fuel-cell vehicles.

Within California, demonstration projects of medium- and heavy-duty electric vehicles have included transit buses, school buses, shuttle buses, medium-duty trucks, and heavy-duty trucks. ARB has commissioned numerous studies, many of which are currently in progress (see Section 6), but current publicly available literature on demonstration results is sparse and OEMs do not share results of internal tests on prototypes. It is notable that no public records could be located discussing findings of the demonstration projects for the 38 medium-duty fuel cell vehicles noted in Table 3.1 as being in active or planned demonstration in California. Table 5.1 provides summary details of notable projects that fall into heavy-duty/medium-duty categories for each of the three main fuel types. Select projects from Table 5.1 are discussed in greater detail in the following sections.

Table 5.1. Notable demonstration projects in each category

	Heavy duty	Medium duty
Electric	NREL comparative evaluation of Foothill Transit buses manufactured by Proterra (12 vehicles) Port of LA evaluation of class 8 trucks manufactured by TransPower (7 vehicles)	NREL evaluations of electric delivery vehicles manufactured by Smith Newton and Navistar eStar and deployed by a variety of users (>300 vehicles) NREL comparative study of electric and diesel vans manufactured by Smith-Newton in use at Frito-Lay (10 vehicles)
Fuel Cell	NREL comparative evaluation of buses deployed by the Zero Emissions Bay Area and manufactured by Van Hool (12 vehicles) NREL comparative evaluation of SunLine Transit buses assembled by ElDorado National-California (4 vehicles)	
Hybrid	EPRI and NREL evaluations of class 6-8 trucks manufactured by Odyne and deployed through many companies (119 vehicles)	NREL comparative evaluation of FedEx delivery trucks manufactured by Balance (20 vehicles but only 3 included in comparative study) NREL comparative evaluation of Coca Cola class 8 hybrid delivery trucks manufactured by Kenworth (5 vehicles) NREL comparative evaluation of UPS delivery trucks manufactured by Freightliner Corp. (6 vehicles)

5.1 Electric Demonstrations

5.1.1 Port of LA Heavy-duty Electric Trucks

The Port of LA has tested what it states are the first known pure battery-electric class 8 heavy duty trucks to reliably haul loads of up to 80,000 lbs (Port of Los Angeles, 2016). There are seven of these trucks in total, with four of them in use with port operators since late 2015, and three more undergoing testing prior to assignment to operators as of mid-2016. The seven trucks have so far accumulated a combined 25,000 miles of test driving. Each of the four battery electric trucks currently in service with operators at the Port of LA has a slightly different configuration, as these trucks were rolled out successively so lessons from each previous truck's demonstration testing can be incorporated in the subsequent trucks' design. These trucks are also all assigned to different terminals and operators, so experience different driving conditions. Demonstration trucks successfully met the minimum test requirements that Port of LA set, specifically that demonstration trucks manufactured by TransPower were able to travel 70-100 miles at average load of 65,000 lbs GCWR while consuming less than 3 kWh per mile at average load (Port of Los Angeles, 2016). However, reports also indicate that these vehicles at present require considerable calibration and frequent upgrades and maintenance to address issues including those with electrical and software systems, such that these vehicles appear to not yet be ready for use outside dedicated demonstration projects.

The Port of LA is aggressively pursuing electric truck demonstration projects as part of a strategy to meet its air quality goals to reduce health impacts of port operations on the surrounding communities (Barboza, 2017; Port of Long Beach & Port of Los Angeles, 2017). This includes phasing out diesel trucks over the next two decades. The demonstration projects have been financially supported by numerous agencies including the California Energy Commission, the U.S. Department of Energy, the South Coast Air Quality Management District, and the U.S. Environmental Protection Agency (Port of Los Angeles, 2016).

5.1.2 Frito-Lay Medium-duty Electric Trucks

The demonstration analyzed by NREL and using Smith-Newton manufactured trucks operated by Frito-Lay provides a nearly apples-to-apples comparison between electric and diesel class 6 trucks traveling along similar routes (Prohaska et al., 2016b). This demonstration project did not seek to establish the operability of these trucks, but rather examined their technical capabilities compared to those of diesel trucks while collecting information on actual operating including daily driving, charging behavior, and driving characteristics.

5.1.3 Foothill Transit Buses

Foothill transit ran a demonstration project comparing 12 electric buses manufactured by Proterra to 8 Compressed Natural Gas (CNG) buses, with analysis provided by NREL (Eudy et al., 2014). This demonstration of electric buses is notable in that it used a fast-charger at the mid-point of the bus route to recharge the electric buses in [less than 10 minutes], allowing the buses to operate reliably despite having limited battery capacity. The project also noted that the bus routes had to be carefully selected due to the range limitations of battery buses.

Reporting from Foothill, and from other bus operators, is particularly useful for insights into comparative maintenance needs/costs and reliability of their electric buses.

5.1.4 Smith-Newton Nation-wide Demonstration

NREL has an ongoing, non-comparative analysis project looking at the basic operating characteristics of electric delivery vehicles manufactured by Smith-Newton (class 6) and Navistar (class 3) that are currently deployed nation-wide across the US (Duran et al., 2014). While this demonstration cannot provide comparisons, it provides useful statistics for fuel economy and typical daily driving.

5.2 Fuel Cell Demonstrations

5.2.1 ZEBA Fuel Cell Transit Buses

The Zero Emissions Bay Area (ZEBA) transit project compares the operation of fuel cell buses to diesel buses, with the buses in active service (Eudy et al., 2016). This project is part of the ongoing and widespread analysis of fuel cell transit buses being conducted by NREL, and is largest of the fuel cell bus demonstration projects. Like the Foothill transit demonstration, it provides detailed maintenance and reliability assessments. The buses in this project refueled a hydrogen station built as part of the demonstration project.

5.2.2 Sunline Fuel Cell Transit Buses

Sunline has taken part in fuel cell bus demonstrations since at least 2003 (Kevin Chandler and Eudy, 2003). A more recent comparative project examined fuel cell vs. CNG buses deployed on Sunline's routes (Eudy et al., 2011). More fuel cell bus demonstrations are planned at this agency in future. As with the ZEBA and Foothill demonstration, Sunline provides detailed maintenance and reliability information alongside operation notes and fuel economy assessments.

5.3 Hybrid Demonstrations

5.3.1 Odyne Vehicles (NREL and EPRI)

The United States Department of Energy (DOE) funded a large demonstration project for medium- and heavy-duty trucks using American Recovery and Reinvestment Act of 2009 (ARRA) funding (EPRI, 2015). This project included 119 heavy-duty hybrids manufactured by Odyne in classes 6-8, which NREL tracked for 1,057 days of driving, providing aggregated operational data but not comparative data (NREL, 2016). NREl reports that the majority of these vehicles are bucket body-types (72%), with a smaller portion of walk-in vans (11%) and assorted other vocation types (fuel tanker: 3%; digger: 10%; compressor: 3%; vacuum: 1%). A separate study by EPRI was also conducted examining 119 Odyne vehicles funded by the ARRA, likely the same 119 vehicles. The EPRI provides additional information on vehicle configuration and testing (EPRI, 2015).

5.3.2 FedEx Study

NREL tracked 3 gasoline hybrids manufactured by Balance and compared them to three diesel trucks also operating at FedEx. The report provides information on maintenance costs and fuel economy.

5.3.3 Coca Cola Study

Coca Cola used 5 diesel hybrid vehicles manufactured by Kenworth under similar operating conditions to 5 comparable diesel trucks, and NREL analyzed the comparative performance of these vehicles. The study provides comparative fuel economy data.

5.3.4 UPS Study

NREL tracked 6 diesel hybrids manufactured by Freightliner Corp. and compared them to 6 diesel trucks also operating at FedEx. The report provides information on maintenance costs and fuel economy.

Table 5.2. Major comparative projects analyzed by NREL

Fuel types	Vehicle class	Project operator	Manufacturer of ZEV vehicles	Vehicles and vocation	Analysis year
Electric vs. Diesel	6	Frito-Lay	Smith Newton	10 electric vs. 9 diesel delivery trucks	2016
Electric vs. Diesel	8	Foothill Transit	Proterra	12 electric vs. 8 CNG buses	2014
Fuel cell vs. Diesel	8	Zero Emission Bay Area (ZEBA)	Van Hool	13 fuel cell vs. 10 diesel buses	2016
Fuel cell vs. CNG	8	Sunline Transit	ElDorado National-California	4 fuel cell vs. 5 CNG buses	2011
Gasoline hybrid vs. diesel	4	FedEx	Balance	3 gasoline hybrid vs. 3 diesel delivery trucks	2011
Diesel hybrid vs. diesel	8	Coca Cola	Kenworth	5 diesel hybrid vs. 5 diesel delivery trucks	2012
Diesel hybrid vs. diesel	4	UPS	Freightliner Corp.	6 diesel hybrid vs. 6 diesel delivery trucks	2012

5.4 Technical Capabilities

Demonstration projects of heavy-duty electric trucks have found that these vehicles are capable of meeting minimum specified operating requirements for range and load-hauling (Port of Los Angeles, 2016), and a demonstration of 12 35-foot electric buses, operated by Foothill Transit and manufactured by Proterra also found that buses using battery electric technology were capable of operating along the selected routes and had no major issues with the advanced fuel technology components (Eudy et al., 2014). Medium-duty electric trucks have been operated successfully on delivery routes during a comparative study of diesel and electric vehicles conducted by NREL at Frito-Lay using Smith-Newton vehicles, though it was found that drive cycle characteristics and vehicle operation would have significant impact on the success of widespread adoption of such vehicles (Prohaska et al., 2016b).

Fuel cell 40-foot buses operated as part of the Zero Emission Bay Area (ZEBA) demonstration project, and were compared to equivalent diesel buses. The fuel cell buses improved their reliability over the course of the study, though their maintenance costs were found to be twice that of the diesel buses (Eudy et al., 2016). Hybrid vehicles in the class 6-8 range have been developed and tested to reach the in-production stage of commercial viability. The Plug-In Hybrid Medium-Duty Truck Demonstration and Evaluation Program (sponsored by the United States Department of Energy (DOE) using American Recovery and Reinvestment funding) produced 119 class 6-8 test vehicles working with manufacturers Odyne and Via, and vehicles validated through this program are now in commercial production (EPRI, 2015). Medium-duty hybrid vehicles are already at the stage where they can be integrated into existing fleets, and a study comparing diesel and hybrid vehicles running FedEx delivery routes found that the hybrid vehicles could be integrated with minimal technical or operational issues (Barnitt, 2011). Evaluations of the technical capabilities of hybrid vehicles are also ongoing at NREL, with a fleet of 120 Odyne hybrid utility trucks being monitored (NREL, 2016).

Overall, demonstration projects indicate that ZEV and near-ZEV heavy-duty vehicles are able to operate along selected routes during pilot projects, but have also revealed areas for improvement and highlighted the importance of operational characteristics. These projects have also shown strengths of these ZEV and near-ZEV vehicles, particularly in the area of fuel efficiency. The following sections present additional detail on selected technical characteristics.

5.4.1 Fuel Economy

Tables 5.3 and 5.4 summarize fuel economies for ZEV and near-ZEV heavy- and medium-duty trucks as found in demonstration projects. In existing comparative demonstration projects, medium-duty electric trucks have shown high fuel economy compared equivalent diesel trucks (Duran et al., 2014; Prohaska et al., 2016a), as have electric buses (Eudy et al., 2014). Heavy-duty electric trucks demonstrated at the Port of LA, while loaded with GCWR 65,000 lb (Port of Los Angeles, 2016), have demonstrated lower fuel economy than medium-duty electric vehicles but higher fuel economy than gasoline trucks (CARB, 2017b). It should also be noted that electric vs. diesel comparative vehicle efficiencies are affected by their operating conditions (CARB, 2017b), in particular by speed, such that higher energy efficiency ratios of electric compared to diesel trucks are seen at lower speeds (see Figure 5.1).

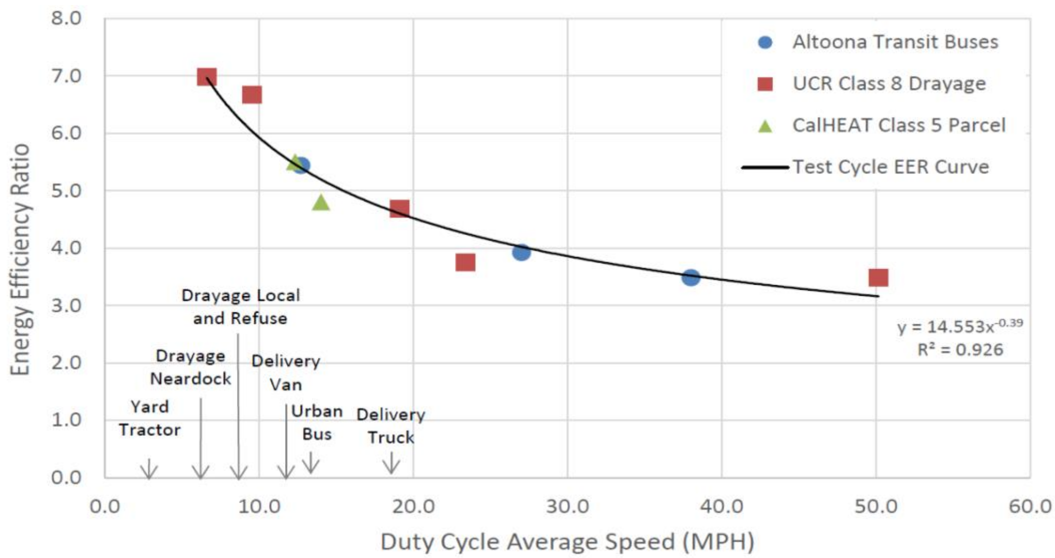


Figure 5.1. Vehicle Energy Efficiency Ratio at Different Average Speeds taken from CARB *(2017b)*

Table 5.3. Fuel economy of ZEV and near-ZEV heavy- and medium-duty vehicles: Fuel Type, Electric

Demonstration project	Class	Fuel	Vehicles	Fuel economy (miles/DGE)
Port of LA trucks (Port of Los Angeles, 2016)	8	Electric	7	>10.8[a]
Foothill bus comparative study (Eudy et al., 2014)	8	Electric	12	17.48
		CNG	8	4.51
Transpower yard tractor, IKEA in-use, comparison drawn from CARB study (CARB, 2017b)	8	Electric	Not given	.45 DGE/hr
		Diesel	Not given	2.4 G/hr
Transpower yard tractor, Port of LA in-use comparison drawn from CARB study (CARB, 2017b)	8	Electric	Not given	0.345 DGE/hr
		Diesel	Not given	2.4 G/hr
Altoona bus Commuter test cycle, comparison drawn from CARB study (CARB, 2017b)	8	Electric	Not given	26.0
		Diesel	Not given	7.5
Altoona bus CBD test cycle, comparison drawn from CARB study (CARB, 2017b)	8	Electric	Not given	21.3
		Diesel	Not given	3.9
UC Riverside (UCR) drayage tractor, dock test cycle, comparison drawn from CARB study (CARB, 2017b)	8	Electric	Not given	18.3
		Diesel	Not given	2.6

Demonstration project	Class	Fuel	Vehicles	Fuel economy (miles/DGE)
Frito-Lay delivery truck comparative study (Prohaska et al., 2016b)	6	Electric	10	24.09
		Diesel	9	7.63
Smith Newton trucks (Duran et al., 2014)	6	Electric	259	24.9
CalHEAT step van, comparison drawn from CARB study (CARB, 2017b)	5	Electric	Not given	56.2
		Diesel	Not given	11.7
SD Airport V6 shuttle van in use, comparison drawn from CARB study (CARB, 2017b)	3	Electric	Not given	80.6
		Diesel	Not given	17.9
CalHEAT step van (in-use) comparison drawn from CARB study (CARB, 2017b)	3	Electric	Not given	76.8
		Diesel	Not given	11.2
Navistar eStar trucks (Duran et al., 2014)	3	Electric	101	46.1

[a] 3 kWh or less per mile converted to miles/DGE using a conversion of 0.031 from kWh to diesel *https://epact.energy.gov/fuel-conversion-factors*

Fuel cell vehicles currently have much poorer fuel economy than electric vehicles, and fuel cell bus demonstrations have not yet met the US DOE technical target of 8 miles/DGE set for fuel cell electric buses (Eudy et al., 2016). Demonstration projects of gasoline-electric delivery trucks have not found significant differences in fuel economy compared to standard gasoline delivery trucks (Barnitt, 2011). Recent projects have designed and validated class 6-8 hybrid trucks, which developers are now producing (EPRI, 2015); these heavy-duty PHEVs were found to have significant fuel economy benefits.

Table 5.4. Fuel economy of ZEV and near-ZEV heavy- and medium-duty vehicles: Fuel Type, Fuel cell and hybrid

Demonstration project	Class	Fuel	Vehicles	Fuel economy (miles/DGE)
Sunline bus (Kevin Chandler and Eudy, 2003)	8	Fuel cell	1	11.5
ZEBA bus comparative study (Eudy et al., 2016)	8	Fuel cell	13	6.18
		Diesel	10	4.25
Sunline bus comparative study (Eudy et al., 2011)	8	Fuel cell	4	6.13
		CNG	5	3.24
Coca cola comparative study (Walkowicz et al., 2012)	8	Hybrid (diesel)	5	5.79
		Diesel	5	4.93
Odyne utility trucks (NREL, 2016)	6-8	Hybrid	119	6.4
	4	Hybrid	6	13.0

Demonstration project	Class	Fuel	Vehicles	Fuel economy (miles/DGE)
UPS comparative study (Lammert and Walkowicz, 2012)		(diesel)		
		Diesel	6	10.6
FedEx gasoline hybrid delivery vehicle comparative study (Barnitt, 2011)	4	Hybrid (gasoline)	3	7.54
		Diesel	3	7.91

5.4.2 Range and Refueling

Range of electric and fuel cell vehicles can limit applications of this technology, and both availability of fueling stations and time taken for vehicles to refuel can raise concerns. Demonstration projects in Europe often observed that the actual vehicles ranges fell short of the range promised by the manufacturer (Quak and Nesterova, 2014). In bus applications, electric buses could only be deployed on selected routes due to inability to meet range requirements of some routes, and Foothill transit used a fast-charger at the mid-point of the route to allow frequent recharging (Eudy et al., 2014). Electric vehicles are considered to be promising for class 6 and smaller, especially in applications where they can frequently return to a home base to refuel.

Table 5.5 summarize refueling conditions and times from demonstration projects. Electric drayage trucks in demonstrations at the Port of LA have all exhibited differing ranges and differing numbers of loads able to be pulled each day due to differing operating conditions, but one truck was temporarily suspended from use when operators refused to drive it due to only being able to pull two loads a day on their usual route rather than three thus losing revenue (Port of Los Angeles, 2016). The medium-duty electric trucks in the Frito-Lay demonstration did not appear to face operational issues due to range, but typically only drove 32 miles a day such that 79% of trips utilized less than 55 of the available 80 kWh (Prohaska et al., 2016b). These Frito-Lay trucks would complete their delivery route then return to the depot and begin charging around 11.30am; after a period of charging they would then be moved to be reloaded, then returned to continue charging (Prohaska et al., 2016b).

Table 5.5. Refueling and range characteristics of ZEV and near-ZEV medium- and heavy-duty vehicles in demonstrations

Demonstration project	Class	Fuel	Refueling time	Refueling conditions	Fuel capacity	Range (miles)
Navistar eStar delivery vans (Duran et al., 2014)	3	Electric	Average charge duration 3.5 hours	Predominantly charged in the night/evening	80 kWh battery	100 (av. daily use 20)
Smith-Newton delivery vans (Duran et al., 2014)	6	Electric	Average charge duration 6.4 hours	Predominantly charged in the night/evening	80 kWh battery	100 (av. daily use 25)

Demonstration project	Class	Fuel	Refueling time	Refueling conditions	Fuel capacity	Range (miles)
Port of LA (Port of Los Angeles, 2016)	8	Electric	4 hours with single 70 kW charger from 20% charge	Dedicated infrastructure	Not given	70-100 at av. load (65,000 lbs GCWR)
Frito-Lay delivery truck (Prohaska et al., 2016b) (subset of Smith-Newton vehicles)	6	Electric	Average 6.1 hours to recharge from 42% (post-loading) to 100%	Recharged at depot, recharging occurs in two steps (separated by loading)	80 kWh battery	Drove 32 miles/day on average after full charge
Foothill bus (Eudy et al., 2014)	8	Electric	Reaching full charger with overhead chargers <10 mins	On-route fast-charge station at mid-way point in route. Bus charged through overhead charger.	88 kWh battery	Not given
ZEBA bus (Eudy et al., 2016)	8	Fuel cell	30 kg of H_2 in 6 mins	Central station with H_2 produced on-site	40 kg H_2	235
Sunline bus (Eudy et al., 2011)	8	Fuel cell	Not given	Fueled at least once daily at station (?)	50 kg H_2 & 11 kWh battery	270
Coca Cola	8	Diesel hybrid	Not given	Not given	56 gallon diesel tank and 1.8 kWh battery	Not given
Odyne trucks (NREL, 2016)	6-8	Diesel Hybrid	Not given	Not given	28.4 kWh battery (and diesel tank, size not given)	Not given

Fuel cell vehicles often pair a hydrogen fuel cell with a battery, to achieve an overall much greater range than could be achieved with a battery electric vehicle alone. The DOE has set a target for fuel cell buses to achieve a range of 300 miles by 2016, though demonstration projects completed by mid-2016 had not yet reached this goal (Eudy et al., 2016). During the ZEBA demonstration project, there were some issues with real-world bus range being lower than expected and with range anxiety occurring when the fuel light came on (Eudy et al., 2016). Demonstration projects involving fuel cell buses are ongoing with frequent reporting updates and fleet additions. Fuel cell bus demonstrations often involve additional installation of infrastructure to produce hydrogen on-site for refueling (Eudy et al., 2016).

According to the California Fuel Cell Partnership (CAFCP), there are no public hydrogen truck fueling stations available now. There are three fueling stations for buses in operation, but these all have limited capacity. These are at SunLine Transit's station in Thousand Palms (opened in 2000), AC Transit's Emeryville station (opened in 2011 and the largest such fueling station in the country), and AC Transit's Oakland station (opened in 2014). Only Emeryville has plans to open to the public (in 2018). The expected fuel capacity for trucks is equivalent to buses and takes 6-8 minutes to fill using "fast-fill" technology. Although there are numerous existing hydrogen fueling stations available statewide for passenger vehicles, these cannot be used (without some major modification) for medium and heavy-duty trucks due to the station layout, fuel capacity, and pressure requirements. (CAFCP, 2016a, 2016b) It would be difficult to modify existing light duty stations to accommodate heavy-duty trucks. It is better to build dedicated refueling stations which the exception for highway rest stops that could serve both trucks and passenger vehicles (like Flying J).

Heavy-duty hydrogen truck manufacturer Nikola has announced plans to build stations in California to correspond with its roll-out of their class-8 heavy duty trucks in 2020. These trucks will be leased "inclusive" of fuel. Planned locations can be found at https://nikolamotor.com/stations.

5.5 Operational

5.5.1 Reliability and Maintenance Frequency

Zero emission buses in demonstration projects still do not match combustion vehicles in terms of reliability, with both ZEBA fuel cell and Foothill electric buses travelling far fewer miles between roadcalls than diesel and CNG equivalents. Roadcalls occur when a bus fails in route to the extent that it either has to be replaced with another bus or causes significant delays in service. Table 5.6 summarizes availability, roadcalls, and maintenance for demonstration projects. Alternate fuel buses also had lower availability than the equivalent combustion engine buses they were compared to. It is notable that availability of buses was not only due to issues with ZEV components such as fuel cells or batteries but also due to general bus issues, which in the ZEBA study accounted for 47% of the of unavailability. While the Foothill electric bus demonstration showed cheaper maintenance per mile of the electric buses compared to CNG buses, demonstration projects will fuel cells indicate that per-mile maintenance of fuel cell buses can still be higher than that for diesel and CNG buses.

Maintenance for the ZEBA fuel cell buses was initially carried out by the bus manufacturer, but preventative maintenance was successfully transitioned to AC Transit staff over the course of the demonstration and mechanics at AC Transit are becoming more familiar with the new technology (Eudy et al., 2016). However, AC Transit continues to experience some issues with sourcing parts for repairs of its fuel cell buses. Electric buses in the Foothill demonstration also faced issues due to lack of availability of some component parts when repairs were needed

(Eudy et al., 2014). In European pilots, limited or late technical support for maintenance and repairs has also been an issue with electric freight vehicle adoption (Quak and Nesterova, 2014).

Reliability of heavy-duty electric trucks in demonstration projects has often improved over the course of the demonstration, as in the case where the Port of LA updated the battery systems in their trucks following issues with the battery in the first demonstration truck (EDD1) and found that the following trucks (EDD 2-7) performed reliability throughout trials (Port of Los Angeles, 2016). Numerous issues were observed during the class 8 truck demonstrations at the Port of LA, some of which were easily fixed and some of which required more extensive down-time for trucks to allow repair. EDD-1 experienced severe battery charge and charge regulation issues as previously noted, while EDD-2, EDD-3 and EDD-4 faced minor issues including with the inverter high voltage interface board, the BMS board, transmission shifting, and a glitch in the state-of-charge software, all of which were addressed with either software upgrades or the replacement of a small number of boards. The Port of LA demonstrations also involved continuous improvements to inverters, software, battery modules, and battery configurations (Port of Los Angeles, 2016). These demonstration projects also noted that “port applications can exhibit a corrosive high humidity and salty environment requiring extra protection for certain high voltage equipment.” (Port of Los Angeles, 2016).

Table 5.6. buses and maintenance/reliability

	Class	Fuel	Total maint. ($/mile)	Maint., Prop. system only ($/mile)	Miles between roadcalls (all)	Miles between roadcalls (fuel cell/battery system only)	Miles between roadcalls (prop. system only)	Availability/ uptime
Foothill bus	8	Electric	0.16	0.02	9,331	133,748	25,078	90%
		CNG	0.18	0.08	45,547	NA	91,093	94%
No maintenance cost/reliability information found for electric vehicles class 3-7								
ZEBA bus	8	Fuel Cell	1.15	0.65	4,513	23,260	7,512	86%
		Diesel	0.47	0.14	6,954	NA	15,453	89%
Sunline bus	8	Fuel Cell	0.42	0.21	5,761	16,234	8,117	75%
		CNG	0.48	0.21	10,025	NA	19,631	91%
No maintenance cost/reliability information found for fuel cell vehicles class 3-7								
No maintenance cost/reliability information found for hybrid vehicles class 5-8								
FedEx delivery vans	4	Gasoline Hybrid	0.206	Not given	Not given	Not given	Not given	95.8%
		Diesel	0.223	Not given	Not given	Not given	Not given	98.4%
UPS delivery vans	4	Diesel Hybrid	0.141	Not given	Not given	Not given	Not given	96.3%
		Diesel	0.130	Not given	Not given	Not given	Not given	99.0%

5.5.2 Training and Driver Behaviors

The logistics of freight delivery have been identified as a potential key barrier to adoption of electric freight vehicles, as these routes are currently designed assuming they will be filled by diesel or gasoline vehicles (Quak and Nesterova, 2014). Review of European projects has also established the importance of driver training and determination of appropriate refueling behaviors (Quak and Nesterova, 2014). Comparative demonstrations in the US have also emphasized the importance of logistics and refueling behavior. The Frito-Lay study concluded that vehicle operation and route characteristics would strongly affect the success of electric delivery vehicles adopted for this application, and in particular noted that energy efficiency is highly dependent on vehicle duty cycles (Prohaska et al., 2016b).

Several US demonstration projects provide individual comment on the importance of driver training. Hybrid heavy-duty vehicles in Odyne trials still spend time idling, which was considered to indicate a need for greater driver training since there should be no need to idle a vehicle equipped with hybrid assist (EPRI, 2015). Foothill transit also faced challenges training operators, since the docking procedure for the electric fast-charger was very different from previous driving behaviors needed by bus operators (Eudy et al., 2014). The ZEBA demonstration found that if staff were less familiar with fueling the hydrogen tanks of the fuel cell buses then they often would not completely fill the tank, indicating that greater operator training would likely be necessary in future (Eudy et al., 2016).

5.5.3 Life-time of Vehicles

The expected life-time of alternative fuel vehicles remains somewhat uncertain due to the recent adoption of these technologies, and also due to the continuous improvements still currently being made to these technologies. The DOE has set a target for fuel cell buses to have a lifetime of 12 years/500,000 miles, but the status of buses in 2012 indicated that lifetime would likely be 5 years/100,000 miles (CARB, 2015b). Transit companies considering adopting electric buses already use lifetime estimates of 12 years when projecting costs/benefits compared to diesel buses, though no specific buses that have reached this age are referred to (CARB, 2015a). Longevity of heavy-duty electric trucks is not yet fully known, as these vehicles have only recently been trialed. The Port of LA will continue testing the longevity of these vehicles as part of ongoing demonstration work (Port of Los Angeles, 2016).

5.6 Economic

Most studies offered only incomplete information on costs. Vehicle purchase costs were rare in studies that were not run by public transit agencies – only the Port of LA provided an indication of purchase costs of its heavy-duty electric trucks, while other purchase cost estimates are taken from government agencies. Table 5.7 summarizes available cost information, and notes significant gaps.

5.6.1 Purchase Cost

Electric vehicles are considerably more expensive than diesel vehicles at present. CALSTART estimates for drayage trucks in 2012 compare a diesel vehicle at $104,000 to an electric vehicle at $308,000, but given that Port of LA electric drayage truck costs ranged from $400,000 to $800,000 these CALSTART figures may be optimistic (CARB, 2015a; Port of Los Angeles, 2016). Fuel cell buses are even more expensive, with these vehicles costing $3 million in early demonstrations and reportedly dropping to $1.8 million for more recent demonstrations (Eudy et al., 2016).

Batteries are an expensive component in electric, hybrid, and some fuel-cell vehicles; in a cost-analysis of hybrid heavy-duty trucks by Odyne batteries were found to constitute 38% of the overall cost (EPRI, 2015). In hybrid vehicles, this led to evaluations concluding that reducing battery packs to half the size (28 kWh to 14 kWh) could reduce vehicle costs by about 20% (EPRI, 2015). CALSTART estimates that a 350 kWh battery system suitable for an electric drayage truck cost $210,000 in 2012, but could drop to $74,000 by 2030 (CARB, 2015a). If achieved, these reductions in battery costs would make electric and other ZEV/near-ZEV vehicles significantly more cost-competitive.

5.6.2 Maintenance Cost

Information on maintenance costs is predominantly available from public transit studies and from hybrid fuel studies, so electric and fuel cell system maintenance cost information is largely limited to bus experiences. Maintenance costs and time are affected by transit agency staff still learning how to troubleshoot problems with the new vehicles (Eudy et al., 2016). Maintenance costs may decrease in future as staff gain familiarity with the technology. Some fuel cell buses in the ZEBA test had extended downtime for maintenance, which will have negatively impacted returns on investment for these buses. When fuel cell systems in buses develop problems in some cases the bus needs to be shipped to the manufacturer for repairs, as happened during the Sunline trials (Eudy et al., 2011).

Table 5.7. Costs of ZEV and near-ZEV vs. conventional vehicles

Project	Vehicle class	Fuel type	Purchase cost ($/vehicle)	Maintenance cost ($/mile)	Fuel cost ($/mile)
Port of LA (Port of Los Angeles, 2016)	8	Electric	$800,000 for EDD-1, dropped < $400,000 for EDD-7	Not given	Not given
CALSTART estimates of 2012 drayage truck cost (CARB, 2015a)	8	Electric	308,000	Not given	Not given
		Diesel	104,000	Not given	Not given
CARB transit bus estimates (CARB, 2015e)	8	Electric	800,000	Not given	Not given
		Diesel	485,000	Not given	Not given
		CNG	525,000	Not given	Not given
		Fuel cell	1,300,000	Not given	Not given

Project	Vehicle class	Fuel type	Purchase cost ($/vehicle)	Maintenance cost ($/mile)	Fuel cost ($/mile)
Foothill electric bus (Eudy et al., 2014)	8	Electric	904,490	0.16	Not given
		CNG	575,000	0.18	Not given
Frito-Lay delivery truck (Prohaska et al., 2016b)	6	Electric	Not given	Not given	0.14[1]
		Diesel	Not given	Not given	0.34[2]
Medium duty trucks	3-5	Electric	No studies with cost information found		
ZEBA buses (Eudy et al., 2016)	8	Fuel cell	2,500,000	1.15	Not given
		Diesel	413,826	0.47	Not given
Sunline buses (Eudy et al., 2011)	8	Fuel cell	2,100,000 to 2,400,000	0.42	1.42
		CNG	402,900	0.48	0.33
Medium duty vehicles	3-7	Fuel cell	No studies with cost information found		
Coca cola (Walkowicz et al., 2012)	8	Diesel hybrid	Not given	0.14	0.58
		Diesel	Not given	0.29	0.69
UPS (Lammert and Walkowicz, 2012)	4	Diesel hybrid	Not given	0.141	0.237
		Diesel	Not given	0.130	0.292
FedEx gasoline hybrid (Barnitt, 2011)	4	Gasoline hybrid	Not given	0.21	0.42
		Diesel	Not given	0.22	0.38

*[1]Frito-Lay EVs: 0.87 kWh/km for EV and 0.102 $/kWh for electricity, so 0.87*0.102 = 0.089 $/km = 0.14 $/mile; [2]Frito-Lay diesel: 3.24 km/L of diesel and $1.00/L cost for diesel = 0.324 $/km*

The Coca Cola demonstration showed lower maintenance costs for hybrid vs. diesel trucks (Walkowicz et al., 2012), while the UPS study found the opposite (Lammert and Walkowicz, 2012) and the FedEx study found no significant difference (Barnitt, 2011). All of these studies emphasized that the time-frame had been relatively short, and could not provide a complete understanding of lifetime maintenance costs for hybrids vs. diesel vehicles.

5.6.3 Fuel Cost

Demonstrations of electric buses at Foothill transport raised the issue of electricity costs increasing subject to tiered rates as more electric vehicles were added to the fleet, which is expected to be a widespread problem as more transit agencies begin to increase sizes of electric fleets (Eudy et al., 2014). Fast chargers, such as the one used by Foothill, can also add significant infrastructure costs to fueling. Battery electric vehicle chargers can range from

$1,000 for a basic charger using mains power and accommodating a single vehicle to $350,000 for a fast charger able to accommodate multiple vehicles (CARB, 2015a).

At present, there are extremely high costs associated with providing the hydrogen for fuel cell buses. A dedicated hydrogen transit station was built at Emeryville and utilized by the ZEBA project, and the construction costs for this station were $10 million (Eudy et al., 2016). The Sunline demonstration project estimated costs based on the costs of natural gas for their hydrogen reformer, and found variation in average monthly costs between $3.10/kg to more than $23/kg of hydrogen – indicating highly variable fuel costs for the fuel-cell bus (Eudy et al., 2011). This translated into the high per mile fuel costs as reported in Table 5.7. Hydrogen storage is also expensive, with CARB estimating that storage for fuel cell electric buses cost $100,000 in 2012 (CARB, 2015b).

In medium-duty applications, the higher fuel economy of battery-electric delivery trucks is expected to lead to cost savings relative to deployment of diesel vehicles. Prohaska et al. (2016b) projected that by increasing the annual distance driven by EVs in the fleet from 13,660 to 17,705 km fleet operators could save an average of $750 on fuel (assuming $3.79/gallon of diesel and $0.102/kWh of electricity).

5.7 Environmental

5.7.1 Emissions

Vehicles on road in 2015 needed to meet 2010 federal emission limits requiring heavy-duty diesel engines to emit no more than 0.20 g/bhp-hr NO_X emissions and 0.01 g/bhp-hr particulate matter (PM) emissions (CARB, 2015c). CARB also adopted optional low NO_X standards that are 50%, 75%, and 90% lower than this federal standard. New vehicles using combustion engines are under development to try to meet these optional CARB standards, but as yet are still only in the demonstration phase (Sharp et al., 2017).

Emissions were not reported for any of the bus studies; although the tailpipe emissions of the electric and fuel cell buses will be zero, the electric buses will still have associated emissions since California's electricity is still partially generated from fossil fuels. The EIA reports an emissions factor of 281.68 g of CO_{2e}/kWh of electricity (EIA, 2015). Given that the Foothill bus report states that the bus uses about 2.15 kWh/mile, an approximate emissions load of 605 CO_{2e}/mile can be calculated using the California emissions factor (Eudy et al., 2014), though this is only an approximation and the NREL study examining Frito-Lay trucks considered more factors when calculating emissions (Prohaska et al., 2016c).

Table 5.8. Federal emissions standards

Study		CO_2 (g/bhp-hr)	NO_x (g/bhp-hr)	PM (g/bhp-hr)
Federal standards for current on-road vehicles	1998 federal standards for heavy-duty vehicles		=< 4	
	2010 federal standards for heavy-duty vehicles		=< 0.20	< 0.01
	CARB optional low-NO_x standards (90% lower than federal) for heavy-duty vehicles		=< 0.02	
CARB evaluation of developing low-NO_x technologies (Sharp et al., 2017)	CNG ultra-low NO_x engine trial (using Federal Test Procedure)	547	0.01	
	CNG baseline engine comparison (using Federal Test Procedure)	542	0.115	
	Diesel ultra-low NO_x engine trial (using Federal Test Procedure)	600-604	0.008-0.034	
	Diesel baseline engine comparison (using Federal Test Procedure)	547	0.140	

Ranges are provided for the Coca Cola and FedEx studies as these both tested emissions in the lab under three different drive cycles, each resulting in a different emission load (Barnitt, 2011; Walkowicz et al., 2012). Given that neither of the fuel cell bus studies provided emissions estimates, there is not a good way to estimate these emissions from energy consumption data – unlike the electric bus, these fuel cell buses draw all or the majority of their power from their hydrogen fuel cells, and do not appear to use the grid to charge their batteries (these batteries are used for storing charge from regenerative braking etc.).

Table 5.9. Emissions reported in demonstration projects

Project	Class	Fuel	CO_{2e} g/mile	CO g/mile	NO_x g/mile	PM g/mile
Foothill (Eudy et al., 2014) and author estimates	8	Electric	~605	Not given	Not given	Not given
Frito-Lay (Prohaska et al., 2016c)	6	Electric	958.51	Not given	Not given	Not given
		Diesel	1414.94	Not given	Not given	Not given
No estimates found relevant to fuel cell vehicles						
Coca Cola (Walkowicz et al., 2012)	8	Hybrid	1360-1770	0.35-1.64	5.75-9.94	Not given
		Diesel	1660-2310	0.71-1.70	2.86-7.70	Not given
FedEx (Barnitt, 2011)	4	Hybrid	758.6-1160.9	0.29 – 1.03	0.57-3.24	0.0004 – 0.0016
		Diesel	954 -1468.9	2.50 – 7.60	5.20 – 12.70	0.2820 – 0.7930

6. Future Trends

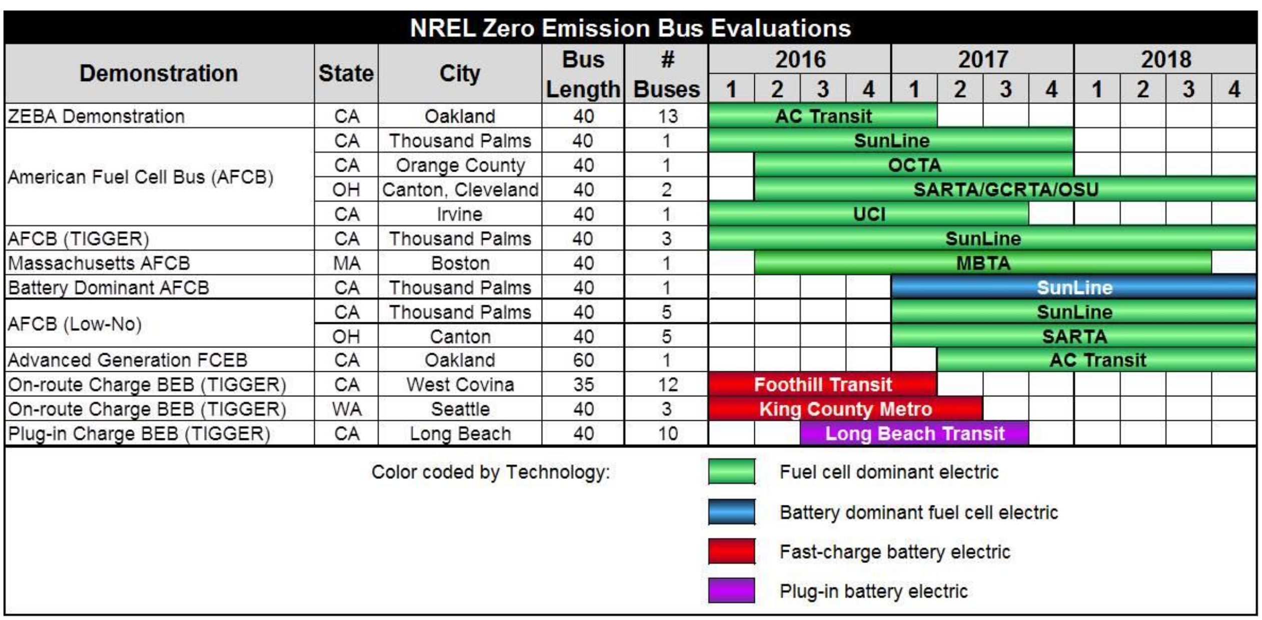
6.1 Ongoing Demonstrations

Many demonstration projects are ongoing, and may help to fill the aforementioned gaps in understanding of some technologies. Since many of the ongoing projects are sponsored by federal or state agencies, the results are expected to be freely available publicly upon project completion. However, some projects such as the fuel cell truck by Toyota appear to be proceeding based on private industry evaluation needs, so data from these projects are expected to be sparse. Table 6.1 below lists some of the ongoing projects that may fill gaps in current technology understanding. Table 6.2 below lists ongoing bus demonstration projects analyzed by NREL.

Table 6.1. Sample of ongoing demonstration projects

Project	Class	Fuel	Vehicles	Vehicle first deployment
Zero-emission trucks at seaports, funded by SCAQMD	8	Battery electric and plug-in hybrid	43 drayage trucks manufactured by BYD, Kenworth, Peterbilt and Volvo	Announced May 2016
BYD California Freight Yard demonstration sponsored by CARB (O'Dell, 2017a)	8	Electric	27 all-electric yard trucks manufactured by BYD	March 2017
BYD Goodwill demonstration in Bay Area supported by CARB and BAAQMD (Field, 2017)	6-8	Electric	10 class 6 trucks and 1 class 8 refuse truck all manufactured by BYD	After May 2017 (exact time unknown)
Toyota Fuel Cell drayage truck at Port of Los Angeles (no national or state agency mentioned as sponsor) (O'Dell, 2017b)	8	Fuel cell	Unknown number of drayage vehicles manufactured by Toyota (possibly only one truck)	Possibly April/May 2017
UPS working with DOE (UPS, 2017)	6	Fuel cell	Medium-duty delivery truck	Third quarter of 2017

Table 6.2. Ongoing ZEV bus evaluations by NREL (figure taken from NREL (2017))

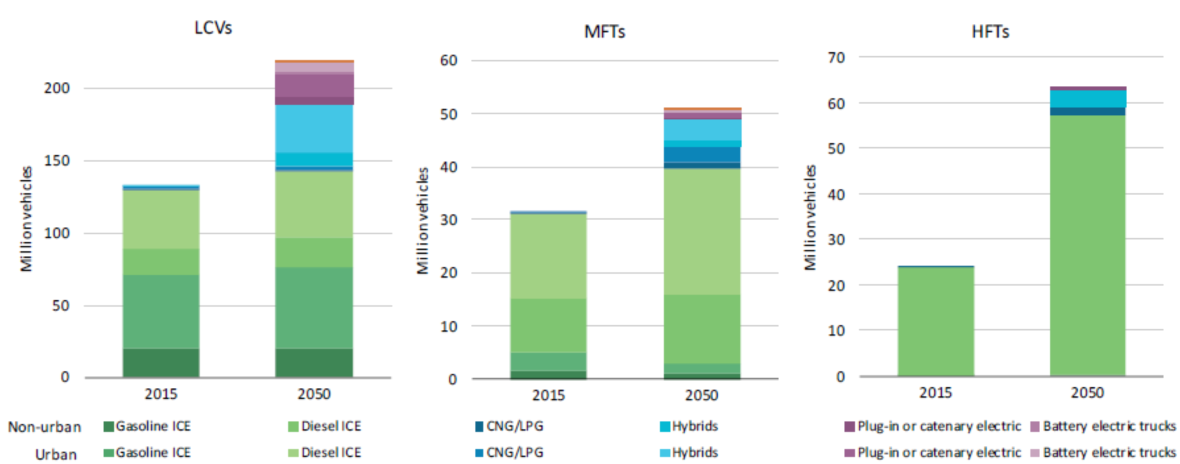


7. Prior Studies of Alternative Fuel HDT Market Analysis and Forecasts

Innovations in vehicle technology may take 5-25 years or even longer to become widespread in vehicle stock (Fridstrøm, 2017). Vehicle fleet managers would typically only acquire a new vehicle when an old vehicle is scrapped or when the fleet needs to be expanded, so stock flow modeling was used to generate the 5-25 year figure (Fridstrøm, 2017). Alternative fuel vehicle uptake rates will also be affected by policy constraints, technological advances, and diesel costs vs. battery costs. The following sections collect several major forecasts of AFV uptake at the global, US national, and California state level, followed by a section briefly considering battery cost projections. Forecasts deal primarily with electric vehicles and hybrids – fuel cell vehicles are still in the demonstration stage and have extremely low adoption even in the light vehicle market (1,300 of all classes in CA as of 2017 (CARB, 2017c)), so there is very little existing data from which to project trends in heavy-duty fuel cell vehicle adoption.

7.1 Global Forecasts

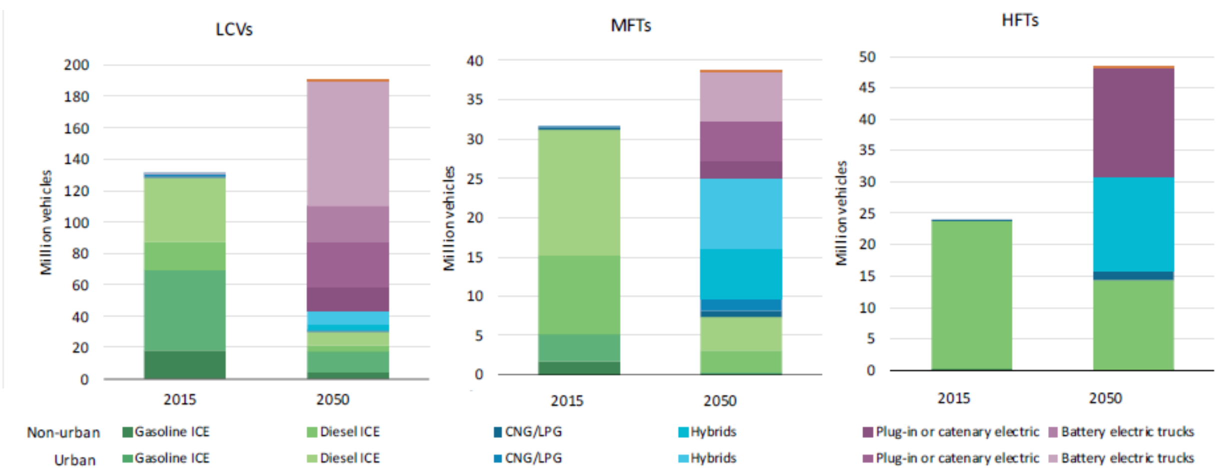
The IEA projects in a reference scenario (assuming no major policy shifts) that global road freight activity will increase to over 65 trillion tonne-kilometers by 2050, with the reference model showing large growth in India and China while the US remains relatively flat near 7 trillion tonne-kilometers (IEA, 2017). Global demand for oil in this reference scenario is projected to grow to 5 million barrels per day. Projected global freight vehicle stock associated with this increase is shown in Figure 7.1. Figure 7.1 shows a marked growth in hybrid, plug-in, and battery electric light commercial vehicles (LCVs) in both urban and non-urban settings, with the largest growth area being urban plug-in electric light commercial vehicles. The growth of zero-emission HFTs is projected to be much smaller globally.



Note: CNG = compressed natural gas; ICE = internal combustion engine; LPG = liquefied petroleum gas.
Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Figure 7.1. Global road freight vehicle stock in IEA reference scenario; HFT: heavy-freight truck, MFT: medium-freight truck, LCV: light commercial vehicle (IEA, 2017)

In both IEA and NREL examinations of freight vehicle future trends, alternative fuel vehicles are included as a complement or subset of fuel efficiency measures (Grenzeback et al., 2013; IEA, 2017). That is, it is expected that regulations to improve fuel economy will drive alternative fuel vehicles to be more cost-competitive. In contrast to the reference scenario, the IEA also estimates a “Modern Truck” scenario that assumes vehicle efficiency improvements starting immediately and being pushed for over several decades, systemic logistic and operations improvements in freight movement, and support for alterative fuels and technologies that enable their use. The Modern Truck scenario is predicted to require 45% less energy for transport needs compared to the reference scenario. This scenario predicts high uptake of electric light commercial vehicles, and high uptake of hybrid and electric medium-freight vehicles, in both urban and non-urban settings. It also projects high uptake of catenary-enabled electric heavy-freight vehicles.



Note: CNG = compressed natural gas; ICE = internal combustion engine; LPG = liquefied petroleum gas.
Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Figure 7.2. Global road freight vehicle stock in IEA ‘Modern Truck’ scenario; HFT: heavy-freight truck, MFT: medium-freight truck, LCV: light commercial vehicle (IEA, 2017)

7.2 US National Forecasts

In a joint 2013 report, NREL and Cambridge Systematics Inc. reviewed several forecasting models for projecting future freight demand in the US, but found that none of the available models were able to account for all factors expected to influence freight demand including economic, logistic, policy, and transportation factors (Grenzeback et al., 2013). Data limitations were also considered to be a significant issue with forecasting. Models reviewed included macroeconomic/commodity models, time series models, and behavioral/choice models. Review included software/analysis steps, data availability, and contact persons for several ways of running each model. The models were also considered for the usefulness in predicting freight demand at-large, not demand for alternative fuel vehicles specifically.

The research firm Navigant has produced several reports in this area (e.g., “Market Data: Electric Drive Trucks” focused globally, “Transportation Forecast: Medium and Heavy Duty Vehicles” focused globally, “Market Data: EV Geographic Forecasts” focused on North America, and “The Future of Last-Mile Logistics” focused on North America), but these reports were not included within the research institution’s data access and so are not summarized here. Reporting from GreenFleet magazine interviewing a senior analyst at Navigant indicated that there were roughly 1,000 all-electric medium-duty trucks on US roads in 2014, and at that point in time the segment was projected to reach 2,500-3,500 units a year by 2020 (Lyden, 2014).

NREL has also run models to forecast which areas of the country will have the highest demand for specific types of alternative fuel vehicles, though the analysis is not specific to freight vehicles (Johnson and Hettinger, 2014). Figure 7.3 shows the forecast areas with the highest potential for electric vehicle uptake.

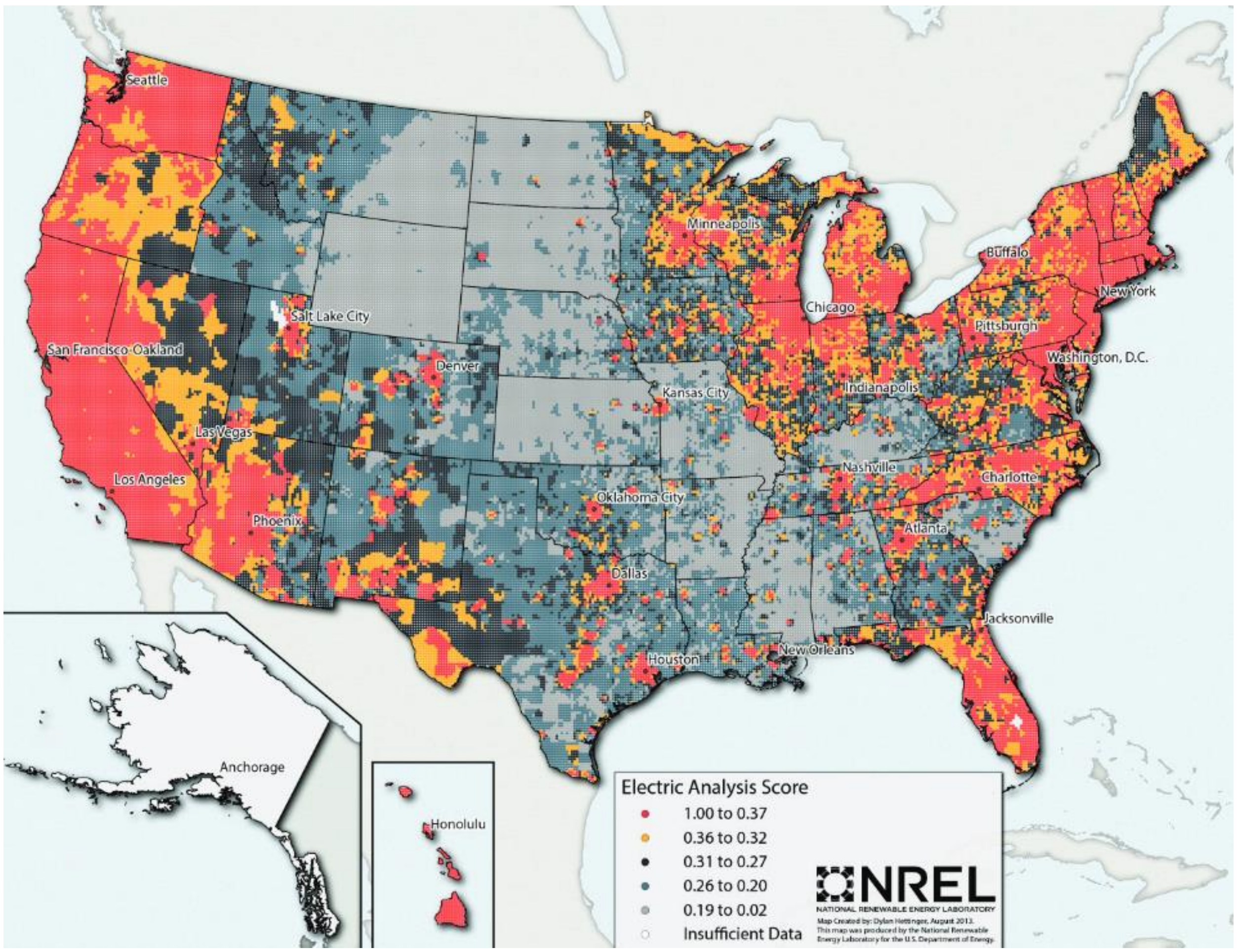


Figure 7.3. Map of most active markets for electric vehicles in the US (Johnson and Hettinger, 2014)

7.3 California Forecasts

A recently released energy forecast by the California Electricity Commission (CEC) includes a stock forecast for medium- and heavy-duty vehicles in California (CEC, 2017). Due to slow turnover of truck stock (every 5-7 years or every 20 years depending on truck vocation), even a high market share for alternative fuel vehicles (AFVs) is expected to result in only modest increases in AFV percentage of vehicle stock over the study horizon (2018-2030) (see Table 7.1). For heavy-duty trucks (class 7-8), diesel is expected to remain the dominant fuel while natural gas is expected to be the dominant AFV type for all policy scenarios with high, mid, or low support for battery vehicles; diesel-electric hybrid trucks are expected to reach significant numbers only in the high case (see Figure 7.4). Battery electric and hybrid truck numbers are expected to grow much more quickly for classes 4-6 with over 50,000 of these vehicles projected to be on-road by 2030 (see Figure 7.5 and note).

Table 7.1. Truck stock forecast (classes 3-8) by fuel type and policy scenario (CEC, 2017)

		2017	2020	2025	2030
High case	Diesel	748,041	852,973	886,491	887,741
	Diesel-Electric Hybrid	2,802	10,449	21,169	41,715
	Electric	1,166	6,690	19,851	42,580
	Ethanol		756	2,639	16,085
	Gasoline	233,183	243,272	245,682	231,347
	Gasoline Hybrid		112	694	5,045
	Natural Gas	9,939	13,164	33,307	61,117
	Propane	1,996	3,156	4,785	5,829
Mid case	Diesel	710,322	757,938	827,310	866,487
	Diesel-Electric Hybrid	1,919	6,665	18,244	32,233
	Electric	1,020	4,207	16,562	29,722
	Ethanol		441	2,707	16,582
	Gasoline	229,129	229,248	235,893	237,505
	Gasoline Hybrid		54	597	3,826
	Natural Gas	9,642	11,919	17,938	29,653
	Propane	1,626	2,349	3,616	4,622
Low case	Diesel	712,314	754,492	823,344	877,244
	Diesel-Electric Hybrid	1,999	6,490	16,707	29,683
	Electric	830	819	1,099	5,085
	Ethanol		323	1,775	10,459
	Gasoline	229,485	231,473	241,053	242,483
	Gasoline Hybrid		99	679	4,429
	Natural Gas	9,658	11,562	15,090	18,664
	Propane	1,672	2,451	3,460	4,174

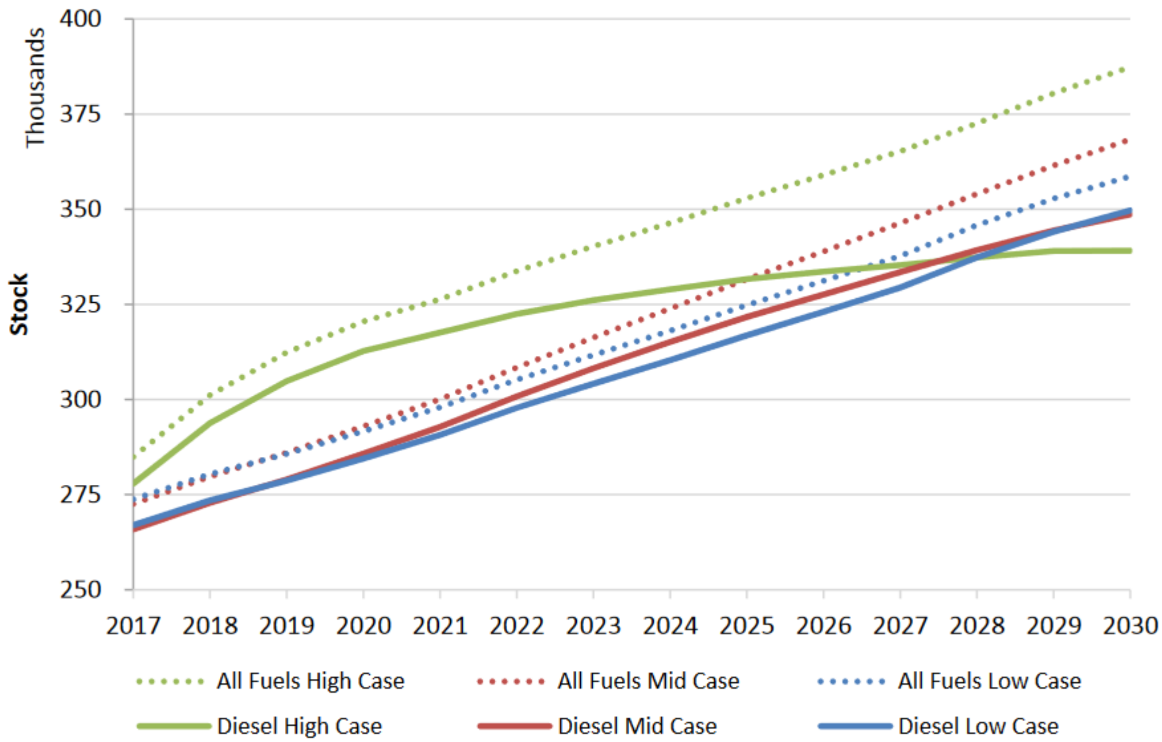


Figure 7.4. Forecast Heavy-duty Truck stock class 7-8 – Diesel and All Fuels (CEC, 2017)

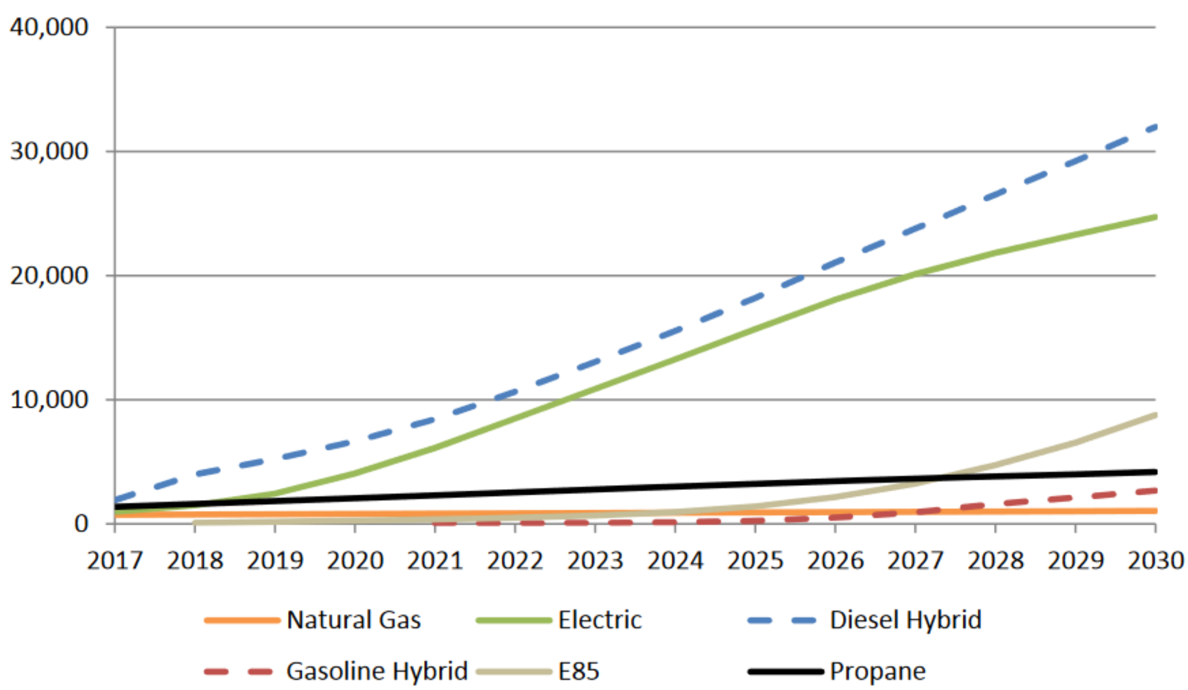


Figure 7.5. Forecast Alternative Fuel Classes 4-6 Truck Stock, mid-case (CEC, 2017). (Compared to approx. 200,000 diesel vehicle stock holding roughly constant over the same time frame. Mid refers to mid-level policy support for plug-in electric vehicles, vs. low or high support.)

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7.4 Battery Cost Forecast

Battery costs make up a large component of electric truck costs. CALSTART's 2012 estimates suggest that a 350 kWh battery system in a drayage truck would comprise nearly 70% of the electric truck's total cost, though this would drop to 44% by 2030 as battery and other costs decline (CALSTART, 2013). Estimates of costs in 2017 covered a wide range, from 180-500 $/kWh (IEA, 2017)(see Table 7.2). As higher volumes of batteries are manufactured and technological improvements are made, costs may eventually fall to the 80-150 $/kWh range (IEA, 2017). A comprehensive review of lithium-ion battery pack costs found that the cost reduction following a cumulative doubling in production of batteries is a 6-9% cost decrease (Nykvist and Nilsson, 2015)(see Figure 7.6). For electric vehicles to be competitive, the cost of batteries will need to fall below $150/kWh (Nykvist and Nilsson, 2015).

Table 7.2. Costs of vehicle batteries reported by various sources (IEA, 2017)

$/kWh	Source
250	(IEA, 2017)
180-200	(Ayre, 2015; Field, 2016; Lambert, 2016)
300	(Slowik et al., 2016)
500	(US DOE, 2017)

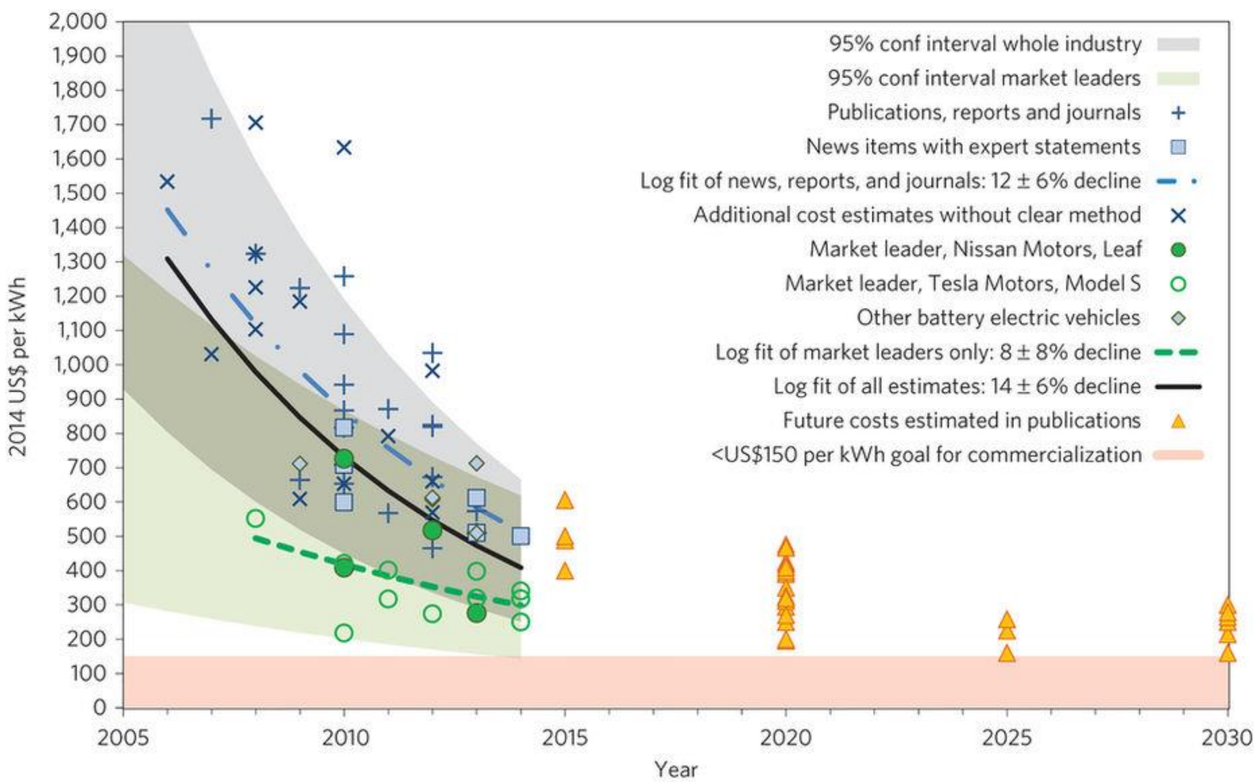

Figure 7.6. Cost of Li-ion battery packs in BEV, from (Nykvist and Nilsson, 2015) (150 $/kWh is considered the threshold for commercial competitiveness)

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