Medium- and Heavy-Duty Electrification in California

Literature Review – Final Report

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In Partnership With:
BYD
Ceres
EarthJustice
Natural Resources Defense Council
NextGen Climate America
Union of Concerned Scientists
Tesla

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Abbreviations and Acronyms

AQIP	Air Quality Improvement Program
ARB	California Air Resources Board
Bcf	Billion cubic feet
BCG	Boston Consulting Group
BEB	Battery electric bus
BET	Battery electric trucks
BEV	battery electric vehicle
BNEF	Bloomberg New Energy Finance
BTE	Brake thermal efficiency
CCFC	California Cleaner Freight Coalition
CI	Carbon intensity
CNG	Compressed natural gas
CO	carbon monoxide
CO_2	Carbon dioxide
CPUC	California Public Utilities Commission
DC	Direct current
EPA	United States Environmental Protection Agency
EPRI	Electric Power Research Institute
ERS	Electrified road systems
EVSE	Electric Vehicle Supply Equipment
FREVUE	Freight Electric Vehicles in Urban Europe
g/bhp-hr	grams per brake horsepower hour
gCO_2/Megajoule	grams of CO2 per Megajoule
GHG	greenhouse gas
GNA	Gladstein, Neandross & Associates
GVWR	gross vehicle weight rating
HD	heavy-duty
HDV	Heavy-duty vehicle
HEV	Hybrid electric vehicle
HGAC	Houston Galveston Area Council
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
ICT	Innovative Clean Transit
IOU	Investor Owened Utility
kWh	kilowatt-hour
L	Liter
LACMTA	Los Angeles County Metropolitan Transportation Authority
LCFS	Low Carbon Fuel Standard
LFP	lithium-iron phosphate

LHF	Low hanging fruit
LMO	lithium-manganese spinel
LTO	lithium titanate
MD	medium-duty
MD/HD	Medium- and heavy-duty
mpgge	Miles per gasoline gallon equivalent
NAAQS	National Ambient Air Quality Standards
NREL	National Renewable Energy Laboratory
NCA	lithium-nickel-cobalt-aluminum
NGV	Natural Gas Vehicle
NMC	lithium-nickel-manganese-cobalt
NO_x	nitrogen oxides
NRDC	Natural Resources Defense Council
O_3	ozone
OEM	original equipment manufacturers
Pb	lead
PEV	plug-in electric vehicle
PG&E	Pacific Gas and Electric
PM10	particulate matter less than 10 microns
PM2.5	particulate matter less than 2.5 microns
RNG	Renewable natural gas
RPS	Renewable Portfolio Standard
SCAQMD	South Coast Air Quality Management District
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SO_2	Sulfur dioxide
SOC	State-of-charge
UC Davis	University of California at Davis
UCS	Union of Concerned Scientists
UPS	United Parcel Services
VMT	vehicle miles traveled
VOCs	volatile organic compounds
Wh/kg	watt-hours/kilogram
ZEV	Zero emission vehicle

Executive Summary

The key messages and findings from the literature review include:

- Medium- and heavy-duty (MD/HD) battery electric vehicle (BEV) technologies are advancing quickly with available models spanning Class 4-6, Class 7-8 and bus applications; Class 7-8 and vocational vehicles, while advancing, are still in the early stages of commercialization.
- The overall cost of MD/HD BEVs are decreasing due to operational efficiencies from increased vehicle production and steady declines in battery costs.
- Batteries are the biggest contributor to BEV cost (upwards of 40%-60%) and the literature agrees that battery costs are decreasing rapidly–faster than anticipated even a few years ago–and will continue to come down in future years.
- Overall MD/HD BEVs have lower operation, maintenance, and fuel costs compared to conventional fueled vehicles, but electrical rate structures must be reviewed closely including time-of-use rates and demand charges to determine the fuel cost savings.
- MD/HD BEVs provide the largest per vehicle opportunity for greenhouse gas (GHG) and criteria pollutant emission reductions compared to conventional vehicles.

Federal and state air quality standards and climate goals, and the subsequent policies and plans to meet the standards, are the driving force behind the implementation of MD/HD BEVs. In response, planned and existing public and private investments in MD/HD truck technology, incentives, and charging infrastructure is in the billions of dollars. Electrified technologies are well positioned to assist in achieving these standards and goals having near-zero (plug-in hybrid electric vehicle, PHEV) or zero tailpipe emissions (full BEV) of criteria pollutants, and electricity has a much lower carbon intensity than conventional fuels. Increasing renewables in the California electricity grid mix is improving the GHG benefits from BEVs.

The purpose of this literature review is to understand the current status of Medium- and Heavy-Duty Electrification technologies, current and forecasted trends in vehicle and battery costs, and the emissions benefits from these technologies. Currently MD/HD BEV technology is best-suited for urban and suburban duty cycles that generally do not exceed 80 to 100 miles of daily range, with the except of transit buses. On-road vehicle vocations that are expected to be more widely deployed in the near-term future include electric transit buses, shuttle buses, delivery trucks, and drayage trucks. Other vocations that have the potential for increased deployment include refuse trucks, terminal tractors, and school buses with Class 7-8 short-haul and long-haul trucks still in the demonstration stage. In 2015, the California Air Resources Board (CARB) and other sources predicted widespread implementation of Class 4-6 trucks in the next five to 10 years. Adoption across all Class 7-8 duty cycles will take longer as issues related to vehicle range and battery weight are resolved.

The costs of MD/HD BEVs have been declining with decreased battery costs and lower MD/HD manufacturing costs from increased demand. When Proterra began selling buses, they initially cost $1.2 million per bus in 2010, which then dropped to $900,000 per bus three years later, and now they are currently $750,000 per bus. According to a study by Bloomberg New Energy Finance (BNEF) conducted in 2017, light-duty battery prices are $209 per kWh, which is down by 24% from just a year prior. CARB echoes this, stating that battery costs have decreased 20% to 35% per year since 2012,[1] and the Boston Consulting Group (BCG) notes that battery prices have dropped about 20% per year since 2009.[2] BNEF forecasts that battery prices will keep falling to $73 per kWh by 2030.

A trend in charging for MD/HD is the development of standards (like J3068), that allow third party charger manufacturers to produce the chargers that will be compatible with all vehicle manufacturers. This allows for higher load chargers to become commercialized faster, subsequently commoditized, and eventually yielding lower per unit costs.

On a life cycle basis, MD/HD BEVs demonstrate both GHG and criteria pollutant and air toxics emissions reductions compared to conventional natural gas and diesel vehicles. BEVs are zero-emission when referring to tailpipe emissions. Emissions associated with producing electricity can also be zero using renewable energy.[3] In addition, low carbon emission fuels, such as renewable natural gas (RNG) and renewable diesel are able to reduce GHG emissions. Based on the models evaluated in this literature review, it can be concluded that significant reductions in MD/HD vehicle emissions require time and aggressive BEV and low emission vehicle deployment strategies. An electricity grid that is increasingly powered by renewable energy sources will increase the emissions impact from the deployment of BEVs.

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[1] Curry, C., *Lithium-Ion Battery Costs and Market,* presentation, 2017.

[2] Boston Consulting Group (BCG), *The Electric Car Tipping Point*, presentation, 2017a.

[3] CARB, *Draft Technology Assessment: Medium- and Heavy-Duty Fuel Cell Electric Vehicles*, November 2015f.

I. Purpose

The purpose of this literature review is to understand the current status of Medium- and Heavy-Duty Electrification technologies, current and forecasted trends in vehicle and battery costs, and the emissions benefits from these technologies. The literature review is divided into the following sections:

- Vehicle Technology Status and Cost
- Battery Technology Status and Cost
- Charging Technology Status and Cost
- Emissions

The background section will review regulations and policies that are driving MD/HD electrification and investments being made to advance and implement the technologies.

II. Background

Requirements to meet Federal and State regulations are the main driving forces to transform the MD/HD trucking industry in California. The two main regulatory drivers are the Federal National Ambient Air Quality Standards (NAAQS) regulating criteria pollutant emissions and California’s GHG emission reduction regulations which includes the Global Warming Solutions Act or Assembly Bill 32 (AB) 32, Senate Bill (SB) 32 (2016), and Executive Order S-3-05.

In South Coast and San Joaquin, the South Coast Air Quality Management District (SCAQMD) and San Joaquin Valley Air Pollution Control District (Valley Air District), combined with CARB, are the lead agencies administering NAAQS programs. CARB solely administers AB32 programs.

California’s Senate Bill 350 (SB 350) set an aggressive target of 40% GHG emission reductions from 1990 levels by 2030 to be achieved in part through widespread transportation electrification. The regulations, and resulting plans and public and private economic investments are discussed in the following sections.

1. Regulations and Plans

National Ambient Air Quality Standards - Criteria Pollutants

The Federal Government sets NAAQS for six different criteria pollutants: carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO2), particulate matter less than 10 microns in diameter and 2.5 microns in diameter (PM10 and PM 2.5), ozone (O_3) and sulfur oxides (SOx). SCAQMD and Valley Air District are currently in extreme non-attainment of the eight (8) hour ozone standard and in non-attainment for the 24 hour PM2.5 standard. Between O_3 and PM2.5, the ozone standard is the main driver of regulatory policies and plans because the reductions required to meet the 2023 and 2031 standards are so dramatic (Table II-1).

Table II-1. NAAQS Classification and Latest Attainment Year for SCAQMD and Valley Air District

Standard	Concentration	Nonattainment Classification	Latest Attainment Year[4]
2008 8-hr Ozone	75 ppb	Extreme	2032
1997 8-hr Ozone	80 ppb	Extreme	2023
2006 24-hr PM2.5	35 µg/m3	Serious	2019

SCAQMD and Valley Air District are planning to achieve significant ozone and PM2.5 reductions through reductions in NOx emissions. South Coast will require a 67% reduction in NOx emissions from current levels to achieve the 2023 standard and 75% to achieve the 2031 standard. Valley Air District will require a 50% reduction to achieve the 2023 standard and 60% to achieve the 2031 standard. Figure II-1 below shows the total tons per day of NOx emissions, the sources of these emissions, and the emission levels required to meet the 2023 and 2031 standards for both SCAQMD and Valley Air District. It will be difficult to meet the current standard by 2023 and near impossible to meet the future standard without significant reductions.

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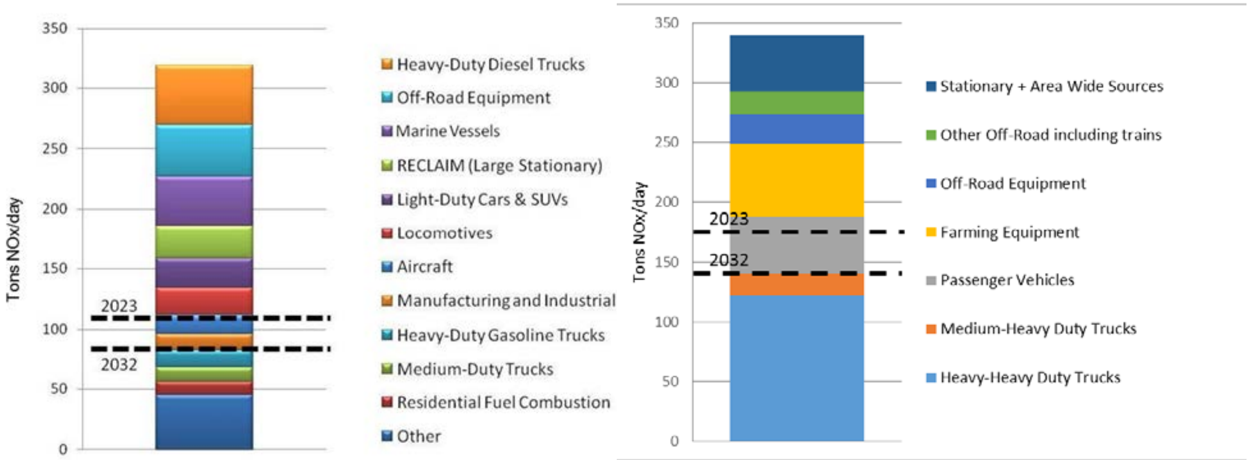
[4] SCAQMD, *Final 2016 Air Quality Management Plan*, March 2017. Available online at: http://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan/final-2016-aqmp

Figure II-1. SCAQMD and Valley Air District NOx Emissions by Source[5,6]



SCAQMD Emissions Inventory

Valley Air District Emissions Inventory

On-road emissions from MD/HD trucks constitute a significant portion of the NOx emissions and show how important criteria pollutant reductions in the goods movement and freight sectors are for achieving the ambient ozone standards.

The health impacts from on-road combustion emissions are an environmental justice issue since many of main trucking and distribution routes go through or are adjacent to disadvantaged communities. When specifically looking at the Ports of Los Angeles and Long Beach, zero emission technologies supplemented by near-zero tailpipe emission technologies for combustion engines (e.g., drayage trucks at ports) will be needed to reach targets. Transportation electrification, especially of the MD/HD sectors can directly affect the health outcomes in the South Coast Air Basin and San Joaquin Valley because both of these regions are heavily impacted by transportation through and within their areas. In fact

> 30% of the PM2.5 emissions in the South Coast Air Basin are attributable to transportation–related activities (on-road, other mobile, and Port emissions), about 85% of the NOx emissions, and over 95% of the diesel particle matter across the Basin.[7]

California GHG Regulations

Assembly Bill 32, signed by Governor Schwarzenegger in 2006, looks to achieve 1990 GHG emission levels by 2020, a reduction of approximately 15% below emissions expected under a business as usual scenario. In addition, Governor Schwarzenegger's Executive Order S-3-05

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[5] SCAQMD Technology Advancement Office Clean Fuels Program, *2013 Annual Report and 2014 Plan Update*, March 2014. Available online at: http://www.aqmd.gov/docs/default-source/Agendas/Governing-Board/2014/2014-mar7-029.pdf

[6] Data from: San Joaquin Valley Air Pollution Control District, *2016 Plan for the 2008 8-Hour Ozone Standard, Appendix B, Emissions Inventory*, June 16, 2016. Available online at : http://www.valleyair.org/air_quality_plans/Ozone-Plan-2016/b.pdf

[7] Martinez, A. and O'Dea, J. Opening Testimony of Jimmy O'Dea on Behalf of Union of Concerned Scientists and Testimony of Michelle Hasson, Ericka Flores, Taylor Thomas, Angelo Logan, and Ed Avol on Behalf of Center for Community Action and Environmental Justice and East Yard Communities for Environmental Justice on Medium and Heavy-Duty and Fleet Charging Infrastructure and Commercial EV Rates.

calls for all sectors to reduce GHGs by 80% by 2050 and SB 32[8] established the 2030 GHG reduction of 40% below 1990 levels. The following set of AB 32 and complementary climate change inspired policies comprise the main climate change regulatory drivers:

- Cap-and-Trade – Emissions from various sectors of the economy are capped and the reductions can be traded via allowances
- Low Carbon Fuel Standard (LCFS) – Reduces the carbon intensity of transportation fuels by 10% by 2020 using a market based credit trading system
- Senate Bill 375 (SB375): Sustainable Community Strategies – Reduces the vehicle miles traveled (VMT) from light-duty vehicles through land use planning
- Advanced Clean Cars Program – Includes the ZEV Program and complementary fuel efficiency programs to reduce fuel consumption and GHG emissions from light-duty vehicles
- Renewable Portfolio Standard (RPS) – Sets a standard of 20% renewables for power generation and 33% renewable electricity by 2020. SB350 increased the renewable electricity share to 50% by 2030.
- Multiple energy efficiency and conservation measures including SB350[9] which requires the California Public Utilities Commission (CPUC) to focus energy procurement decisions on reducing GHGs by 40% by 2030 including efforts to double energy efficiency and promote transportation electrification.

While the 2030 and 2050 goals are very challenging, there are a variety of alternative fuels and technologies in the transportation sector to help achieve the GHG reduction levels:

- Alternative Technology Fuels: Electricity, renewable natural gas, and hydrogen
- Biofuels/Liquid Fuels: Biodiesel, renewable diesel, low carbon ethanol
- Technologies: hybridization of conventional fuel vehicles

ZEV and Sustainable Freight Action Plans

Governor Brown has been an advocate for zero emission technologies and through multiple Executive Orders, has mobilized State agencies to use incentives, plans and policies to advance the use of zero emission technologies. Two of the major actions spurred by Executive Orders are the ZEV and Sustainable Freight Action Plans.

In 2012 Governor Brown signed Executive Order B-16-12 to direct the state government to help accelerate the market for ZEVs. This led to the 2013 ZEV Action Plan and the updated 2016 ZEV Action Plan. The 2016 ZEV Action Plan included a priority for making ZEV technologies commercially viable in targeted applications for the MD/HD and freight sectors. The ZEV Action Plan specifically highlights transforming shuttle buses to zero emission, establish a clearinghouse website for MD/HD vehicles and equipment, and increase awareness of ZEVs and incentive programs.[10]

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[8] California Legislature, SB-32: California Global Warming Solutions Act of 2006: Emissions Limit, September 8, 2016. Available online at: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32

[9] California Energy Commission, Clean Energy & Pollution Reduction Act: SB 350 Overview, http://www.energy.ca.gov/sb350/. Accessed February 23, 2018.

[10] Office of Governor Edmund G. Brown Jr., Governor's Interagency Working Group on Zero-Emission Vehicles, 2016 ZEV Action Plan, October 2016. Available online at: https://www.gov.ca.gov/wp-content/uploads/2017/09/2016_ZEV_Action_Plan.pdf

The process that developed the Sustainable Freight Action Plan[11] was started with Governor Brown's Executive Order B-32-15. The plan was developed to support the State's economic goals in the coming decades while also reducing harmful pollution. As shown in Figure II-1 freight transportation generates a large portion of the local pollutants. The development of the plan brought together seven different state agencies intended to integrate investments, policies, and programs across the State. This included setting a target to transition to zero emission technologies. The Plan's zero emission technology target is: "Deploy over 100,000 freight vehicles and equipment capable of zero emission operation and maximize near-zero emission freight vehicles and equipment powered by renewable energy by 2030." The Ports of Los Angeles and Long Beach new Clean Air Action Plan, released July 2017, builds on the Sustainable Freight Plan and calls for replacing diesel trucks and cargo equipment with zero-emissions technology over the next two decades.[12]

2. Investments in MD/HD Electrification

The following sections summarize the multi-billion dollar investments that are being made by the State of California, vehicle manufacturers and private companies, and California Investor Owned Utilities (IOUs) to promote and advance MD/HD ZEVs.

Public Investment

The State of California, through multiple policies, has a significant amount of public funding available for MD/HD ZEVs. Table II-2 shows the public funding available through the programs listed below for the 2017-2018 fiscal year that total over $400 million:

- Low Carbon Transportation[13]
- Air Quality Improvement Program (AQIP) [14]
- Warehouse Program[15]

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[11] Governor Edmund G. Brown, Jr., California Sustainable Freight Action Plan, July 2016. Available online at: http://www.casustainablefreight.org/documents/PlanElements/Main%20Document_FINAL_07272016.pdf

[12] Barboza, T. "Plan calls for L.A., Long Beach ports to go to zero-emissions technology; cost could hit $14 billion," Los Angeles Times, July 19, 2017. Available online at: http://www.latimes.com/local/lanow/la-me-ports-clean-air-20170719-story.html

[13] Low Carbon Transportation investments funded with Cap-and-Trade Auction Proceeds appropriated to CARB in Assembly Bill (AB) 134 (Committee on Budget, Chapter 254, Statutes of 2017).

[14] Air Quality Improvement Program (AQIP) appropriated to CARB in AB 97 (Ting, Chapter 14, Statutes of 2017), the Budget Act of 2017.

[15] New Zero- and Near Zero-Emission Warehouse Program appropriated to CARB in Senate Bill (SB) 132 (Committee on Budget and Fiscal Review, Chapter 7, Statutes of 2017).

Table II-2. MD/HD Proposed Fiscal Year 2017-2018 Funding for Clean Transportation Initiatives[16]

Project	Low Carbon Transportation	AQIP	Warehouse Program	Total
Rural School Bus Pilot	$10M			$10M
Zero- and Near Zero-Emission Freight Facilities (including warehouses)	$100M		$50M	$150M
Zero-Emission Off-Road Freight Voucher Incentive Project	$40M			$40M
Clean Truck and Bus Vouchers (HVIP + Low NOx Engine Incentives)	$180	$8M		$188M
Truck Loan Assistance Program		$20M		$20M
Total	$330M	$28M	$50M	$408M

From Fiscal Year 2013-2014 to 2017-2018, the Low Carbon Transportation Program has appropriations of over $1.25 billion. The VW Settlement will also provide a source of funding for future fiscal years include proceeds from the VW settlement.[17] In addition, the Ports of Los Angeles and Long Beach new Clean Air Action Plan discussed above will cost approximately $8-14 billion for the next two decades from both public and private investment.[18] There are other local and state programs that could be sources of funding including the Carl Moyer Program (funded with around $60 million/yr)[19].

Private and Vehicle Manufacturer Investment

In addition to public funds, individual vehicle manufacturers have been making or are planning significant private investments for MD/HD ZEVs. Worldwide, carmakers (including light-, medium- and heavy-duty) are expected to invest at least $90 billion in electric vehicles.[20] Table II-3 highlights many of the significant planned vehicle manufacturer and battery production investments. This does not include significant investments that have already been made by established MD/HD ZEV manufacturers such as BYD, Proterra, Zenith, and Motiv.

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[16] CARB, *Proposed Fiscal Year 2017-18 Funding Plan for Clean Transportation Incentives*, November 9, 2017. Available online at: https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_1718_funding_plan_final.pdf

[17] CARB, Volkswagen Settlement – California ZEV Investments, https://www.arb.ca.gov/msprog/vw_info/vsi/vw-zevinvest/vw-zevinvest.htm. Accessed February 23, 2018.

[18] Barboza, 2017

[19] CARB, Carl Moyer Program Guidelines, https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm. February 23, 2018.

[20] Lienert, P., "Global carmakers to invest at least $90 billion in electric vehicles," Reuters, January 15, 2018. Available online at: https://www.reuters.com/article/us-autoshow-detroit-electric/global-carmakers-to-invest-at-least-90-billion-in-electric-vehicles-idUSKBN1F42NW

Table II-3. Private/Vehicle Manufacturer Planned Investment

Company/Vehicle Manufacturer	Investment in MD/HD	Other ZEV Investments
Daimler	€2.6 Billion[21]	
Volkswagen	$1.7 Billion[22]	
Chanje/Hong Kong FDG	$1 Billion[23]	
Cummins	$500 Million[24]	
Proterra		$195 Million in Private Investments to expand production[25]
Nikola	$1 Billion Fuel Cell Truck Factory[26]	
Tesla and Partners		$4-5 Billion Gigafactory[27]

IOU Investment

As part of SB350, the California IOUs submitted proposals to the CPUC for transportation electrification projects. The utilities' programs totaled over $1billion. Table II-4 shows the proposed investments that could directly affect MD/HD ZEVs of over $800 million. The public direct current (DC) fast charging is included because MD/HD ZEVs could also utilize this infrastructure.

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[21] Reuters Staff, "Daimler to invest 2.6 billion euros in trucks division by 2019," Reuters, February 21, 2018. Available online at: https://www.reuters.com/article/us-daimler-trucks-electrification/daimler-to-invest-2-6-billion-euros-in-trucks-division-by-2019-idUSKCN1G51FM

[22] Graham, K., "Volkswagen to invest $1.7 billion in electric truck technology," Digital Journal, October 11, 2017. Available online at: http://www.digitaljournal.com/business/volkswagen-to-invest-1-7-billion-in-electric-truck-technology/article/504781

[23] Lambert, F., "A new startup launches a commercial all-electric van in the US," Electrek, August 10, 2017. Available online at: https://electrek.co/2017/08/10/commercial-all-electric-truck-us-chanje/

[24] Lazo-Cruz, J. "Cummins Chooses India to Invest $500 million to Develop Electric Powertrain Manufacturing," Green Optimist, February 20, 2018. Available online at: https://www.greenoptimistic.com/cummins-india-electric-powertrain-manufacturing-20180219/

[25] Proterra, "Proterra Closes $55 Million Series 6 with Generation Investment Management LLP and BMW i Ventures," June 13, 2017. Available online at: https://www.proterra.com/press-release/proterra-closes-55-million-series-6-with-generation-investment-management-llp-and-bmw-i-ventures/

[26] Hirsch, J., "Nikola Plans $1 Billion Arizona Fuel Cell Truck Factory," Trucks.com, January 30, 2018. Available online at: https://www.trucks.com/2018/01/30/nikola-plans-arizona-truck-factory/

[27] Tesla, Gigafactory slide deck. Available online at: https://www.tesla.com/sites/default/files/blog_attachments/gigafactory.pdf

Table II-4. IOU Planned Investment[28]

California IOU	MD/HD Infrastructure	Off Road Infrastructure	Public DC Fast Charging	Rate Design Proposals
Pacific Gas and Electric (PG&E)	MD/HD Fleet - $3.4M	Idle-Reduction Technology - $1.7M	Fast Charge Infrastructure - $22M	-
	Electric School Bus Renewables Integration - $2.2M			
	FleetReady Make-Ready - $210M			
San Diego Gas and Electric (SDG&E)	Fleet Delivery Services - $3.7M	MD/HD and Forklift Port Electrification - $2.4M	Electrify Local Highways	Commercial Grid Integration Rate
	MD/HD EV Charging Infrastructure Program - $152M[29]			
Southern California Edison (SCE)	Transit Bus Make-Ready and Rebate - $4M	Port of LB ITS Terminal Yard Tractor - $0.5M	Urban DC Fast Charger Clusters - $4M	Commercial EV Rate
	MD/HD Charging Infrastructure - $554M			

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[28] CPUC, Summary of IOU Investments, http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442455419. Accessed on February 23, 2018.

[29] SDG&E, Application for Approval of Senate Bill 350 Transportation Electrification Proposals Regarding Medium and Heavy-Duty Electric Vehicles and a Vehicle-to-Grid Pilot, January 2018.

III. Vehicle Technology

1. Vehicle Technology Status

ICF reviewed 31 resources that assess the current and future ability of vehicle electrification to meet the needs of the MD/HD vehicle sectors. In particular, these resources discussed the status of MD/HD electrification, as well as successes of the technology and any barriers it must overcome. The commercialization status of vehicle electrification varies significantly across MD/HD vehicle classes due to the wide array of vocations and vehicle platforms.[30] MD/HD vehicle manufacturers face issues with suppliers charging high prices, as often they would rather sell to high volume customers. In addition, it takes a significant amount of time, effort, and money for manufacturers to certify these new vehicles to federal and state regulations which can especially be cumbersome for small volume vehicle manufacturers.[31] As such, it can be challenging for original equipment manufacturers (OEMs) to increase production capacity and economies of scale.[30]

A majority of the BEVs currently on the market are best-suited for urban and suburban duty cycles that generally do not exceed 100 miles of daily range.[32,33] However, even this relatively limited range can cover a significant portion of people and goods movement needs. In 2007, 40% of the goods moved in the United States traveled less than 100 miles.[34] Urban and suburban transit and school bus routes also typically fall within this range. Longer range battery electric trucks with ranges upwards of 200 miles are not far behind; Tesla released the prototype for its battery electric semi-truck in late 2017 and Daimler is expecting to have a long range battery electric truck on the U.S. market by 2020.[35,36] Table III-1 and Table III-2 show the commercialization status and characteristics of some of the service, goods movement, and people movement vehicle vocations.[34] On-road vehicle vocations that are expected to be more widely deployed in the near term include electric transit buses, shuttle buses, delivery trucks, and drayage trucks. Other vocations that have the potential for increased deployment include refuse trucks, terminal tractors, and school buses.[37,38]

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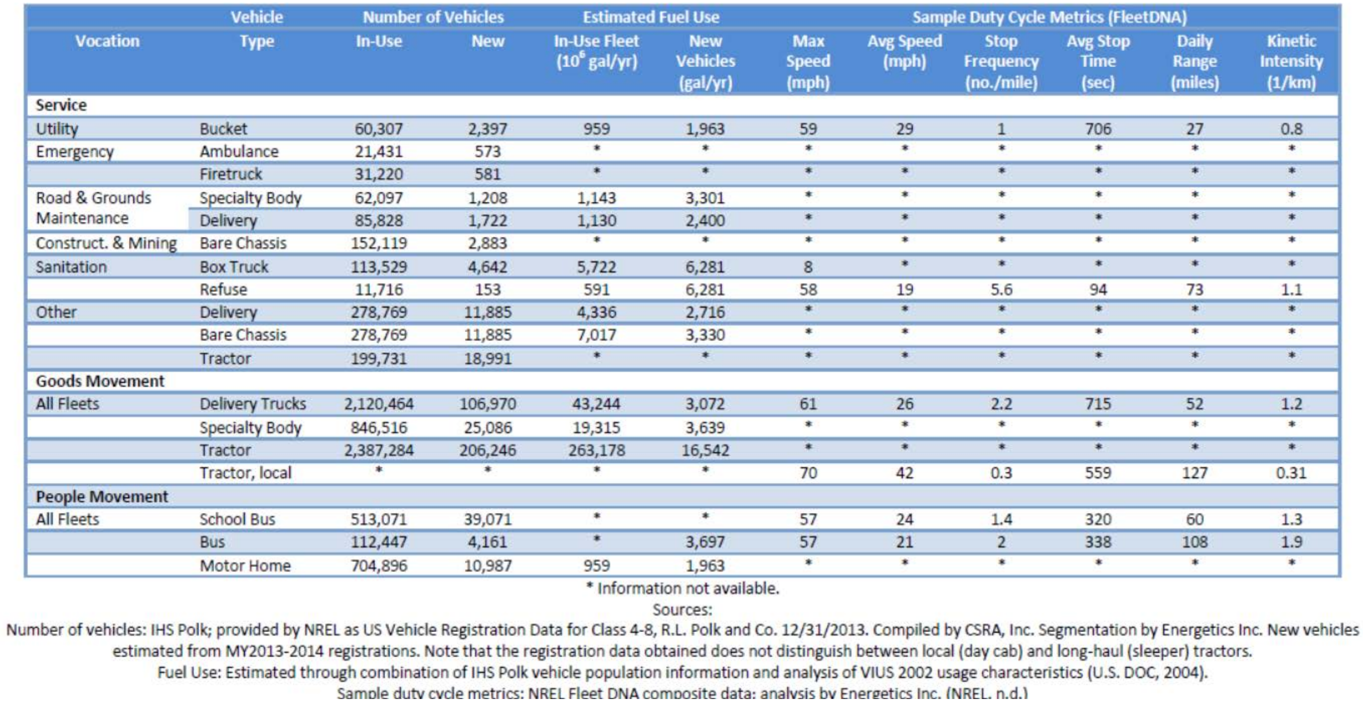
[30] CARB, *Draft Technology Assessment: Heavy-Duty Hybrid Vehicles*, November 2015e.
[31] U. Nagrani, Motiv, personal communication, February 7, 2018.
[32] Birky. A., M. Laughlin, K. Tartaglia, R. Price, and Z. Lin, *Transportation Electrification Beyond Light Duty: Technology and Market Assessment*, Energetics Incorporated, prepared for Oak Ridge National Laboratory, 2017.
[33] Moultak, M., Lutsey, N., and Hall D., *Transitioning to Zero-Emission Heavy-Duty Freight Vehicles,* 2017. International Council on Clean Transportation
[34] Birky et al., 2017
[35] Moultak, M., Lutsey, N., and Hall D., 2017
[36] Tyggestad, C., N. Sharma, J. van de Staaij, and A. Keizer, *New Reality: Electric Trucks and their Implications on Energy Demand*, McKinsey Energy Institute, 2017.
[37] Chandler, S., J. Espino, and J. O'Dea, *Delivering Opportunity: How Electric Buses and Trucks Can Create Jobs and Improve Public Health in California*, Union of Concerned Scientists and The Greenlining, Institute, 2017.
[38] Moultak, M., Lutsey, N., and Hall D., 2017

Table III-1. Commercialization Status of Various MD/HD Electric Vehicles

Commercialization Status	Vehicle Category
Commercially Available	Transit Bus
Limited Commercial Availability	Shuttle Bus, Delivery Truck, School Bus, Refuse Truck, Terminal Tractor, Drayage Truck
Demonstration/Prototype	Long-Haul Freight

Table III-2. U.S. Highway Vehicle Data and Characteristics[39]



	Vehicle	Number of Vehicles		Estimated Fuel Use		Sample Duty Cycle Metrics (FleetDNA)					
Vocation	Type	In-Use	New	In-Use Fleet (10^6 gal/yr)	New Vehicles (gal/yr)	Max Speed (mph)	Avg Speed (mph)	Stop Frequency (no./mile)	Avg Stop Time (sec)	Daily Range (miles)	Kinetic Intensity (1/km)
Service											
Utility	Bucket	60,307	2,397	959	1,963	59	29	1	706	27	0.8
Emergency	Ambulance	21,431	573	*	*	*	*	*	*	*	*
	Firetruck	31,220	581	*	*	*	*	*	*	*	*
Road & Grounds Maintenance	Specialty Body	62,097	1,208	1,143	3,301	*	*	*	*	*	*
	Delivery	85,828	1,722	1,130	2,400	*	*	*	*	*	*
Construct. & Mining	Bare Chassis	152,119	2,883	*	*	*	*	*	*	*	*
Sanitation	Box Truck	113,529	4,642	5,722	6,281	8	*	*	*	*	*
	Refuse	11,716	153	591	6,281	58	19	5.6	94	73	1.1
Other	Delivery	278,769	11,885	4,336	2,716	*	*	*	*	*	*
	Bare Chassis	278,769	11,885	7,017	3,330	*	*	*	*	*	*
	Tractor	199,731	18,991	*	*	*	*	*	*	*	*
Goods Movement											
All Fleets	Delivery Trucks	2,120,464	106,970	43,244	3,072	61	26	2.2	715	52	1.2
	Specialty Body	846,516	25,086	19,315	3,639	*	*	*	*	*	*
	Tractor	2,387,284	206,246	263,178	16,542	*	*	*	*	*	*
	Tractor, local	*	*	*	*	70	42	0.3	559	127	0.31
People Movement											
All Fleets	School Bus	513,071	39,071	*	*	57	24	1.4	320	60	1.3
	Bus	112,447	4,161	*	3,697	57	21	2	338	108	1.9
	Motor Home	704,896	10,987	959	1,963	*	*	*	*	*	*

* Information not available.

Sources:

Number of vehicles: IHS Polk; provided by NREL as US Vehicle Registration Data for Class 4-8, R.L. Polk and Co. 12/31/2013. Compiled by CSRA, Inc. Segmentation by Energetics Inc. New vehicles estimated from MY2013-2014 registrations. Note that the registration data obtained does not distinguish between local (day cab) and long-haul (sleeper) tractors.

Fuel Use: Estimated through combination of IHS Polk vehicle population information and analysis of VIUS 2002 usage characteristics (U.S. DOC, 2004).

Sample duty cycle metrics: NREL Fleet DNA composite data; analysis by Energetics Inc. (NREL, n.d.)

Heavy-duty, long-haul electrification faces challenges with battery weight and size, as well as vehicle range.[40,41] That said, battery technology is advancing quickly, with energy density increasing, resulting in lower overall battery weight.[42]

It is expected that the increased PEV deployment will yield a corresponding increase in demand for electricity (Figure III-1). One estimate predicts that electricity supply in the United States will have to increase by 5% in 2030 and 13% in 2050 to support PEVs. This estimate does include light-duty, MD/HD and off-road transportation electrification sectors and aggressive assumptions of light-duty vehicle sales market share reaching 50% around 2030 and leveling off at 67% in 2045.[43] However, as PEVs become more efficient, the electricity consumption per vehicle will decrease (Figure III-2).[44]

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[39] Birky et al, 2017

[40] CARB, *Draft Technology Assessment: Medium- and Heavy-Duty Fuel Cell Electric Vehicles*, November 2015f.

[41] CARB, *Technology Assessment: Freight Locomotives*, November 2016.

[42] CARB, *California's Advanced Clean Cars Midterm Review: Summary Report for the Technical Analysis of the Light Duty Vehicle Standards*, 2017a.

[43] Electric Power Research Institute (EPRI) and Natural Resources Defense Council (NRDC), *Electrifying Transportation Reduces Greenhouse Gases and Improves Air Quality*, 2015

[44] EPRI and NRDC, 2015.

Figure III-1. On-road vehicle electricity consumption from 2015-2050[45]

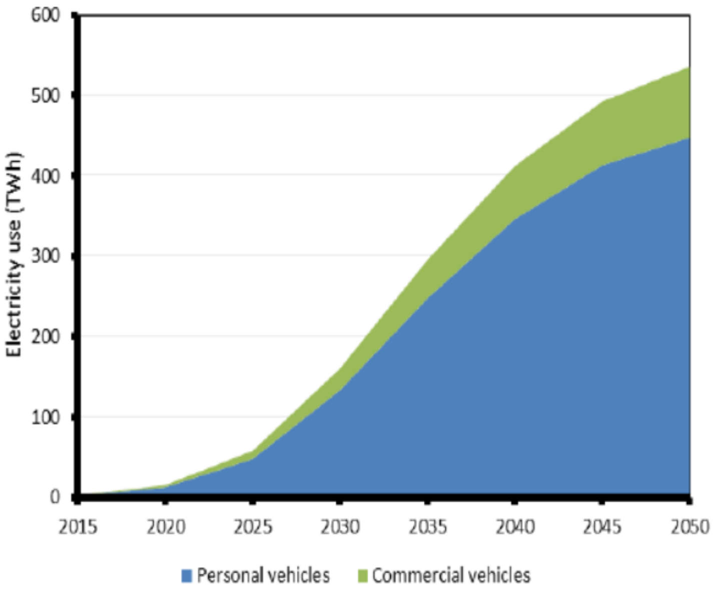
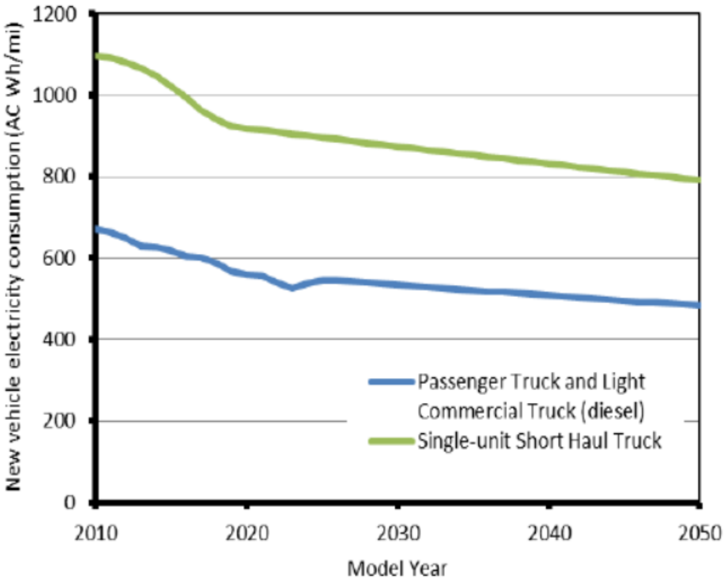


Figure III-2. Electricity consumption of MD/HD vehicles from 2015-2050



To evaluate the potential improvements in MD/HD PEV technology, NREL's Electrification Futures Study developed three scenarios—Slow Advancement, Moderate Advancement, and Rapid Advancement—to project changes in technology from 2020 through 2050. Given the uncertainty of PEV technology advancement, it should be noted that these scenarios are not intended to predict future MD/HD technology advancement, but rather to investigate the various technology advancement pathways that are plausible.

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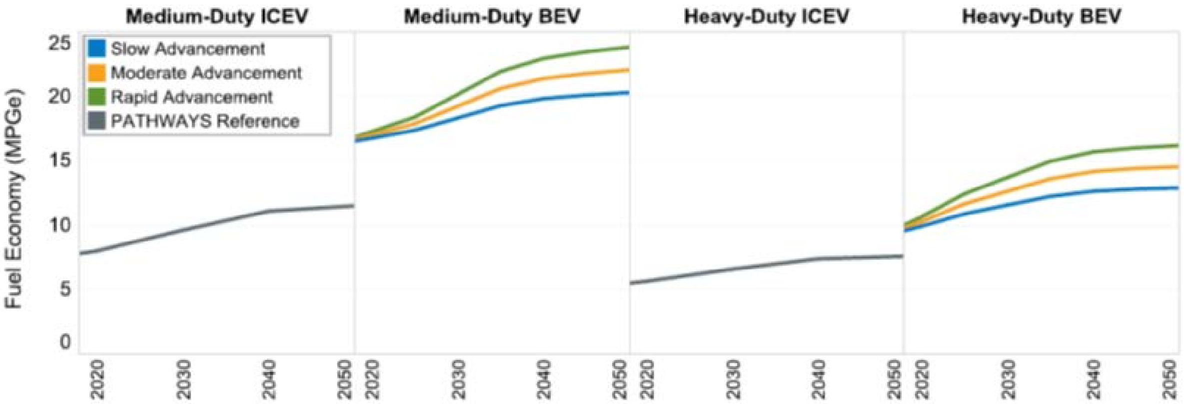
[45] EPRI and NRDC, 2015

- The Slow advancement case, which was developed using the U.S. Energy Information Administration's reference case in the Annual Energy Outlook 2017, assumes a business-as-usual trajectory for MD/HD PEV technology with no major advancements.
- The Moderate Advancement case assumes more quickly advancing technology advancement than the Slow Advancement technology scenario due to research and development (R&D) and additional innovations.
- The Rapid Advancement case assumes public and private R&D, increased efficiency in MD/HD manufacturing, increased demand for MD/HD electrification, and policies that support MD/HD commercial penetration.

Figure III-3 shows NREL's projections based on these three scenarios.[46]

Figure III-3. NREL Projections for MD/HD Vehicle Fuel Efficiency through 2050[47]



For combustion engine technologies, including lower NOx natural gas and diesel engines, additional emissions reductions will be necessary to meet California's emissions goals. The extent to which the advancing lower NOx natural gas and diesel engine technologies will impact MD/HD electrification varies depending on the rate at which BEV technology progresses. It is expected that, as regulations become more stringent, the gap in greenhouse gas emissions between conventional and plug-in electric vehicles may narrow, though a large gap will remain. MD/HD PEVs are considered to be anywhere from two to eight times more efficient than their conventional diesel and natural gas counterparts.[48,49,50,51] Additionally, PEVs require less upkeep as the battery and electric motor do not need regular maintenance. Moreover,

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[46] Jadun, P., C. McMillan, D. Steinberg, M. Muratori, L. Vimmerstedt, and T. Mai, Electrification Futures Study: End-Use Technology Cost and Performance Projections through 2050, NREL, 2017.
[47] Jadun et al., 2017
[48] Chandler et al., 2017
[49] CARB, *Innovative Clean Transit*, 2017b.
[50] Eudy, L. and M. Jeffers, *Foothill Transit Battery Electric Bus Demonstration Results: Second Report*, National Renewable Energy Laboratory (NREL), 2017.
[51] CARB, *Analyses Supporting the Addition or Revision of Energy Economy Ratio Values for the Proposed LCFS Amendments, 2018.*

regenerative braking reduces the need for brake maintenance and there are fewer engine fluids to change.[52]

1.1 Battery Electric Buses

Transit Buses

Of the MD/HD vehicle vocations, battery electric buses (BEBs) are the most widely deployed.[54,53] Battery electric transit buses are well-suited for electrification, as they run the same or similar routes daily, have a high stop frequency, operate at low speeds, cover short distances, and are capable of being centrally fueled.[54] Over 135 BEBs have been successfully deployed in the State of California alone, with about 386,000 deployed worldwide--over 80% of which were deployed in China. [53,55,56] BYD alone deployed 14,000 electric buses last year and has cumulatively deployed over 40,000 buses worldwide.[57] However, according to the American Public Transit Association, only 0.1% of transit buses in the United States are fully electric, while 17.5% are hybrid electric.[58] Many of the BEB demonstrations in California have concluded that battery electric transit buses can meet or even exceed the specifications needed for the buses to be deployed in daily operations. Compared to conventional diesel buses or natural gas buses, they have been shown to have comparable acceleration times, gradeability, and reliability.[59,60]

Transit buses have the advantage of longer idle times both on and in-between routes compared to other MD/HD vehicle vocations. They are also typically stationed in a central location overnight, which affords BEBs ample time to recharge. Average charge times range from 10 minutes to 5 hours depending on the vehicle's battery capacity and the power output of the electric vehicle supply equipment (EVSE). The charging method will vary based on the transit bus route and model. For example, Proterra's 40-foot transit bus model with a 100 kWh battery pack can travel up to 50 miles per charge and takes only about 10 minutes for a full charge using a 500 kilowatt (kW) overhead DC fast charger.[54] National Renewable Energy Laboratory's (NREL's) Proterra demonstration cited an average charge time of seven minutes.[60] When deployed, this model typically charges at the end of its route using an overhead inductive DC fast charger. The BYD 40-foot transit bus model, on the other hand, can travel up to 155 miles on a single charge due to its larger battery pack but, as a result, can take from two to five hours to charge depending on the EVSE power output. This BEB model is typically charged overnight at the transit depot using a conductive charger with a lower power output.[60]

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[52] CARB, *Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses*, October 2015d.

[53] Dixon, T., "China 100% Electric Bus Sales Drop to ~89,546 in 2017," January 25, 2018. Available online at: https://evobsession.com/china-100-electric-bus-sales-drop-to-89546-in-2017/

[54] CARB, 2015d

[55] California HVIP, Program Numbers, https://www.californiahvip.org/tools-results/#program-numbers. Accessed February 23, 2018.

[56] Energy Times, "Half of World's City Buses Electric by 2025," February 6, 2018. Available online at: http://www.theenergytimes.com/new-utility-business/half-worlds-city-buses-electric-2025

[57] R. Schenker, BYD, personal communication, April 5, 2018.

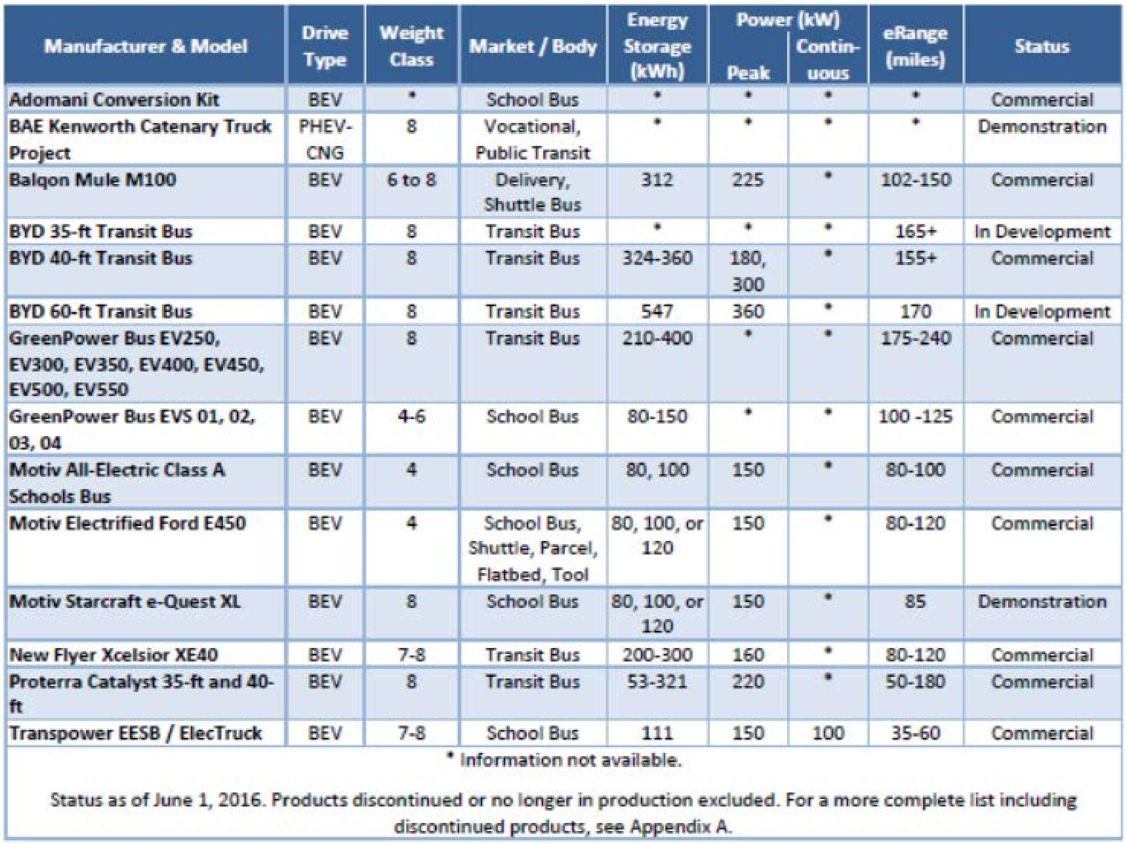
[58] Birky et al. 2017

[59] Chandler et al., 2017

[60] Eudy, L. and M. Jeffers, 2017.

While a majority of transit bus routes in California do not exceed 150 miles, the electric range of BEBs is expected to increase in the future.[66] This range increase will result, in part, from advances in battery technology. Many commercially available 40-foot BEBs today have a battery capacity from 70 to 400 kilowatt hours, with conservative estimates predicting that capacity will increase by a third by 2025.[61,62] In terms of maintenance, vehicle batteries are expected to last the full lifetime of the vehicle or longer. BYD's battery pack for its 40- and 60-foot models, for instance, is designed to last from 20 to 25 years. [63] The 20 to 25 years includes a second-life as stationary energy storage, while the battery is warrantied for the full 12 year transit bus life. [64] Table III-3 lists the BEB models and specifications from 2016.[65]

Table III-3. PEV Models for People Movement[65]



Manufacturer & Model	Drive Type	Weight Class	Market / Body	Energy Storage (kWh)	Power (kW)		eRange (miles)	Status
					Peak	Contin-uous		
Adomani Conversion Kit	BEV	*	School Bus	*	*	*	*	Commercial
BAE Kenworth Catenary Truck Project	PHEV-CNG	8	Vocational, Public Transit	*	*	*	*	Demonstration
Balqon Mule M100	BEV	6 to 8	Delivery, Shuttle Bus	312	225	*	102-150	Commercial
BYD 35-ft Transit Bus	BEV	8	Transit Bus	*	*	*	165+	In Development
BYD 40-ft Transit Bus	BEV	8	Transit Bus	324-360	180, 300	*	155+	Commercial
BYD 60-ft Transit Bus	BEV	8	Transit Bus	547	360	*	170	In Development
GreenPower Bus EV250, EV300, EV350, EV400, EV450, EV500, EV550	BEV	8	Transit Bus	210-400	*	*	175-240	Commercial
GreenPower Bus EVS 01, 02, 03, 04	BEV	4-6	School Bus	80-150	*	*	100 -125	Commercial
Motiv All-Electric Class A Schools Bus	BEV	4	School Bus	80, 100	150	*	80-100	Commercial
Motiv Electrified Ford E450	BEV	4	School Bus, Shuttle, Parcel, Flatbed, Tool	80, 100, or 120	150	*	80-120	Commercial
Motiv Starcraft e-Quest XL	BEV	8	School Bus	80, 100, or 120	150	*	85	Demonstration
New Flyer Xcelsior XE40	BEV	7-8	Transit Bus	200-300	160	*	80-120	Commercial
Proterra Catalyst 35-ft and 40-ft	BEV	8	Transit Bus	53-321	220	*	50-180	Commercial
Transpower EESB / ElecTruck	BEV	7-8	School Bus	111	150	100	35-60	Commercial

* Information not available.

Status as of June 1, 2016. Products discontinued or no longer in production excluded. For a more complete list including discontinued products, see Appendix A.

One of the larger-scale battery electric transit bus demonstrations is currently being conducted by Foothill Transit, in partnership with the NREL and Proterra. Foothill Transit has been operating twelve 40-foot BEBs since 2014 on a 16.1 mile route in the San Gabriel and Pomona Valley regions of Los Angeles, California. Based on NREL's scale of "Technology Readiness

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[61] Lowell, D., D. Seamonds, V. Jayaram, J. Lester, and L. Chan, *Zero Emission Bus Options: Analysis of 2015-2055 Fleet Costs and Emissions*, Ramboll Environ US Corporation and M.J. Bradley & Associates, LLC, developed for Los Angeles County Metropolitan Transportation Authority, 2016.

[62] CARB, 2017b

[63] CARB, 2015d

[64] R. Schenker, BYD, personal communication, April 5, 2018.

[65] Birky et al., 2017

Levels" from one to nine, with nine being full commercial deployment, BEBs were give a score of seven, indicating that they have been successfully operated in their intended environment and are well on their way to being commercially deployed on a larger scale.[66] NREL found that the BEBs in operation had a reliability (i.e., vehicle miles traveled divided by number of vehicle failures) of 90%, compared to their conventional natural gas transit bus counterparts, which had a reliability of 93%. The average efficiency of the BEBs at the end of NREL's second evaluation period was eight times greater than that of the compressed natural gas (CNG) baseline buses.[66] Notably, the Union of Concerned Scientists (UCS) and the Greenlining Institute emphasize BEB efficiency compared to CNG buses as well, pointing out that a BEB powered by electricity produced from natural gas will have up to twice the range of a CNG bus using the same amount of natural gas, due to the efficiency of BEBs.[67]

Shuttle Buses

Similar to transit buses, shuttle buses run fixed routes and travel relatively short distances. As such, electric shuttle buses are closer to reaching widespread commercialization than some of the other MD/HD vehicle vocations. Although the market for electric shuttle buses is still in its early stages, it is expected to grow significantly over the next decade.[68,69,70] Shuttle bus manufacturers include Motiv Power Systems, BYD, and Zenith Motors. Battery pack sizes range from 52 to 135 kilowatt hours (kWh), with an electric range of up to 120 miles.[68] There have been a total of 78 HVIP vouchers utilized for electric shuttle buses in California.[71]

School Buses

When running routes in urban and suburban areas, school buses fit the appropriate duty cycle for currently available MD/HD electric vehicle technology.[68,72] They travel a fixed short route in the morning and afternoon, and are generally stationary for the remainder of the day. This also gives school buses ample time to recharge, and makes them prime candidates for vehicle-to-grid integration. SDG&E has proposed a V2G pilot using electric school buses as part of their January 2018 application to the CPUC.[73] PG&E is conducting a pilot to test new incentive structures to target EV charging for school buses during period of high renewable generation.[74] Power from electric school buses could help offset some of the electricity demand during peak hours.[68]

There are a limited number of electric school bus models on the market, although the number is expected to grow over the next five to ten years. Type A (<14,500 lbs GVWR or 14,500 lbs to 21,500 lbs GVWR, depending on classification), Type C (19,000 to 33,000 lbs GVWR), and Type D (>33,000 lbs GVWR) school buses are all available in electric models from manufacturers such as Motiv Power Systems, Blue Bird, and Lion. As of 2015, CARB had funded around 60 electric school bus demonstrations in California and continues to offer funding

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[66] Eudy and Jeffers, 2017
[67] Chandler, S., 2017
[68] CARB, 2015d
[69] CALSTART, *Electric Truck & Bus Grid Integration,* 2015.
[70] CARB, 2015a
[71] California HVIP
[72] Chandler et al., 2017
[73] SDG&E, 2018
[74] CPUC, "Decision on the Transportation Electrification Priority Review Projects," January 11, 2018.

opportunities for the technology.[68] Some limitations to the increasing deployment of electric school buses include stringent school bus safety standards (which apply to all fuels and technologies), and the lack of available school bus models, as major school bus manufacturers such as IC Bus, and Thomas Built either have not yet, or have not until recently, become involved in the electric school bus market.[68]

Moving Forward

As BEB deployment increases, there are an increasing number of BEB models coming to market, with larger battery capacities and increasing ranges. In addition, more OEMs are breaking into the market. In fact, Cummins is expected to produce battery electric drivetrains for buses by 2019.[75] According to CALSTART, battery electric and electric-assist buses comprised 17% of the transit bus fleet in the United States in 2014, a majority of which were gasoline or diesel hybrid electric buses.[76] Zero emission buses, including battery electric and fuel cell electric, are estimated to comprise 20% of the transit bus market by 2030.[76] BEBs have contributed significantly to the market penetration of electrification in the MD/HD sectors and have provided valuable information about the impacts of electrification on the electricity grid and fleet operations in general.[77] Moving forward, fleets are interested in extending BEB range, increasing charging infrastructure availability to allow buses the flexibility of switching routes, on-site energy generation, and energy storage capabilities.[76,78] The current market for new transit buses in the US is around 5,000 – 6,000 buses per year.[79] BYD, recently completing a facility expansion to produce up to 1,500 buses per year, and Proterra, whose facility can currently produce around 600 buses per year, can produce almost 40% of the current US market for new buses.[79]

1.2 Class 4-6 Electric Vehicles

Class 4 - 6 electric vehicles have had limited commercial penetration, but generally the technology has progressed from the demonstration phase to early deployment. [80,81] Local delivery and utility vehicles appear to be the most commonly electrified vocations for these vehicle classes, although MD electric shuttle and school buses are also expected to grow their market share, as mentioned previously. [80,81,82,83] It is estimated that there are more than 300 MD electric vehicles across the United States, primarily in delivery vehicle applications.[81,83] Manufacturers of these vehicles include but are not limited to Motiv, Zenith Motors, BYD, TransPower, Workhorse, and EVI. In California, 87 vouchers have been funded for Class 4-6

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[75] CARB, 2017b
[76] CALSTART, 2015
[77] California Cleaner Freight Coalition, *Vision for a Sustainable Freight System in California*, 2017.
[78] Eudy and Jeffers, 2017
[79] Z. Kahn and R. Schenker, BYD, personal communication, February 9, 2018; K. Leacock, Proterra, personal communication, February 9, 2018.
[80] CARB, 2015d
[81] International Energy Agency (IEA), *The Future of Trucks: Implications for Energy and the Environment*, 2017a.
[82] CARB, 2015e
[83] Chandler et al., 2017

electric vehicles, with 38 being shuttle buses, 36 parcel delivery vehicles, 3 beverage trucks, and the balance other buses and trucks.[84]

MD plug-in hybrid electric technology has become increasingly deployed in utility truck applications. In 2015, CARB predicted that the utility sector will be one of the primary areas for MD plug-in hybrid electric technology development over the next five to ten years. A number of plug-in hybrid electric utility and bucket trucks have already been deployed across the country.[97] Notably, electrification of utility trucks offers unique benefits, such as the ability of plug-in electric utility trucks to export electricity to power the vehicle's auxiliary equipment. Utility plug-in hybrid electric vehicles (PHEVs) can export anywhere from 18 kW to 75 kW of power to operate the auxiliary equipment, which can reduce vehicle idling.[85]

MD PEVs have been deployed by companies such as Frito Lay, Coca-Cola, and Staples, which have tested Smith Electric delivery trucks. The United Parcel Service (UPS), FedEx, and Goodwill have also transitioned a portion of their delivery fleets to electric.[86,87] UPS recently announced plans to deploy an entirely electric delivery fleet of 170 vehicles in London.[88] Both UPS and Goodwill are piloting BYD delivery trucks, which have a range of around 100 miles, and UPS is also purchasing Workhorse step vans with electric range extenders. EVI also offers a parcel delivery van model that has a range of up to 90 miles.[89] BYD would like to increase the use of all-electric Class 6 refuse trucks, which have been deployed with success internationally, and is demonstrating an all-electric Class 8 refuse truck to suit traditional US refuse operations. BYD is demonstrating two Class 8 refuse trucks in Palo Alto, CA. Chanje is expecting to produce several thousand Class 4 delivery vans over the next few years to meet global demand from a facility in China that has the capacity to produce 100,000 vehicles per year.[90] Ryder has already placed an order for 125 of the Chanje vans. Another pilot conducted in Europe, Freight Electric Vehicles in Urban Europe (FREVUE), deployed 78 MD/HD electric vehicles in cities across Europe and evaluated their ability to perform in regular operations and reduce air pollution.[91]

Local governments have implemented programs to encourage the deployment of MD PEVs. In particular, the Houston Galveston Area Council (HGAC), in an effort to reduce local air pollution from the freight industry, is in the midst of a pilot project to deploy 30 all-electric Workhorse delivery trucks, in partnership with UPS and Workhorse.[92] The vehicles travel, on average, 49 miles per trip with about two stops every mile. So far, the pilot has found that the fleet average efficiency of energy use is significantly higher for the all-electric fleet than its conventional diesel counterpart. It also found that initial utilization of the electric trucks was low, with 41% utilization on average at the start of the pilot, due to limited participation in the pilot by the fleet. HGAC

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[84] California HVIP
[85] CARB, 2015e
[86] California Cleaner Freight Coalition, 2017
[87] Swanton, A., *The Pathway to Battery Electric*, presentation, 2017.
[88] United Postal Service, "UPS Switches On Smart Grid In London To Super-Charge Electric Delivery Fleet," March 19, 2018.
[89] CARB, 2015d
[90] S. Jayanthi, Chanje, personal communication, February 8, 2018.
[91] Federal Highway Administration (FHWA) and European Commission (EC), *Noteworthy Practices in Urban Freight Planning: Electrification of Freight Fleets*, presentation, 2017.
[92] Winston, 2018

plans to work with its partners to increase vehicle utilization for the remainder of the pilot, through January 2019.

In 2015, CARB predicted that MD vehicles, specifically trucks and shuttle buses, will reach widespread commercial deployment in five to ten years.[89] Similarly, the California Hybrid, Efficient and Advanced Truck Research Center estimates that electric delivery trucks will be in the widespread commercialization phase by 2020.[93] The pilots mentioned above identified some crucial needs in order for MD electrification to become more widespread. The FREVUE pilot concluded that there is a need for local fast charging hubs for accessible charging and that electricity must come from sustainable sources in the future to reduce emissions. Fleets should also be educated about how to operate the technology so that is it utilized.[94]

1.3 Class 7-8 Electric Trucks and Vocational Vehicles

Heavy-duty vehicle electrification has been slower to evolve than light- and medium-duty electrification, especially for heavy-duty trucks and vocational vehicles. In fact, it is expected that as the uptake of PEVs across vehicle classes increases, there will be an insufficient supply of electrified heavy-duty trucks to meet demand, especially for long-haul transportation, assuming that Class 7-8 truck demonstrations are successful.[95] That said, the technology has recently moved into the demonstration phase of commercialization, with an increasing number of vehicles being deployed across the country.[96,97,98,99] There have only been 6 vouchers funded under the HVIP program for Class 7-8 trucks.[100] However, many of the Class 7-8 electric trucks in California have been deployed in vehicle demonstrations rather than via funding from HVIP, as vehicle models that are not yet commercialized do not qualify for HVIP funding. Specifically, commercially available plug-in electric models are limited in the drayage, refuse, and other work truck applications. Drayage and refuse trucks are promising applications for electrification, as they fit within the short range and frequent braking operational limitations of current PEV technology.[101]

Manufacturers that have been involved in heavy-duty truck and vocational vehicle electrification include TransPower, Motiv Power Systems, US Hybrid, and BYD. However, Kenworth, Peterbilt, and Volvo are becoming bigger players in Class 7-8 heavy-duty truck electrification as well. In addition, Motiv Power Systems offers an all-electric refuse hauler with an 80 mile range. A handful of TransPower's Class 8 drayage trucks, with a range of up to 100 miles on a single charge, have also been deployed.[96] Tesla will be entering the Class 7-8 truck market with a Class 8 truck in the next few years with a goal of 100,000 trucks worldwide per year.[102]

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[93] Moultak et al., 2017
[94] FHWA and EU, 2017
[95] Tyggestad, C., N. Sharma, J. van de Staaij, and A. Keizer, 2017.
[96] CARB, 2015d
[97] CARB, 2015e
[98] Chandler et al., 2017
[99] IEA, 2017a
[100] California HVIP
[101] Moultak et al., 2017
[102] Lambert, 2018

A number of heavy-duty vehicle demonstrations have been focused on electric drayage trucks. Over 40 all-electric drayage trucks have been deployed in California. Generally, these drayage trucks do not travel over 60 miles in a day, making them a feasible application of currently available heavy-duty technology, which has range limitations.[98] An electric drayage truck demonstration at the Port of Los Angeles found that as the pilot progressed, the vehicle's battery life and performance of the inverter increased significantly.[103] In addition, the results of BYD's all-electric yard truck demonstration demonstrated that the vehicles were capable of operating around 29.5 hours between charges.[104]

Currently BYD has over 1,000 electric trucks globally (Class 4-8) on the road with only 20-30 in the US. They believe the current US deployment will double by end of year and 2019 could be the year for some of the biggest orders of trucks. Motiv has 50 electric vehicles on the road spanning school buses to trucks and could add another 100 vehicles on the road.

According to the International Energy Agency, conventional internal combustion engine (ICE) trucks have engine-to-wheel efficiency of 30%, while all-electric trucks have vehicle efficiencies upwards of 85%.[105] Heavy-duty electric vehicles also require less maintenance and generate less noise than conventional ICE vehicles.[105]

One of the biggest barriers to advancing heavy-duty electrification is the lack of sufficient vehicle range.[105] Many of the reviewed resources did not evaluate the potential for heavy-duty long-haul electrification due to the significant deficit in PEV range compared to ICE vehicle range.[106][107] In addition, the infrastructure necessary to charge long-range PEVs quickly is not yet commercially available.[108] The short range of PEVs, as mentioned previously, can be partially attributed to the energy density and weight of vehicle batteries.[109] The International Council on Clean Transportation (ICCT) developed Figure III-4 that provides insight into the relative ranges of MD/HD ZEVs, which includes PEVs and fuel cell electric vehicles, based on vehicle models that were either available or announced to be in development as of September 2017.[108] Note that this figure does not include models announced after September 2017, such as the Tesla Semi, which is expected to have a range of 300 or 500 miles.[110] Class 7-8 vehicle models included in Figure III-4 are detailed in Table III-4.

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[103] POLA, 2015
[104] Swanton, A., *The Pathway to Battery Electric*, presentation, 2017.
[105] CARB, 2015d and other
[106] IEA, 2017a
[107] EPRI and NRDC, 2015
[108] Moultak et al., 2017
[109] CARB, 2015d
[110] Tesla, Semi specification.

Figure III-4. ZEV Range by Vehicle Class and Production Phase[108]

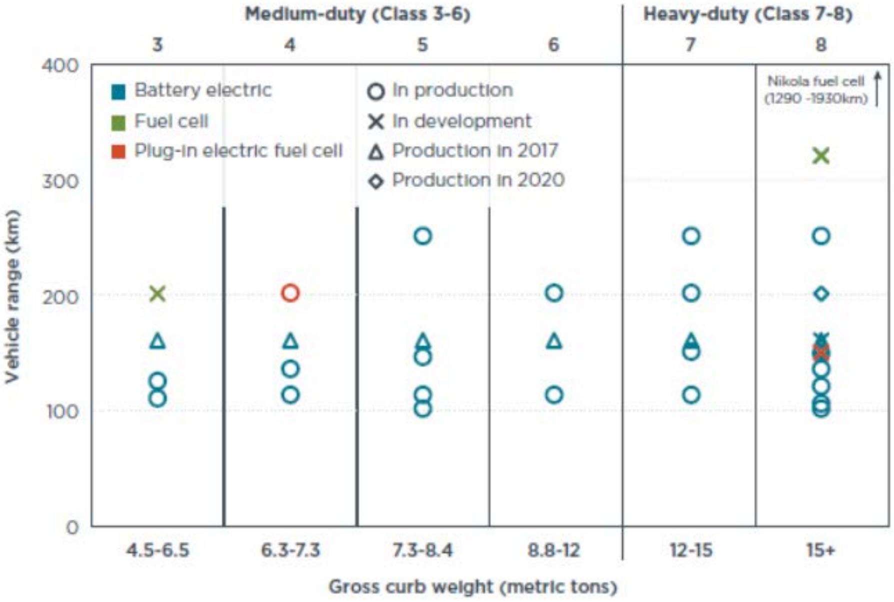
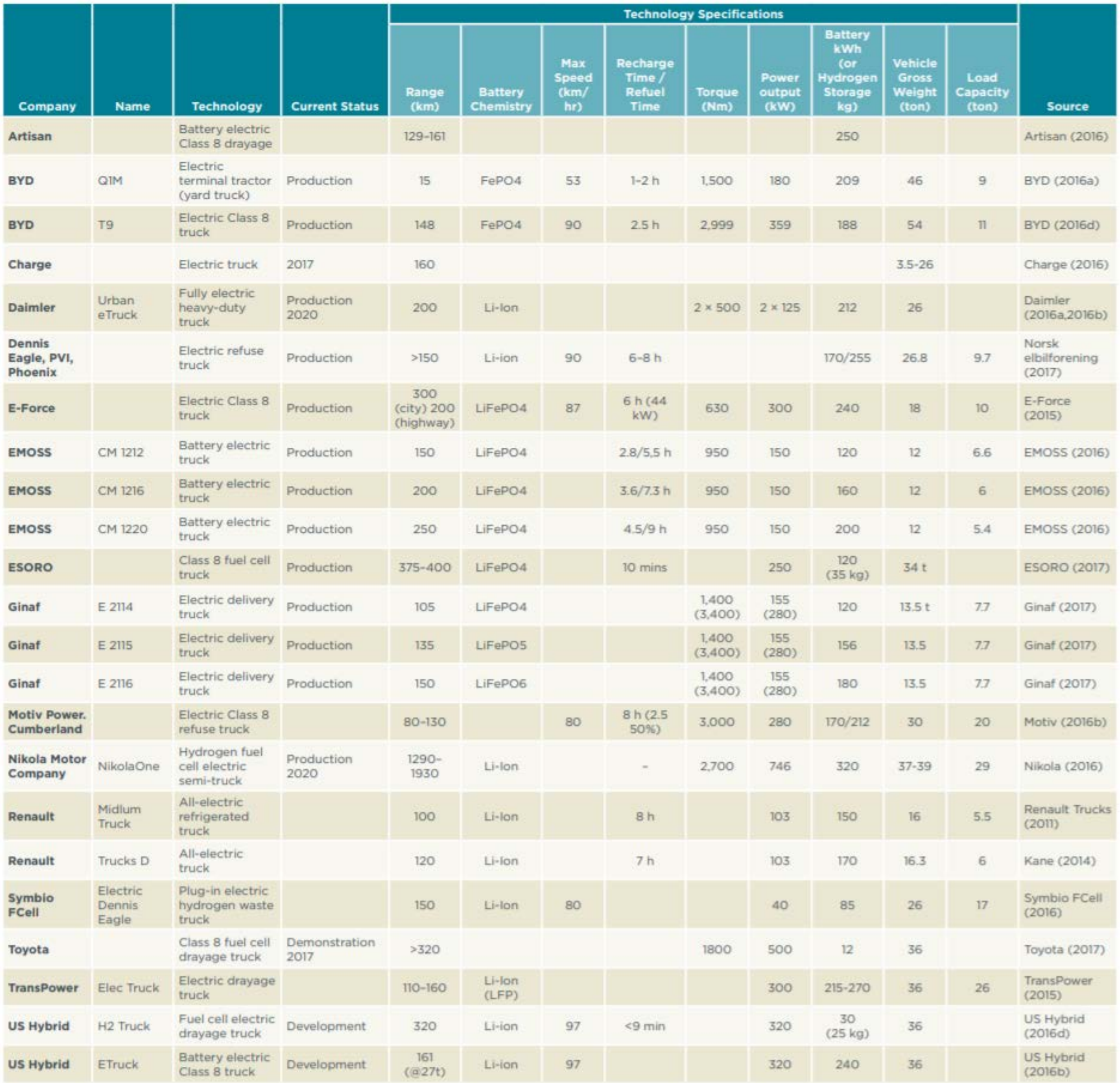


Table III-4. Commercially Available and Production-Phase Heavy-duty ZEVs, September 2017[111]



Company	Name	Technology	Current Status	Technology Specifications									Source
				Range (km)	Battery Chemistry	Max Speed (km/hr)	Recharge Time / Refuel Time	Torque (Nm)	Power output (kW)	Battery kWh (or Hydrogen Storage kg)	Vehicle Gross Weight (ton)	Load Capacity (ton)	
Artisan		Battery electric Class 8 drayage		129-161						250			Artisan (2016)
BYD	Q1M	Electric terminal tractor (yard truck)	Production	15	FePO4	53	1-2 h	1,500	180	209	46	9	BYD (2016a)
BYD	T9	Electric Class 8 truck	Production	148	FePO4	90	2.5 h	2,999	359	188	54	11	BYD (2016d)
Charge		Electric truck	2017	160							3.5-26		Charge (2016)
Daimler	Urban eTruck	Fully electric heavy-duty truck	Production 2020	200	Li-Ion			2 × 500	2 × 125	212	26		Daimler (2016a,2016b)
Dennis Eagle, PVI, Phoenix		Electric refuse truck	Production	>150	Li-ion	90	6-8 h			170/255	26.8	9.7	Norsk elbilforening (2017)
E-Force		Electric Class 8 truck	Production	300 (city) 200 (highway)	LiFePO4	87	6 h (44 kW)	630	300	240	18	10	E-Force (2015)
EMOSS	CM 1212	Battery electric truck	Production	150	LiFePO4		2.8/5,5 h	950	150	120	12	6.6	EMOSS (2016)
EMOSS	CM 1216	Battery electric truck	Production	200	LiFePO4		3.6/7.3 h	950	150	160	12	6	EMOSS (2016)
EMOSS	CM 1220	Battery electric truck	Production	250	LiFePO4		4.5/9 h	950	150	200	12	5.4	EMOSS (2016)
ESORO		Class 8 fuel cell truck	Production	375-400	LiFePO4		10 mins		250	120 (35 kg)	34 t		ESORO (2017)
Ginaf	E 2114	Electric delivery truck	Production	105	LiFePO4			1,400 (3,400)	155 (280)	120	13.5 t	7.7	Ginaf (2017)
Ginaf	E 2115	Electric delivery truck	Production	135	LiFePO5			1,400 (3,400)	155 (280)	156	13.5	7.7	Ginaf (2017)
Ginaf	E 2116	Electric delivery truck	Production	150	LiFePO6			1,400 (3,400)	155 (280)	180	13.5	7.7	Ginaf (2017)
Motiv Power. Cumberland		Electric Class 8 refuse truck		80-130		80	8 h (2.5 50%)	3,000	280	170/212	30	20	Motiv (2016b)
Nikola Motor Company	NikolaOne	Hydrogen fuel cell electric semi-truck	Production 2020	1290-1930	Li-Ion		-	2,700	746	320	37-39	29	Nikola (2016)
Renault	Midlum Truck	All-electric refrigerated truck		100	Li-Ion		8 h		103	150	16	5.5	Renault Trucks (2011)
Renault	Trucks D	All-electric truck		120	Li-Ion		7 h		103	170	16.3	6	Kane (2014)
Symbio FCell	Electric Dennis Eagle	Plug-in electric hydrogen waste truck		150	Li-Ion	80			40	85	26	17	Symbio FCell (2016)
Toyota		Class 8 fuel cell drayage truck	Demonstration 2017	>320				1800	500	12	36		Toyota (2017)
TransPower	Elec Truck	Electric drayage truck		110-160	Li-Ion (LFP)				300	215-270	36	26	TransPower (2015)
US Hybrid	H2 Truck	Fuel cell electric drayage truck	Development	320	Li-ion	97	<9 min		320	30 (25 kg)	36		US Hybrid (2016d)
US Hybrid	ETruck	Battery electric Class 8 truck	Development	161 (@27t)	Li-ion	97			320	240	36		US Hybrid (2016b)

OEMs hope to increase battery energy density, which would decrease battery size and allow for a lighter battery to have a longer vehicle range.[112] For example, BYD is on the path to nearly doubling the energy density of its iron phosphate batteries since its initial bus roll-outs in 2011. Another area of consideration that could extend vehicle range is increasing electric motor efficiency. Currently, electric motors have an efficiency of around 94% to 96%. Increasing this efficiency to 97% could help extend vehicle range.[113] Further, OEMs and EVSE manufacturers have been investigating overhead catenary charging systems to extend vehicle range and help

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[111] Moultak et al., 2017
[112] CARB, 2015d
[113] CARB, 2015e

conserve battery energy on steep grades or other challenging terrains.[114] Implementing centralized DC fast charging hubs has also been considered as a solution to electric vehicle range limitations.[115] Lastly, some demonstrations in China and India have been conducted to evaluate the feasibility of battery swapping, or exchanging a low state of charge (SOC) vehicle battery with a newly charged battery.[111]

1.4 Natural Gas Vehicles

Compared to diesel and gasoline vehicles, natural gas vehicles (NGVs) have the potential to reduce emissions in the transportation sector in California, although to a lesser extent than ZEVs. Understanding the impact of NGVs on the landscape of California's vehicle fleet is useful in evaluating the role that both NGVs and PEVs will have in meeting California's emissions goals moving forward.

As natural gas has a lower energy density than conventional diesel, NGVs typically have a shorter range with the same size tank as conventional diesel vehicles. Further, the lower energy density of the fuel means that it must be stored in a fuel tank that is both larger and heavier than a conventional diesel fuel tank, which impacts vehicle performance and range. These vehicle range and fuel storage issues mean that, similar to PEVs, MD/HD NGVs using CNG are better suited for urban duty cycles than long-haul duty cycles.[116] LNG fueled NGVs have longer ranges that are more comparable to diesel vehicles and can be used for long-haul duty cycles.

While NGVs are often powered by fossil based natural gas (in compressed or liquefied version), RNG is also a potential fuel option. RNG and fossil natural gas are interchangeable in NGV applications—they can be distributed through the same pipelines and dispensed at the same fueling stations.[117] In 2016, Californians consumed around 102 million gasoline gallon equivalents of RNG, fueling 60% of the NGV demand in California.[118] California has enough dairy waste, landfill, municipal solid waste (MSW), and wastewater feedstocks to increase its production of RNG by at least 94.6 billion cubic feet (Bcf) per year. The University of California at Davis (UC Davis) estimates that there is potential for growth in the RNG industry to 14 Bcf by 2020 with California's Low Carbon Fuel Standard credits priced at $120 per metric ton of carbon dioxide.[117] A majority of this RNG would be produced from landfill gas, followed by dairy waste, MSW and wastewater.[119] If used entirely in transportation applications, 14 Bcf of RNG would replace 85% of the conventional CNG used in California vehicles in 2015.[117]

An increasing number of OEMs have been bringing heavy-duty natural gas buses and trucks to market. Many OEMs have also begun developing partnerships with NGV component and fueling equipment providers. There are currently around 250,000 NGVs on the road in the United

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[114] California Cleaner Freight Coalition, 2013
[115] FHWA and EU, 2017
[116] CARB, *Technology Assessment: Lower NOx Heavy-Duty Diesel Engines*, September 2015c.
[117] Jaffe, 2017a
[118] CARB, Data Dashboard: 2011-2016 Performance of the Low Carbon Fuel Standard, https://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm. Accessed on March 1, 2018.
[119] Jaffe, A.M., R. Dominguez-Faus, and A. Brown, *Renewable Natural Gas Provides Viable Commercial Pathway for Sustainable Freight*, University of California, Davis – Sustainable Transportation Energy Pathways, 2017b.

States today, 65,000 of which are MD/HD trucks.[120] Natural gas engines do not have the same low speed, low temperature, low load operation issues as diesel engines typically do—they can maintain both low GHG (when consuming RNG) and NOx tailpipe emissions levels. As a result, low NOx NGV technology may be able to penetrate the heavy-duty truck market more quickly than low NOx diesel and PEV technology. Some natural gas engines have successfully certified to NOx levels below the U.S. Environmental Protection Agency's (EPA) 2010 NOx emissions standard of 0.20 grams per brake horsepower hour (g/bhp-hr). Notably, Cummins Westport certified both its 8.9 liter (L) and 11.9 L natural gas engines to 0.02 g/bhp-hr in Model Year 2016 (Table III-5).[121]

Table III-5. Available Heavy-Duty Natural Gas Trucks[121]

Heavy-Duty Truck OEM	Existing Models using CWI ISL G 8.9L	Existing Models using CWI ISX12 G 11.9 L
Freightliner	Cascadia 113	M2 112, 114 SD
Kenworth	T660, T680, T800SH, T880S, W900S	T440, T470, W900S
Peterbilt	579, 567, 384, 365, 320	384, 365, 320
Volvo Trucks	VNL	VNM
Mack	Pinnacle	LR, TerraPro
International	TranStar	(None)

It is likely that natural gas engines will continue to make technology advancements to meet the optional low NOx standards of 0.02 g/bhp-hr, 0.05 g/bhp-hr, and 0.1 g/bhp-hr. These targets can be achieved by improving engine controls, advanced three way catalysts, and combustion optimization systems. As for PEVs, CARB estimates that "[the] deployment of 350,000 electric trucks over the next 15 years would require technology development and cost that are well beyond what will be needed to deploy low-NOx trucks."[122]

2. Technology Costs—Vehicle, Maintenance, Fuel, and Incentives

Over half of the publications reviewed discussed MD/HD BEV technology costs. The publications reviewed quantified the vehicle, maintenance, charging infrastructure, and fuel costs. The literature agrees that vehicle costs and total costs of ownership are decreasing as the market and technology mature, which means that even the most recent cost estimates could be outdated.

Some publications identified the benefits from incentives such as the LCFS or the HVIP program, while others summarized the life cycle cost of vehicle deployment or overall payback

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[120] Jaffe, A.M., *The Potential to Build Current Natural Gas Infrastructure to Accommodate the Future Conversion to Near-Zero Transportation Technology*, 2017a.
[121] CARB, *Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines*, September 2015b.

periods. Most publications include cost comparisons with diesel vehicles. However, for studies of fleets that have already made a commitment to another technology (e.g., natural gas), relevant comparisons were included. The sections below review trends in each of these areas.

Some publications looked at the total cost of ownership or levelized costs compared to other fuel and vehicle technologies, or total cost to achieve certain goals. For example, Southern California Edison compared electrification (for transportation and heating systems) scenario using clean power to two other pathways to achieve California's climate and air quality goals – RNG and hydrogen. The study found that the incremental abatement cost of electrification using clean power was $79 per ton, compared to $137 per ton for RNG and $262 per ton for hydrogen.[123] Other studies conclude that to achieve the same overall emissions reductions, electrification is the most cost effective alternative.[124] However, significant investment is necessary to expand the market. For example, one study found that completely electrifying the goods movement sector will require ten times the current amount of public and private investment.[125]

While the literature includes sufficient data on the prices of current MD/HD vehicle technology, projections are lacking. A study by NREL agrees, noting, “The literature search reveals a gap in sources for projected cost and performance of electrification beyond the light-duty subsector.”[126]

The literature agrees that electric MD/HD vehicles have not yet reached price parity with their conventional counterparts. According to CARB, as of 2015, the upfront capital cost of a BEB or battery electric truck (BET) is twice as much as diesel vehicles.[127] However, costs are coming down because of the increasing (U.S. and global) market share for these vehicles, economies of scale along the manufacturing supply chain, continuing research and development, advancements along the learning curve, standardization of parts, and increasing motor and battery efficiency. In addition, increasing federal and state standards and incentives are facilitating the development and deployment of MD/HD vehicles.

CALSTART estimates that incremental cost of electric drayage trucks will decrease to $100,000 in 2020 and $60,000 in 2030.[127] While the market for BEB and BET technologies is not as mature as their light-duty counterparts, DNV GL predicts that passenger BEVs will reach price parity with gasoline vehicles in 2022 assuming incentive levels stay the same.[128] McKinsey Energy Institute projects commercial BETs will reach price parity on a Total Cost of Ownership (TCO) basis by 2025, with the exact point of parity depending on vehicle application. The same report notes that light-duty trucks that drive 60—120 miles per day are the most cost-effective (i.e., they have sufficient range with comparatively low battery costs), whereas heavy-duty trucks will be the last to achieve price parity. [129]

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[123] Southern California Edison (SCE), The Clean Power and Electrification Pathway: Realizing California’s Environmental Goals, 2017.
[124] Moultak et al., 2017
[125] ICF, *Goods Movement Landscape Analysis*, 2015.
[126] Jadun et al., 2017
[127] CARB, 2015d
[128] DNV GL, *Energy Transition Outlook 2017, A Forecast to 2050*, 2017.
[129] Tyggestad, C. et. al., 2017

CARB points out that while BEVs will become less expensive in the coming years, the cost of diesel vehicles is expected to increase to meet NOx standards. Specifically, the Manufacturers of Emission Control Association estimates that the technologies necessary to meet the 0.02 grams per brake horsepower hour (g/bhp-hr) standard will cost an average of $500 per vehicle.[130] While this is a relatively small increase in cost, it is notable that the cost of these vehicles may not be decreasing in step with electric models.

The sections summarize vehicle costs identified for buses, as well as other MD/HD vehicles (i.e., trucks and vans).

2.1 Bus Costs

Table III-6 summarizes the BEB costs cited in the literature, based on actual deployment project costs, manufacturer retail prices, or assumptions for modeling efforts. The costs vary from $200,000 to $1,200,000, with the least expensive being a school bus cost estimate and the most being a 35 foot fast-charge bus purchased by a fleet in 2009. While it is difficult to compare various cost estimates, if the outliners are removed, the average cost of a new bus based on the recent literature is approximately $820,000.

Table III-6. BEB Costs Cited in the Literature

Vehicle Specifics	Timeframe	BEB Cost	Comparable Conventional Bus Cost	Incremental Cost	Source
35 foot fast charge	2009	$1,200,000			[131]
35 foot fast charge	2013	$904,490			[131]
200 amp/hour cells	2013	$980,000			[135]
40 foot catalyst extended range	2014	$825,000			[131]
School bus	2015	$200,000-$300,000	$140,000	$60,000-$160,000*	[132]
Transit bus	2015	$800,000-$840,000	$485,000-$525,000	$275,000-$355,000*	[132]
40 foot catalyst extended range	2015	$789,000			[131]
Without any optional equipment; depot charge; 324 kWh	2016	$770,000	$435,000	$335,000*	[136]
Without any optional equipment; on-route charge	2016	$750,000	$435,000	$315,000*	[136]
Without any optional equipment; depot charge; 330 kWh	2016	$750,000	$435,000	$315,000*	[136]
Without any optional equipment; depot charge; 440 kWh	2016	$821,000	$435,000	$386,000*	[136]
Without any optional equipment; depot charge; 550 kWh	2016	$892,000	$435,000	$457,000*	[136]
Without any optional equipment; depot charge; 660 kWh	2016	$963,000	$435,000	$528,000*	[136]

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[130] CARB, September 2015c
[131] Eudy and Jeffers, 2017
[132] CARB, 2015f

Vehicle Specifics	Timeframe	BEB Cost	Comparable Conventional Bus Cost	Incremental Cost	Source
None	2017	$750,000	$450,000	$300,000*	[133]
Remanufactured bus	2017	$580,000	Comparable	$0*	[134]
None	2017			$300,000	[135]
290 amp/hour cells	2017	$770,000			[135]
BYD; 12-year battery warranty	Recent	$770,000	$417,000	$353,000*	[136]
Proterra; extended range and on-route charging	Recent	$749,000	$417,000	$332,000*	[136]

* Calculated based on other values provided.

Table III-7 shows the costs from major BEB manufacturers provided through interviews as part of this literature review. Prices for BEB had dropped significantly from the early prices of $1.2 million to $900,000 and now currently in the $750,000 - $770,000 range for a 40 foot transit bus.[137]

Table III-7. BEB Costs from Manufacturer Interviews

Vehicle Specifics	Manufacturer	Battery Size	BEB Cost	Comments
30’ Transit Bus	BYD	197 kWh	$520,000	Base cost, no add-ons or volume discount; 40-80kW charging; ability to do 100-200 kW at AC Charging as well as 150-300kW DC Fast Charging[138],[139]
35’ Transit Bus	BYD	270 kWh	$700,000	
40’ Transit Bus	BYD	324 kWh	$770,000	
60’ Articulated Bus	BYD	591 kWh	$1.2 Million	
23’ Coach	BYD	135 kWh	$250,000	
40’ Coach	BYD	365 kWh	$800,000	
45’ Coach	BYD	365 kWh	$850,000	
35’ Transit Bus	Proterra	440 kWh	$650,000	Small Volume, standard features[140]
40’ Transit Bus	Proterra	440-660kWh	$750,000	
Type A School Bus	Motiv	85-127 kWh	$250,000-$275,000	208V, 25kW charging[141]
Type C School Bus	Motiv	106-127 kWh	$250,000 - $300,000	208V, 25kW charging[141]

As noted in the table above, the costs do not include volume discounts. BYD’s bid to LA Metro in 2017[142] was for $750,000 per bus, a $20,000 per bus discount.

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[133] Swanton, 2017

[134] Chandler et al., 2017

[135] Chandler et al., 2017

[136] CARB, 2017b

[137] K. Leacock, Proterra, personal communication, February 9, 2018.

[138] Z. Kahn and R. Schenker, BYD, personal communication, February 9, 2018.

[139] R. Schenker, BYD, personal communication, April 5, 2018.

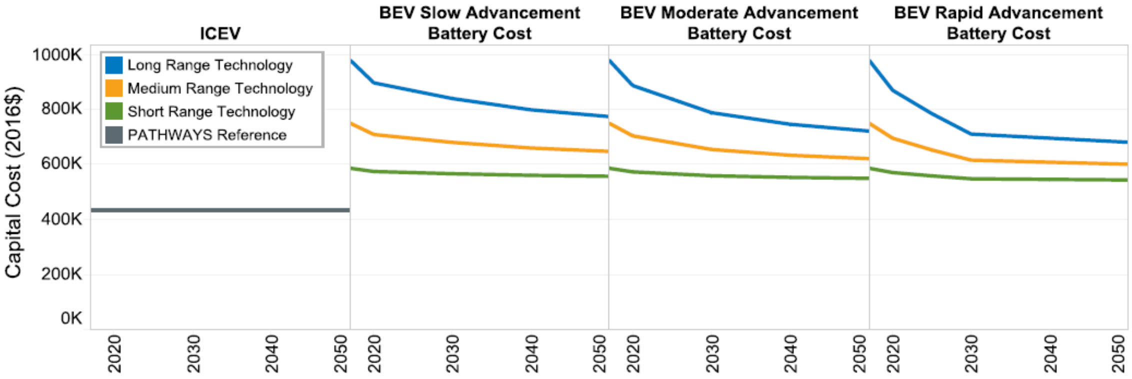
[140] K. Leacock, Proterra, personal communication, February 9, 2018.

[141] U. Nagrani, Motiv, personal communication, February 7, 2018.

[142] Los Angeles Metropolitan Transportation Authority (LAMTA), *Procurement Summary: Sixty 40-Foot Zero Emission Transit Bus Contract / OP28367-002 (Group C)*, October 11, 2016. Available online at: https://metro.legistar.com/View.ashx?M=F&ID=5316637&GUID=34DF4D9F-E6E2-4BDF-BE5C-4E9F1C5F10F9

Only one study, NREL's Electrification Futures Study, provided projections on the cost of BEBs. Based on estimates from Proterra and CARB, the study laid out the projections shown in Figure III-5 below. The figure includes three different vehicle types (short, medium, and long), based on the driving range of the vehicle (68 to 426 miles), which dictates the overall battery pack size (94 to 660 kWh). In all three cases, the projections show a less drastic decrease in price than those included later for MD/HD trucks. NREL explains that the share of vehicle cost attributed to batteries (which are quickly becoming less expensive) is lower for buses than other MD and HD vehicles because of the cost of additional bus components (e.g., seats), resulting in the slower price reduction.[143] It should be noted that NREL is relying on DOE's battery cost forecasts that level out at $100/kWh. DOE's leveling is due to an assumption that uncertainties around DOE's funding levels could affect the trajectory of battery prices. By comparison, and as noted previously, BNEF forecasts battery prices to reach $100/kWh around 2025 and achieve $73/kWh by 2030.

Figure III-5. NREL Projections for BEB Costs through 2050[143]



As a point of reference, recent CNG bus costs identified in the literature range from approximately $470,000 to $575,000, or between $30,000 and $50,000 incremental cost over diesel vehicles,[144] with the total cost of ownership around $1,700,000.[145] While the technology is discussed in the literature, the costs of near-zero-emission HD NGVs are largely unknown, including capital, fuel, and maintenance costs and availability of incentives.[146] The bids LA Metro received for their most recent rounds of buses showed CNG buses costing $675,000[147] for new near-zero-emission buses but only $67,000 to retrofit older CNG buses with near-zero engines.[148]

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[143] Jadun et al., 2017; includes capital vehicle costs, but not infrastructure, taxes, registration fees, and manufacturers' incentives

[144] CARB, 2015b

[145] Swanton, A., *BYD*, nd.

[146] GNA, 2016

[147] LAMTA, *Procurement Summary: 295 Forty Foot CNG Transit Bus Contract / OP28367-000 (Group A)*, October 11, 2016b. Available online at: http://metro.legistar1.com/metro/attachments/cff1d37c-b8bc-46de-8f1f-46eef53a0d41.pdf

[148] LAMTA, *Procurement Summary: Near-Zero Natural Gas Fueled Engines / MA39865000*, March 17, 2017. Available online at: https://metro.legistar.com/View.ashx?M=F&ID=5316634&GUID=D66A8CA5-8591-4FDB-A762-B3AEFE421F24

For hydrogen fuel cell buses, the cost is dependent on how dominant the battery is in the system, versus the fuel cell; batteries are currently less expensive than fuel cells.[149] As of 2016, CARB assumed that fuel cell electric buses cost approximately $1,235,000.[150]

2.2 MD/HD Truck Costs

Table III-8 includes recent and projected MD/HD BET prices. Again, the cost of these vehicles varies significantly based on the model.

Table III-8. BET Costs Cited in Literature

Vehicle Specifics	Timeframe	BET Cost	Comparable Conventional Truck Cost	Incremental Cost	Source
MD Vans and Trucks					
Cargo van	2015	$40,400			160
MD vehicle – 8,501-40,000 lbs)	2015	$130,000-$170,000	$80,000	$50,000-$90,000*	160
MD delivery van	2015	$150,000	$65,000	$85,000*	151
Boulder 500 Class 3; 4,000 lbs. payload; 72 kWh battery; 90 mile range	2016	$70,000			152
Azure Transit Connect E; Class 3; 30 kWh battery; 56 mile range	2016	$71,500			152
Modec eStar (Navistar); Class 3; 80 kWh battery; 80 mile range	2016	$150,000			152
Zenith Motors; Class 3; 3,800 lbs. payload; 62 kWh battery; 78 mile range	2016	$100,000			152
Motiv Power; Class 4; 14,050 lbs. payload; 80 kWh battery; 80 mile range	2016	$181,000			152
Motiv Power; Class 4; 14,050 lbs. payload; 100 kWh battery; 100 mile range	2016	$195,000			152
Motiv Power; Class 4; 14,050 lbs. payload; 120 kWh battery; 120 mile range	2016	$212,000			153
ZeroTruck; Class 3-6; 6,500 lbs. payload; 72 mile range	2016	$130,000			153
Workhorse E-100; Class 6; 100 kWh battery; 100 mile range	2016	$133,000			153
Smith Electric Newton; Class 6; 16,000 lbs. payload; 40-120 kWh battery; Up to 100 mile range	2016	$133,000-$166,000			153
Motiv Power; Class 6; 22,000 lbs. payload; 85-127 kWh battery; 58-85 mile range	2016			$125,000	153

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[149] CARB, 2015f
[150] CARB, 2017b
[151] CALSTART, 2015
[152] Bloomberg, *Bloomberg New Energy Finance Price Survey*, 2016.
[153] Bloomberg, 2016

Vehicle Specifics	Timeframe	BET Cost	Comparable Conventional Truck Cost	Incremental Cost	Source
Step van	2016	$175,000	$70,000	$105,000*	154
Class 5 truck	2016	$165,000	$47,888	$117,112*	154
Class 6 truck	2016	$195,000	$85,995	$109,005*	154
Class 6 truck – 23,149 lbs. GVWR	2016t	$300,000	$117,500	$182,500*	154
Class 6 truck – 20,000 lbs. GVWR	2016t	$300,000	$100,000	$200,000*	154
Class 5 delivery truck	2017	$85,000-$97,000	$60,000	$25,000-$37,000*	155
MD vehicle	2030	$100,000	$55,000 (gasoline) - $60,000 (diesel)	$40,000 - $45,000*	156
HD Trucks					
Drayage truck	2012	$308,000	$104,000	$204,000*	160
Short-haul truck	2014	$466,000	$145,000	$321,000	157
Range extended electric truck	2015	$250,000			158
Battery electric truck	2015	$300,000			158
Dual mode plug-in hybrid truck	2015	$250,000			158
HD vehicle – 14,000 lbs+	2015	$200,000-$300,000	$100,000	$100,000-$200,000*	160
Motiv Power refuse truck; Class 8; 60,000 lbs. payload; 200 kWh battery; 60 mile range	2016			$187,500	153
BYD T9; Class 8; 120,000 lbs. payload; 175-300 kWh battery	2016	$300,000			153
HD truck – 400 km range	2017			$250,000+	159
Drayage truck	2020	$208,000	$108,000	$100,000*	160
HD vehicle	2020			$100,000	160
Drayage truck	2030	$169,000	$111,000	$58,000*	160
HD vehicle	2030			$60,000	160
Catenary Trucks					
Electric overhead catenary tractor-trailer	2015	$309,000	$210,000	$99,000*	161
Electric overhead catenary tractor-trailer	2020	$272,000	$220,000	$52,000*	161
Electric overhead catenary tractor-trailer	2025	$227,000	$223,000	$4,000*	161
Electric overhead catenary tractor-trailer	2030	$236,000	$250,000	($14,000)*	161
Wireless Charging Trucks					

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[154] Swanton, nd
[155] Chandler et al., 2017
[156] Energy + Environmental Economics, *Summary of California State Agencies' PATHWAYs Project: Long-term Greenhouse Gas Reduction Scenarios,* 2015.
[157] Fulton, L. and M. Miller, *Strategies for Transitioning to Low-Carbon Emission Trucks in the United States*, University of California at Davis and the National Center for Sustainable Transportation, 2015.
[158] ICF, 2015
[159] IEA, 2017a
[160] CARB, 2015d
[161] Moultak et al., 2017

Vehicle Specifics	Timeframe	BET Cost	Comparable Conventional Truck Cost	Incremental Cost	Source
Electric dynamic induction tractor-trailer	2015	$254,000	$210,000	$44,000*	[161]
Electric dynamic induction tractor-trailer	2020	$234,000	$220,000	$14,000*	[161]
Electric dynamic induction tractor-trailer	2025	$218,000	$223,000	($5,000)*	[161]
Electric dynamic induction tractor-trailer	2030	$226,000	$250,000	($24,000)*	[161]

* Calculated based on other values provided.

Table III-9 provides BET costs from major BET manufacturers communicated during interviews for the literature review.

Table III-9. BET Costs from Manufacturer Interviews

Vehicle	Manufacturer	Battery Size	BET Cost	Comments
Class 8 Truck	BYD	188 kWh	$250,000-$300,000	Iron Phosphate 80 kW charging; 480 V AC 3-phase[162], [163]
Class 6 Truck	BYD	175 kWh	$150,000-$180,000	
Class 5 Truck w/o Box	BYD	145 kWh	$140,000-$165,000	
Step Van	Multiple Manufacturers	100-145 kWh	$150,000-$175,000	Multiple types of charging[164]
Walk-In Van	Motiv	106-127 kWh	$260,000 - $280,000	208V, 25 kW charging[165]
Box Truck	Motiv	85-127 kWh	$227,000 - $249,000	208V, 25 kW charging[165]
Class 8 Truck	Thor	300-900 kWh	$150,000 - $250,000	Projected vehicle cost based on batteries costing <$166/kWh[166]
Class 8 Truck	Tesla	300-500 mile range	$150,000-$180,000	Expected cost for vehicles at time of production[167]

During the interview, BYD noted that current volume discounts for trucks could reach upwards of $50,000 per truck, depending on the product.[168] TransPower discussed the potential cost their technologies and vehicles could see. They are currently in the prototype and demonstration phase and vehicles cost $300,000-$400,000. As the volume and technology

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[162] Z. Kahn and R. Schenker, BYD, personal communication, February 9, 2018.

[163] R. Schenker, BYD, personal communication, April 5, 2018.

[164] Multiple personal communications, specific companies omitted to maintain anonymity

[165] U. Nagrani, Motiv, personal communication, February 7, 2018.

[166] D. Semler, Thor Trucks, personal communication, February 8, 2018.

[167] D. Witt, Tesla, personal communication, April 16, 2018.

[168] Z. Kahn and R. Schenker, BYD, personal communication, February 9, 2018.

progresses, they see costs dropping to $200,000-$300,000 per truck in 2022-2023 down to $150,000-$200,000 in 2025-2030 timeframe.[169]

Similar to BEBs, NREL projected MD/HD BET prices through 2050. Once again, the NREL figures include three different technology types (short, medium, and long), based on the driving range of the vehicle (50 to 200 miles for MD, 92 to 500 miles for HD), which dictates the overall battery pack size (47 to 187 kWh for MD, 188 to 1,022 kWh for HD).[170] Price projections are shown in Figure III-6 and Figure III-7 below. Similar to the previous figures, the results from NREL are conservative based on battery projections that are much more conservative than the prevailing literature. See Section IV.2 for additional details.

Figure III-6. NREL Projections for MD BET Costs through 2050[170]

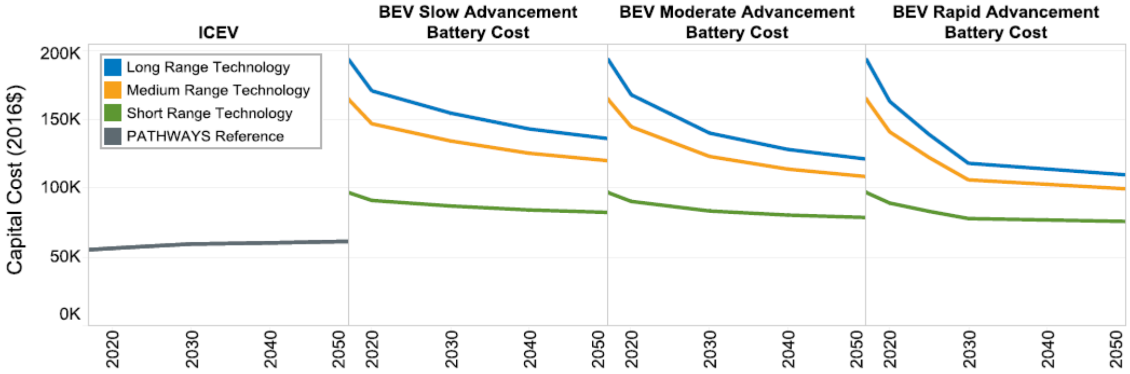
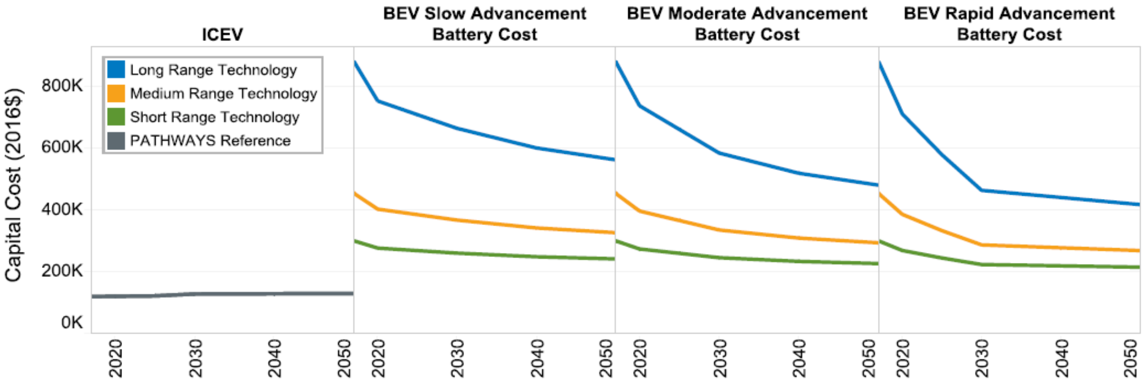


Figure III-7. NREL Projections for HD BET Costs through 2050[170]



By comparison, according to CARB in 2015, natural gas truck incremental costs range from $30,000 to $80,000 compared to diesel.[171] According to a study by the National Center for Sustainable Transportation at University of California at Davis, short-haul CNG and LNG trucks are $168,000 and $209,000, respectively, and long-haul CNG and LNG trucks are $183,000

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[169] J. Goldman, Transpower, personal communication, February 8, 2018.

[170] Jadun et al., 2017; includes capital vehicle costs, but not infrastructure, taxes, registration fees, and manufacturers' incentives

[171] CARB, September 2015b

and $224,000, respectively.[172] Fuel cell electric vehicles, on the other hand, cost $240,000 for short-haul and $255,000 for long-haul.[172]

2.3 Maintenance Costs

It is generally accepted that maintenance is less expensive for BEVs compared to conventional vehicles because the batteries and motors do not need regular attention, regenerative breaking reduces the brake wear, and there are fewer fluids and moving parts.[173] Table III-10 outlines the current maintenance costs for BEVs, in comparison to conventional vehicles.

Table III-10. BEV Maintenance Costs Cited in the Literature

Vehicle Type	Measure	BEV	Conventional Vehicle	Savings	Source
Step van	Annual cost	$3,245	$5,491	$2,246*	[174]
Bus	Annual cost			$3,000	[173]
Delivery truck	Cost per mile			$0.03-$0.10	[173]
Truck	Percent reduction			25-80%	[173]
Class 5 delivery truck	Life time cost			$17,000-$25,000	[175]
Bus	Cost per mile	$0.21	$0.22 (CNG)	$0.01*	[176]
Bus	Cost per mile	$0.60	$0.79	$0.19*	[177]
Truck	Cost per mile	$0.11	$0.12	$0.01	[178]

* Calculated based on other values provided.

** Compared to CNG buses, the scheduled maintenance is lower ($0.07 per mile compared to $0.11 per mile) and the unscheduled maintenance is higher ($0.14 per mile compared to $0.10)

BEV maintenance costs are generally expected to come down as vehicle deployment increases and maintenance providers have more experience with the vehicles. Beyond this assertion, projections for maintenance costs are relatively uncertain. Table III-11 below summarizes NREL's projections, which they assume remain constant through 2050. NREL lays out three scenarios for technology advancement – slow, moderate, and rapid. In the slow advancement case, where more frequent charging is necessary because of the lack of infrastructure deployment, the maintenance costs are the same as conventional vehicles. This is because of the effects of battery degradation due to fast charging. The moderate and rapid case cost are based on the literature and conversations with federal agencies.[179]

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[172] Fulton and Miller, 2015
[173] CARB, 2015d
[174] Swanton, nd
[175] Chandler et al., 2017
[176] Eudy and Jeffers, 2017
[177] CARB, 2017b
[178] Moultak et al., 2017
[179] Jadun et al., 2017

Table III-11. NREL's Projected Maintenance Costs for BEVs[179]

Vehicle Type	Conventional Vehicle Maintenance Cost (2016 dollars/year)	Relative to Conventional Vehicle Maintenance Cost		
		Slow Advancement	Moderate Advancement	Rapid Advancement
BEB	$28,945	1.00	0.76	0.50
MD BET	$1,771	1.00	0.70	0.50
HD MET	$9,201	1.00	0.70	0.50

A few publications cover the maintenance costs of NGVs and fuel cell buses, which can be higher than BEVs due to more frequent oil changes, inspections, and parts (e.g., spark plug) replacement costs. CNG bus maintenance cost were cited in the literature between $0.22 and $0.85 per mile, with fuel cell bus maintenance costs at $1.00 per mile, compared to $0.79 per mile for diesel.[177]

It is notable that maintenance bay and facility upgrades or replacements may cost anywhere from $390,000 to $750,000 for fuel cell buses and $1,000,000 for CNG buses.[177] Electric buses do not require these upgrades, beyond the charging infrastructure discussed in the Section V.

2.4 Fuel Costs

For fleets, reduced (and less volatile) fuel costs are seen as one of the primary benefits of BEVs. According to Transport and Environment, battery electric trucks are one-third cheaper to operate than diesel trucks.[180] CARB notes that light-duty BEV fuel costs are about one-third less than gasoline vehicles, which is generally expected to carry through to MD/HD vehicles.

Table III-12 summarizes the electricity fuel costs cited in the literature, as well as a comparison to conventional fuel where appropriate. When the increased energy efficiency of BEVs is taken into account, operating a BEV is consistently less expensive than a conventional vehicle.

Table III-12. Fuel Costs Cited in the Literature

Vehicle Type	Measure	Electricity Cost	Conventional Fuel Cost	Savings for Electricity	Additional Considerations	Source
School bus	Annual cost			$13,000		181
Transit bus	$/mi	$0.25	$1.00	$0.75**		182
Bus	$/mi	$0.41	$0.25-$0.50 (natural gas)	($0.16)-$0.09	Comparison to natural gas; includes LCFS	183
Bus	Cost			20%		181
Step van	$/mi	$0.08	$0.32	$0.24*		184
Step van	Annual cost	$2,111	$7,959	$5,848*		184

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[180] Transport and Environment, *Electric Trucks' Contribution to Freight Decarbonisation*, September 2017a.
[181] CARB, 2015d
[182] Chandler et al., 2017
[183] Eudy and Jeffers, 2017
[184] Swanton, nd

Vehicle Type	Measure	Electricity Cost	Conventional Fuel Cost	Savings for Electricity	Additional Considerations	Source
MD Truck	Annual cost	\$10,000-\$16,000			Assumes 40,000 km per year	185
HD Truck	Annual fuel costs	\$60,000-\$95,000			Assumes 100,000 km per year	185
N/A	\$/DGE	\$3.80	\$2.71	(\$1.09)	Does not take into account efficiency of BEVs; prices expected to increase to \$4.22/dge (electricity) and \$4.01 (diesel) in 2030	186

* Calculated based on other values provided.
** See Figure III-8.

While standard electricity prices are typically cheaper than diesel, electrical rate structures must be taken into account. Time-of-use rates that offer cheaper charging at off-peak times benefit light-duty BEV drivers, but not necessarily MD/HD fleets. If these fleets must charge during typical business and commuting hours, they will not benefit from time-of-use rates and could be hit hard by demand charges, which are charges for using a lot of power in a short period of time. Demand charges are a significant issue for small fleets, in particular. Larger fleets have enough assets and demand to spread charging out to avoid spikes in usage at particular times of the day. Smaller fleets do not have this luxury.[187] Utilities can address these issues through targeted rate structures for BEV fleets.

CALSTART presented the data in Figure III-8 to show the impact of time-of-use rates.

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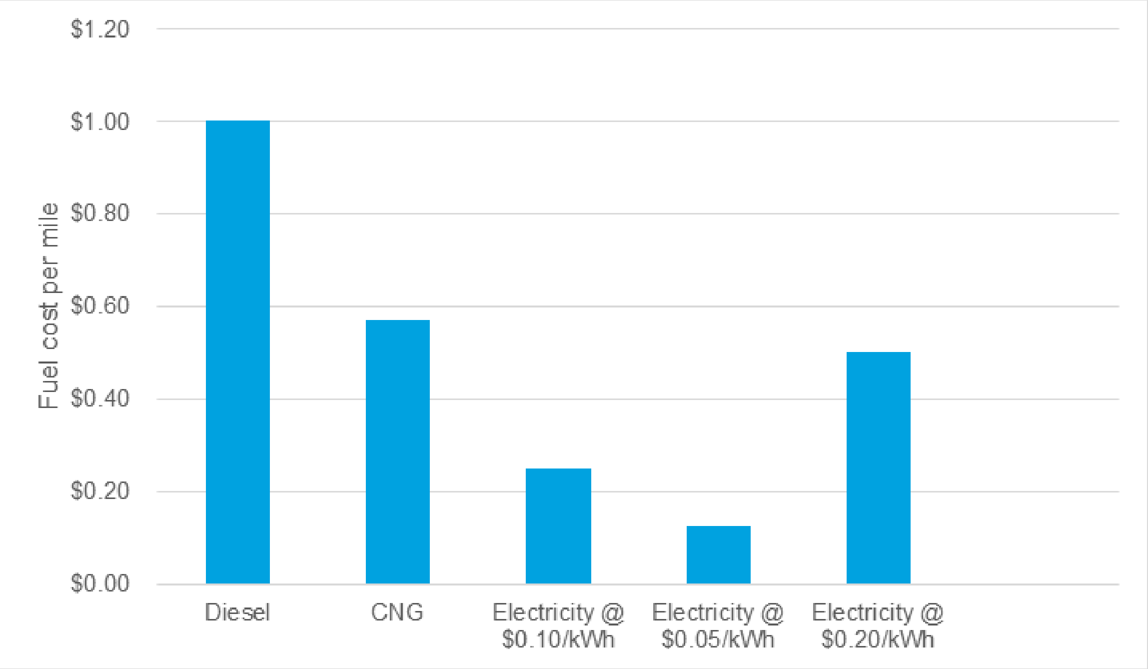
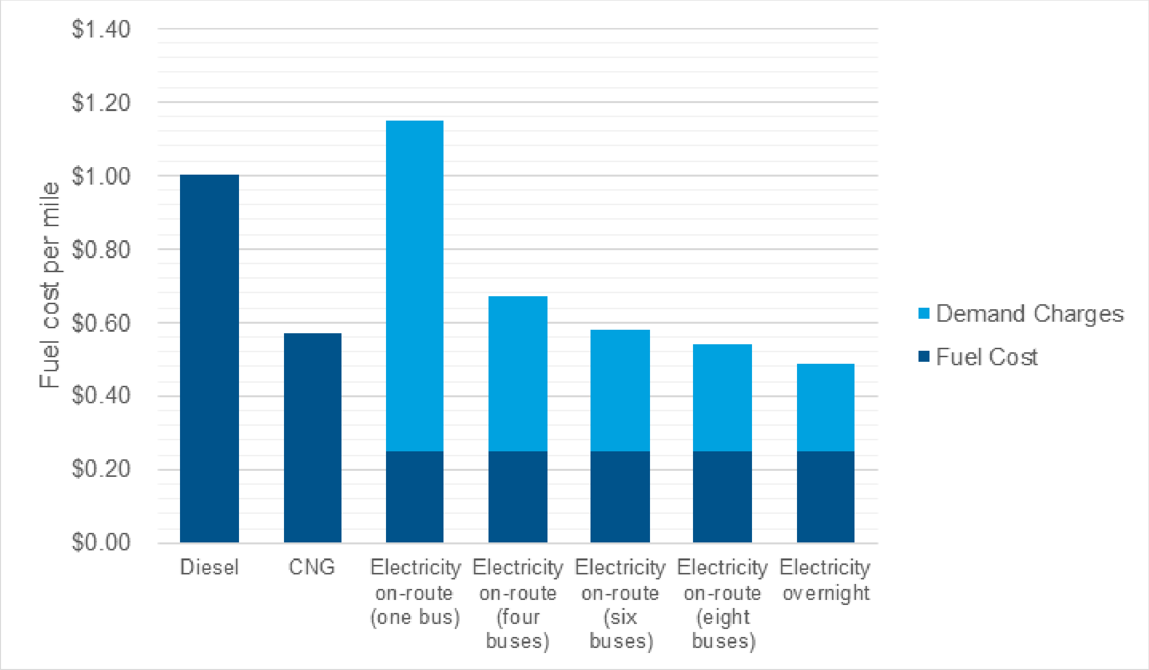
[185] IEA, 2017a
[186] Fulton and Miller, 2015
[187] Chandler et al., 2017

Figure III-8. Fuel Cost per Mile for Various Bus Models[188]



CALSTART built on this analysis (with $0.10/kWh electricity) and demonstrated the impact of demand charges on the cost of electric buses, particularly for small fleets (Figure III-9).

Figure III-9. Fuel Cost per Mile for Various Bus Models including Demand Charges[189]



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[188] CALSTART, 2015
[189] Chandler et al., 2017

The impact of time-of-use rates and demand charges can vary based on the amount that vehicles charge in the depot, versus on their route. To demonstrate these impacts on Los Angeles County Metropolitan Transportation Authority (LACMTA)'s fleet, Ramboll Environ US Corporation and M.J. Bradley & Associates collected the data in Table III-13.

Table III-13. Estimated LACMTA BEB Charging During Various Peak Periods[190]

Location of Charging	Off-Peak	Mid-Peak	High-Peak
Bus Depot Charging	64%	32%	5%
In-Route Charging	24%	65%	11%

CALSTART also conducted an analysis on MD delivery vans showing the impact on high charging infrastructure, electricity, and demand charges. The net benefit of electric delivery vans varied between $308 for high infrastructure, electricity, and demand charges to $40,996 for low infrastructure, electricity, and demand charges.[191]

For fleets looking to quantify fuel costs, CARB developed a Battery Electric Truck and Bus Charging Calculator to estimate energy fees, which takes into account energy distribution (for on-peak, mid-peak, and off-peak), energy use, energy rates, and demand charges by season.[192]

2.5 Incentives

Incentives have been used to offset the capital costs and encourage adoption of electric MD/HD vehicles. A CALSTART study looking at high-efficiency heavy-duty vehicle (HDV) suppliers showed that three main companies in the MD/HD electric drive vehicle space (Proterra, XL Hybrids, and Odyne) benefitted significantly from government incentive programs.[193] In addition, a study by SCE noted that continued incentives for BEV purchases, coupled with consumer education, adequate charging infrastructure, and competitive pricing for electricity are necessary to ensure continued adoption.[194] However, as costs and payback periods come down, incentives will not be as important to the widespread adoption of BEBs and BETs. A Transport and Environment model assumes that by 2050 battery electric short-haul trucks and urban buses will not need incentives to be viable.[195]

Incentives cited in the literature include the LCFS, HVIP, low interest loans, green financing, and non-financial incentives, such as low- and zero-emission zones.[196] For more information on the incentive programs available, see the Background Section.

2.6 Total Cost of Ownership and Payback

Each of the costs discussed above (vehicle, maintenance, fuel), as well as infrastructure discussed below, factor into the total cost of ownership (or levelized costs) and the payback on an advanced technology, such as a BEV. According to a paper out of the University of Michigan,

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[190] Lowell et al., 2017
[191] CALSTART, 2015
[192] CARB, 2017b
[193] CALSTART, *US Heavy-Duty Vehicle High-Efficiency Technology Suppliers*, 2016.
[194] SCE, 2017
[195] Transport and Environment, 2017a
[196] IEA, 2017a

small fleets (1-20 vehicles) are looking for a payback from six months to three years, but larger fleets are more likely to opt for a payback of 18 months to four years.[196]

While the capital investments associated with BEVs are generally higher, the significantly lower maintenance and fuel costs can offset these costs. As a result, the payback period is typically shorter for vehicles that drive more miles per year. And as the vehicle costs come down, so does the payback period.

2.6.1 Buses

Several resources look at the total cost of ownership and payback of BEBs, but not all align. For example, BYD estimates that the total cost of ownership per bus for 50 buses is $1,000,000 for electric bus, versus $1,700,000 for CNG and $1,200,000 for diesel. This includes vehicle and other capital, maintenance, fuel, and facility operating costs.[197] However, according to a 2015 analysis conducted on LACMTA's 2,500 bus fleet, the cost per mile to operate battery electric buses through 2055 is $4.27 to $4.28, depending on the type of charging. This compares to $4.18 per mile for conventional and renewable natural gas and $4.53 to $4.61 per mile for hydrogen fuel cell electric buses, depending on the hydrogen production method.[198] It is important to note these are the results of the draft report and LACMTA has not issued a final version. And looking ahead to 2020, NREL's Electrification Future's study finds that the levelized cost of driving (LCOD) BEBs is $4.43 per mile versus $3.93 per mile for conventional buses.[199]

CARB in 2015 estimated that the payback for an electric school bus is six years.[200] To look at this further, the agency developed the Innovative Clean Transit (ICT) initiative, including a transit fleet cost model that projects total fleet costs (including capital, maintenance, and fuel) through 2050. CARB results showed, for electric buses purchased today a TCO savings of $150,000 to $250,000 per bus compared to diesel and $0 - $100,000 per bus compared to CNG. For electric buses purchased in 2020, CARB showed a TCO savings of $380,000 - $400,00 per bus compared to diesel and $150,000 - $200,000 per bus compared to CNG.[201]

2.6.2 Trucks

In the literature, the overall cost savings associated with BETs is also not consistent. On one hand, several studies report a life time cost savings for BETs. Based on in-use testing in Texas, lifetime vehicle cost savings for MD delivery trucks could be over $1,100 per month.[202] Furthermore, a Transport & Environment study estimates that the cost per kilometer to operate an electric truck is $0.70 to $0.75, compared to $1.08 per km for diesel.[203] And a pilot of electric food delivery trucks in Oslo, Norway found that the vehicles have a €500,000 (or over $600,000) lifetime savings over conventional vehicles.[204] Looking ahead, one SAE International study cited

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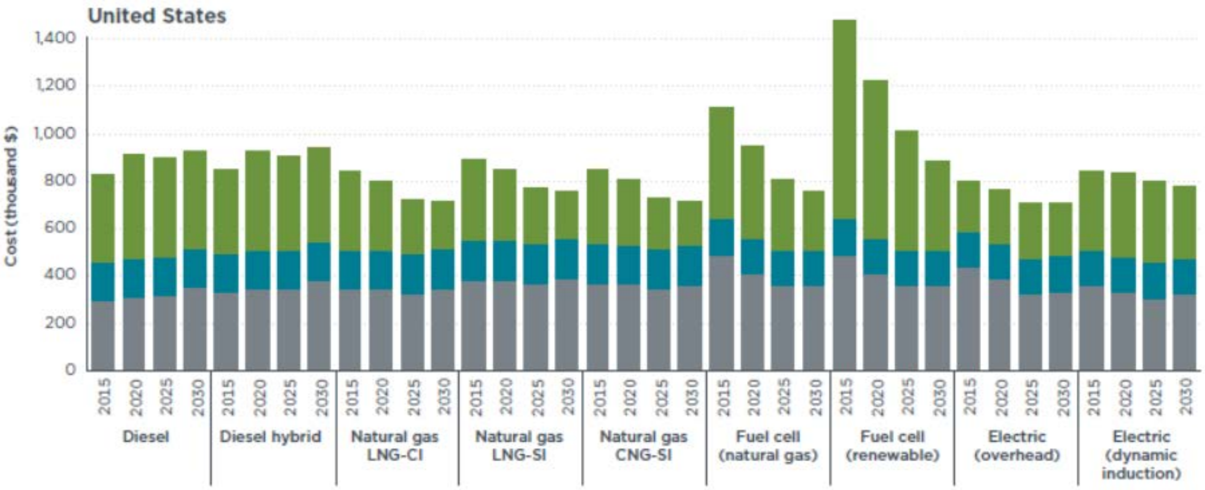
[197] Swanton, nd
[198] Lowell et al., 2016
[199] Jadun et al., 2017; moderate advancement case projection.
[200] CARB, 2015d
[201] CARB, 2016b
[202] FHWA and EC, 2017
[203] Transport and Environment, 2017a
[204] Transport and Environment, *Roadmap to Climate-Friendly Land Freight and Buses in Europe*, 2017b.

by the ICCT predicts that BETs will have the lowest cost of ownership of any powertrain option by 2025.

NREL's Electrification Future's Study projects that the LCOD for a MD BEV in 2020 will be $2.08 per mile, versus $1.21 per mile for a conventional vehicle. For a HD BEV in 2020 the LCOD is $1.40 per mile, versus $1.07 per mile for a conventional HD vehicle.[205] Similarly, the National Center for Sustainable Transportation estimates that the total cost of ownership of an electric truck in 2030 is estimated at approximately $430,000, compared to $250,000 for a diesel truck. This study does predict that life time electric truck costs will come down to $290,000 in 2050.[206]

Figure III-10 is taken from an ICCT study and shows total cost of ownership for various vehicle and fuel types, including vehicle cost (gray), maintenance cost (blue), and fuel cost (green). It demonstrates that BETs with inductive and catenary systems are cost competitive in the 2025 to 2030 timeframe, not including infrastructure costs. Specifically, in 2030, BETs with overhead catenary have 25% to 30% lower costs than diesel vehicles.[207]

Figure III-10. Total Cost of Ownership Projections for Various Truck Types[207]



While payback periods can vary dramatically, CARB estimated in 2015 that MD BEVs have a three to five year payback.[208]

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[205] Jadun et al., 2017; moderate advancement case projection.

[206] Miller, M. Q. Wang, and L. Fulton, *Truck Choice Modeling: Understanding California's Transition to Zero-Emission Vehicle Trucks Taking into Account Truck Technologies, Costs, and Fleet Decision Behavior*, University of California at Davis and the National Center for Sustainable Transportation, 2017.

[207] Moultak et al. 2017

[208] CARB, 2015d

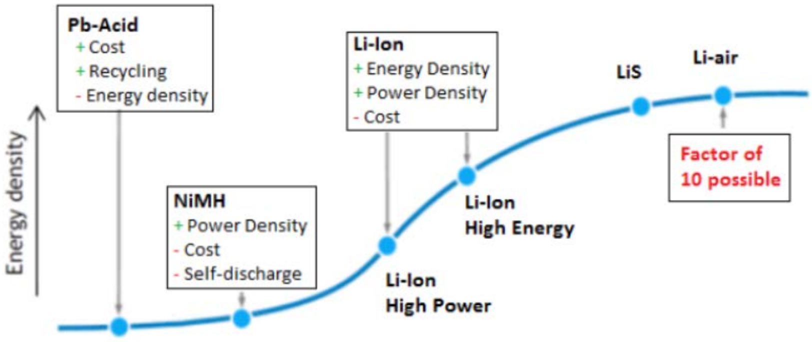
IV. Battery Technology

1. Battery Technology Status

Vehicle batteries are an important component of PEVs, as they determine the vehicle's range and impact vehicle weight. One of the commonly identified challenges with MD/HD electrification, more so for certain applications (e.g., heavy-duty long haul) than others (e.g., transit buses and urban trucks), is the limitations of current battery technology. The energy densities of the batteries on the market constrain the travel distances and operations under more intense duty cycles. The energy density of current battery technology means that batteries must be significantly larger and heavier for MD/HD vehicles than for light-duty vehicles, which can be problematic given the space and weight limitations of MD/HD vehicle applications that are already operating at their weight limits. This major barrier to MD/HD electrification has spurred research by national laboratories and OEMs to investigate the optimal battery chemistries for different vehicle classes and vocations.[209]

Not all batteries used in PEVs today are the same; some battery chemistries are more suited for certain vehicle applications than others. The battery chemistries on the forefront of research and development are lead acid, nickel metal hydride, lithium ion, lithium air, molten salt, and flow. When considering the appropriate battery to use for certain vehicle applications, CARB identified the following evaluation criteria for vehicle batteries: energy-to-volume and energy-to-weight ratios, power density, life span, charge time, performance in various temperatures and conditions, and safety both during vehicle operation and after disposal. The relative energy densities of each of the six battery chemistries are displayed in Figure IV-1 below.

Figure IV-1. Energy Density by Battery Chemistry[210]



(CALSTART, 2013)

The most commonly used battery chemistry in PEVs today is lithium ion. While not the most energy dense of all options, they are widely commercially available and offer higher energy and power densities than some of the other choices. Within the lithium ion category of batteries, there are a number of different battery technologies, including lithium titanate (LTO), lithium-iron phosphate (LFP), lithium-nickel-cobalt-aluminum (NCA), lithium-manganese spinel (LMO), and

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[209] CARB, November 2016
[210] CARB, 2015d

lithium-nickel-manganese-cobalt (NMC). The average energy density of lithium ion batteries is 150 Wh/kg. BYD currently uses LFP battery technology for its BEBs which can run up to 7,200 charge cycles before it reaches 80% of its original capacity.[210,211] BYD is also examining other chemistries for truck products in the near future.[212] TransPower also uses LFP technology for its electric drayage trucks and school buses due to its durability and energy density.[213] LTO technology, which has a long life span and higher stability than other lithium-ion chemistries, is used in Proterra BEBs. NMC batteries are more energy dense and have longer life spans than other lithium-ion battery chemistries, meaning that this particular battery type can be lighter than others without sacrificing vehicle range. NMC batteries are typically used in light-duty vehicles, such as the Chevrolet Volt.[210] There is still potential to improve lithium ion battery technologies. However, other battery chemistries are being investigated as well.[213]

Four of the six battery chemistries listed in Table IV-1 are appropriate for use in MD/HD electric vehicle applications. The energy densities of lead acid and nickel metal hydride batteries are too low to be practical for use in MD/HD applications; the batteries would be far too large and heavy. Molten salt batteries, typically composed of molten sodium and nickel chloride, are currently being tested in a few MD/HD demonstrations. Specifically, the ZEBRA molten salt battery is used for Motiv Power Systems' refuse trucks. The ZEBRA battery is durable and operates well in extreme weather conditions. However, its energy density is lower than the typical lithium ion battery at 90 Wh/kg to 120 Wh/kg. Lithium air batteries have the highest energy density at 5,200 Wh/kg, which is comparable to that of conventional gasoline. The lithium air battery chemistry includes lithium and atmospheric oxygen. Lithium air batteries are still in the research and development stage. Lastly, flow batteries hold their energy in electrolytes. The energy in flow batteries can be replenished by "refueling" the battery with new electrolytes. The energy density of these batteries can be up to ten times higher than lithium ion batteries. Flow batteries are currently used to store energy from the electrical grid, but are also in the research and development phase for vehicle use.[214]

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[211] Swanton, nd
[212] Z. Kahn and R. Schenker, BYD, personal communication, February 9, 2018.
[213] IEA, 2017a
[214] CARB, 2015d

Table IV-1. Characteristics of Various Battery Chemistries[214]

Battery Chemistries	Specific Energy [Wh/Kg]	Life span [Cycles]
Nickel Cobalt Aluminum or Li NCA	160	2000+
Lithium Manganese Oxide or LMO	150	1500+
Nickel Manganese Cobalt Oxide or NMC	150	2000+
Lithium Iron Phosphate or LFP	140	5000+
BYD's Iron Phosphate or LFP	120	7000+
Lithium Titanate or LTO	90	5000+
Lead Acid or PbA	35	500
Nickel Metal Hydride or NiMH	70	3000+
Molten Sodium or ZEBRA	110	2000+
Lithium Air or Li Air	>5200	Unknown (long)
Flow Battery	Unknown	Unknown (long)

(See text, Chapter II A)

In the near term, CARB predicted in 2017 that lithium ion batteries will remain the primary battery chemistry. However, battery technology is continuously developing, resulting in longer vehicle ranges and smaller battery pack sizes.[215] In fact, over the next 10 to 20 years it is expected that battery life will increase and that battery energy density will grow to anywhere between three and ten times its current density.[216] Continued research by national laboratories in conjunction with vehicle demonstrations will help with the development of battery technology.[217] That said, one of the publications reviewed emphasized the importance of evaluating how increasing demand for battery components, such as lithium and cobalt, will impact resource supply and the environment. The ability to recycle batteries for secondary uses will become increasingly important as battery electric vehicle technology becomes more popular.[218] BYD has already announced its plans to open a battery recycling plant in Shanghai,

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[215] CARB, 2017a

[216] den Boer, E., S. Aarnink, F. Kleiner, and J. Pagenkopf, *Zero emissions trucks: An overview of state-of-the-art technologies and their potential,* 2013.

[217] CARB, November 2016

[218] IEA, Global EV Outlook 2017: Two Million and Counting, 2017b.

China in mid-2018.[219] As batteries become lighter and less costly, electrification will become feasible in more vehicle vocations.[220]

2. Battery Technology Cost

Batteries are the biggest contributor to BEV cost. BNEF reports that battery packs make up 48% of light-duty BEV prices and NREL cites other resources that batteries account for anywhere from 13% to 61% of the total price.[221,222] The ICCT notes, "Battery and fuel cell system costs vary widely in the literature, depending on innovation, supplier competition, and economies of scale that are underway largely as a result of light-duty vehicle developments."[223] The literature reviewed indicates across the board that battery costs are decreasing rapidly and will continue to come down in future years, even as energy capacity improves. According to BNEF and other sources, the recent dramatic drop in battery prices is due to battery oversupply, reduced material costs, improved technology that can be used across vehicle applications, increased production, manufacturing improvements, and more competition in the market. In addition, vehicle manufacturers are beginning to see the benefit of launching their own battery products, rather than engaging with a supplier, in order to eliminate up-charges.

Most of the literature is not specific about the battery technology isolated in their cost estimates, presumably most use the least expensive – and most competitive – for their projections. While lithium ion batteries are the current conventional technology, advanced lithium ion (using a silicon alloy-composite anode) and other technologies (e.g., lithium metal, including lithium sulfur and lithium air) are included in the literature.[218]

According to a study BNEF conducted in 2017, battery prices are $209 per kWh, which is down by 24% from just a year prior (see Table IV-2). CARB echoes this, stating that battery costs have decreased 20% to 35% annually since 2012,[215] and BCG notes that battery prices have dropped about 20% per year since 2009.[224]

BNEF predicts that battery prices will keep falling to $73 per kWh by 2030. NREL cites U.S. Department of Energy goals to bring prices down to $100 per kWh in the near term and $80 per kWh in the long term, price points NREL assumes are achievable by 2033 and 2038, respectively.[225] Other publications estimate similar drops. And in 2016 CARB cited studies that estimate battery costs will decrease by about two-thirds by 2030.[226]

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[219] Daly, T. "Chinese carmaker BYD close to completing battery recycling plant," Reuters, March 21, 2018.
[220] Transport & Environment, 2017b
[221] Curry, C., *Lithium-Ion Battery Costs and Market,* presentation, 2017.
[222] Jadun et al., 2017
[223] Moultak et al., 2017
[224] Boston Consulting Group (BCG), *The Electric Car Tipping Point*, presentation, 2017a.
[225] Jadun et al., 2017
[226] CARB, November 2016

Table IV-2. Battery Price Decreases Since 2010[227]

Year	Price per kWh
2010	$1000
2011	$800
2012	$642
2013	$599
2014	$540
2015	$350
2016	$273
2017	$209
2025	*$100*
2030	*$73*

Table IV-3 summarizes additional battery costs and projections found in the literature, most of which align with BNEF's figures.

Table IV-3. Battery Prices Cited in the Literature

Year	Cost ($/ kWh)	Other Considerations	Source
2012	$571	Based on 350 kWh battery	[228]
2014	$500		[229]
2015	$500-$700		[228]
2015	$700		[230]
2015	$230-$420 ($326 average)		[231]
2017	$250		[232]
2017	$300-$500		[232,233]
2017	$203		[234]
2018	$200		[228]
2020	$228		[231]
2020	$317	Based on 350 kWh battery	[235]
2023	$150-$225		[236]
2025	$168		[236]
2030	$200	Based on 350 kWh battery	[235]
2030	$97		[237]
2030	$250		[238]

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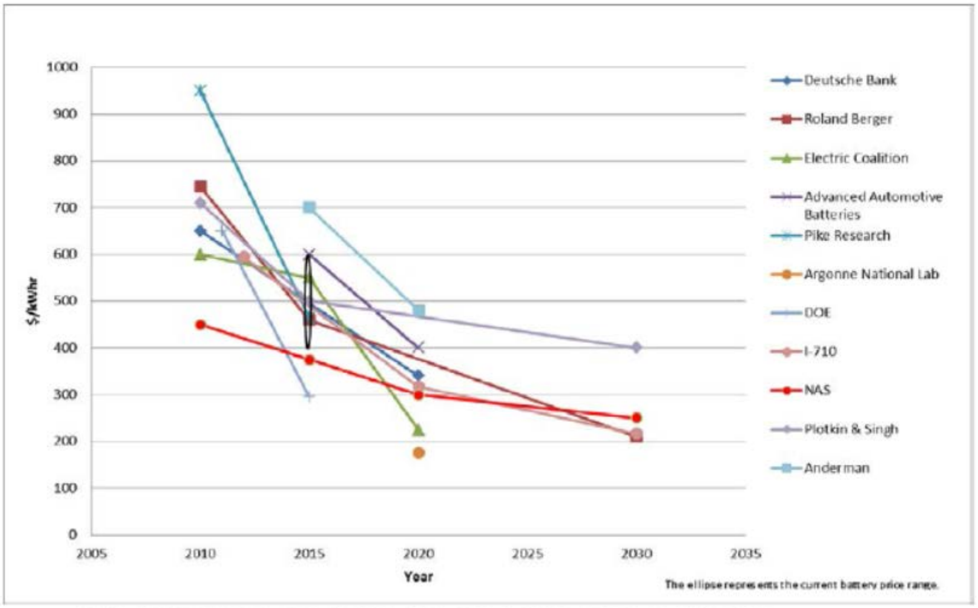
[227] Curry, 2017
[228] CARB, 2015d
[229] Fulton and Miller, 2015
[230] CARB, 2015e
[231] Moultak et al., 2017
[232] IEA, 2017a
[233] IEA, 2017b
[234] BCG, *The Reimagined Car: Shared, Autonomous, and Electric*, 2017b.
[235] CARB, 2015d
[236] Moultak et al., 2017
[237] BCG, 2017b
[238] Fulton and Miller, 2015

Year	Cost ($/ kWh)	Other Considerations	Source
2030	$150		236
2030	$120		236
2033	$100		239
2038	$80		239
Announcements from GM, LGChem, Tesla, Panasonic	$180-$200		240,241
Future costs	$80-$150		240

The following figures from the literature summarize past and future battery cost estimates. The estimates for battery costs in 2020 range from about $100 to $500 per kWh. In 2030, the range comes down to $70 to $400 per kWh. Most publications predict a continued significant price drop in the near term, with a slowdown in coming years. NREL explains, “Costs have decreased rapidly in recent years, falling 19% per year on average from 2010 to 2015, according to Curry (2017). If this trend continued, costs would reach unexpectedly low values, so we assume slower cost reductions through 2050.” Figure IV-2, Figure IV-3, Figure IV-4, and Figure IV-5 show a higher trajectory of decreasing battery costs than the NREL study from studies by CARB, BCG, BYD and IEA.

Figure IV-2. CARB-Compiled Forecasts for Battery Costs[235]



(CALSTART,2013; DOE, 2012; EEI, 2014; NAS, 2013; Sakti, 2015)

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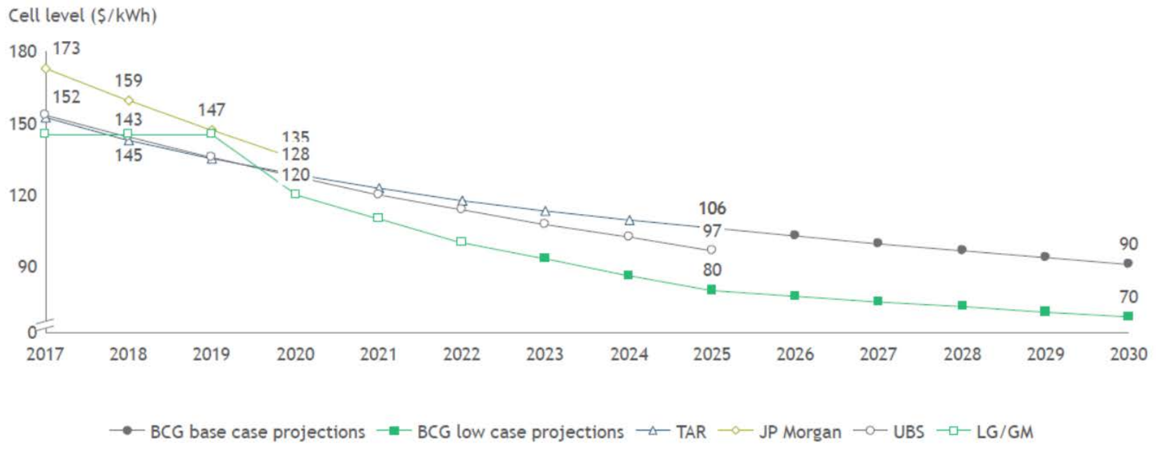
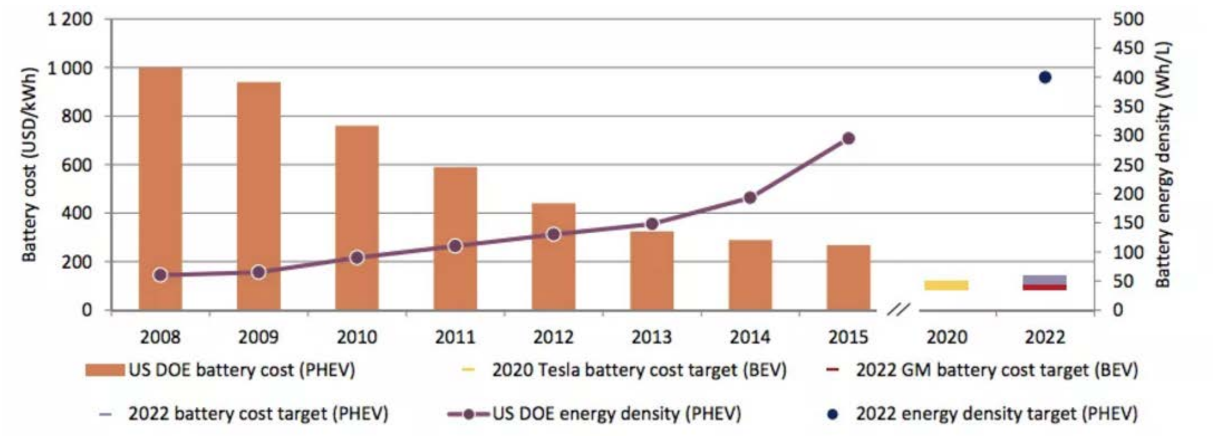
[239] Jadun et al., 2017
[240] IEA, 2017a
[241] IEA, 2017b

Figure IV-3. BCG-Compiled Forecasts for Battery Costs[242]



Note: TAR report D segment battery cell cost used at ~65 kWH to 2025
Sources: BCG analysis and forecast; TAR report; JP Morgan Global xEV Components report; UBS Future of Powertrain report; expert interviews; GM annual global conference

Figure IV-4. BYD-Compiled Forecasts for Battery Costs and Energy Densities[243]



Notes: USD/kWh = United States dollars per kilowatt-hour; Wh/L = watt-hours per litre. PHEV battery cost and energy density data shown here are based on an observed industry-wide trend, include useful energy only, refer to battery packs and suppose an annual battery production of 100 000 units for each manufacturer.

Sources: US DOE (2015 and 2016) for PHEV battery cost and energy density estimates; EV Obsession (2015); and HybridCARS (2015).

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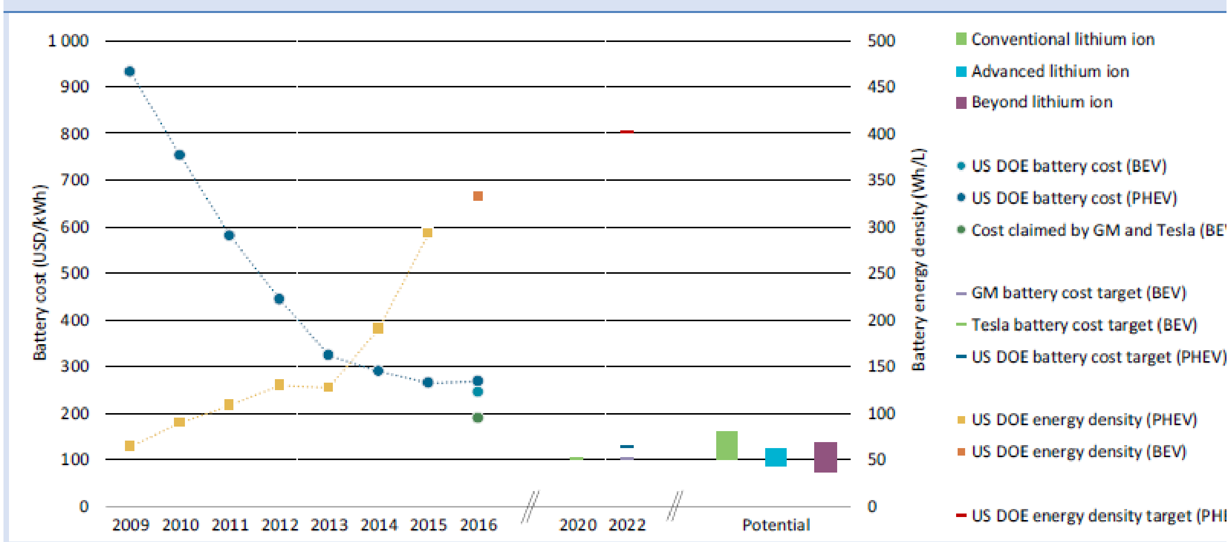
[242] BCG, 2017a
[243] Swanton, 2017

Figure IV-5. International Energy Agency-Compiled Forecasts for Battery Costs and Energy Densities[244]



Notes: Contrary to the results assessed for 2009-15, which targeted PHEV batteries, the 2016 estimates of costs and volum energy density by the US DOE (costs are to be interpreted as projections for the high-volume production of technologies curr being researched) refer to a battery pack that is designed to deliver 320 km of all-electric range and is, therefore, suitable for The latest update of this cost assessment was developed accounting for an advanced lithium-ion technology (with silicon composite anode). Being a technology that is still being researched today, this is currently deemed to have a greater cost but larger potential for cost reductions compared with conventional lithium-ion technologies.

While the discussion of battery costs in most publications does not differentiate between the cost per kWh for a LD vehicle versus a MD/HD vehicle, NREL assumes that battery costs (on a per kWh basis) for MD/HD vehicles should be scaled by a factor of 1.5 to account for the higher costs. The authors explain that the larger vehicles require different packaging and thermal management systems, and are seeing lower production volumes, resulting in higher prices. NREL also notes that there is very limited literature on HD vehicle-specific battery costs and projections,[245] which aligns with the findings of this literature review.

Table IV-4 summarizes total battery costs per vehicle from various sources reviewed.

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[244] IEA, 2017b

[245] Jadun et al., 2017

Table IV-4. Vehicle Battery Pack Costs

Vehicle	Year	Cost	Source
Bus (100 kWh)	2015	Under $60,000	[246]
PHEV truck (25 km all-electric range)	2017	$9,000	[247]
BEV truck (200 km all-electric range)	2017	$70,000+	[247]
Electric truck (400 kWh)	2014	$200,000	[248]
Electric truck (400 kWh)	2030	$100,000	[248]

Little data is available on the frequency and cost of battery replacements for BEVs. As a point of reference, CARB's ICT assumes replacing a battery electric transit bus battery mid-life (at approximately 7 years) will cost $75,000, compared to a diesel or CNG engine rebuild ($35,000) or fuel cell replacement ($200,000).[249] Until there is more clarity around the future of batteries, some companies are selling BEBs for prices comparable to diesel models and offering lease programs for the batteries.[250]

One of the factors that may bring overall vehicle prices down is finding a second use for batteries once they can no longer be used in vehicles. According to CARB, battery reuse is usually feasible if the energy capacity is not less than 70-75% of its nameplate capacity. In these cases, batteries may have a second life as back-up power or energy storage for buildings or in other uses.[251] In addition, it may be possible to recycle battery components if the industry is able to improve separation technology and the flexibility of the recycling process, and standardize materials and designs.[251]

V. Charging Technology

1. Charging Technology Status

In addition to advances in battery technology, improvements in and increasing deployment of PEV charging infrastructure will also play a key role in increasing the deployment of MD/HD electric vehicles. In fact, according to the International Energy Agency, the growth rate of public EVSE, which are primarily utilized for light-duty vehicles, from 2015 to 2016 was 72%.[252] There are two types of charging infrastructure available for PEVs: conductive and inductive. Conductive charging transfers energy directly to the vehicle's battery through a vehicle connection with the vehicle, typically via a plug. Inductive charging does not require a physical

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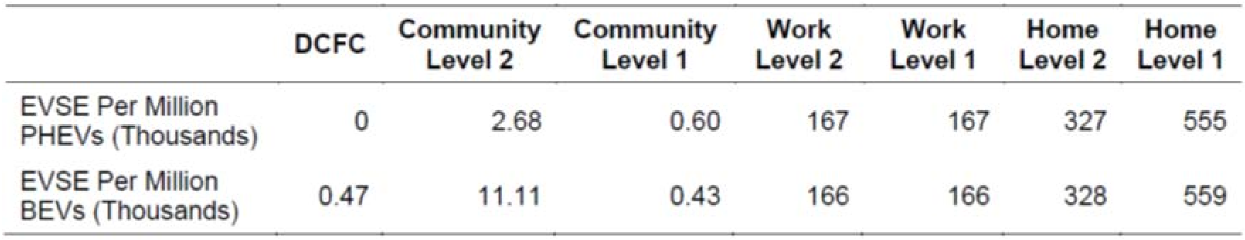
[246] CARB, 2015d
[247] IEA, 2017a
[248] Fulton and Miller, 2015
[249] CARB, 2017b
[250] Chandler et al., 2017
[251] CARB, 2017a
[252] IEA, 2017b

connection with the vehicle. Rather, the vehicle must be in close proximity to the inductive coils of the charger and energy is transferred to charge the battery. Inductive charging can be less efficient than conductive charging, although it can also be more convenient to charge without a direct connection for certain applications.[253]

Lack of available charging infrastructure is another main barrier to widespread PEV deployment. Currently, most PEV drivers rely on charging infrastructure at home or the workplace.[253] As such, running routes other than the typical commute can pose challenges in terms of finding infrastructure to recharge. NREL estimated the EVSE to PEV ratio necessary to meet PEV charging needs based on information from Melaina et al., 2016 (Table V-1). NREL calculated the DCFC ratio based on an estimate of the MD/HD PEV population. Level 1 and Level 2 ratios were calculated based on the estimated light-duty PEV population:[254]

Table V-1. NREL-Estimated EVSE to PEV Ratios by Charge Level and Destination[254]



	DCFC	Community Level 2	Community Level 1	Work Level 2	Work Level 1	Home Level 2	Home Level 1
EVSE Per Million PHEVs (Thousands)	0	2.68	0.60	167	167	327	555
EVSE Per Million BEVs (Thousands)	0.47	11.11	0.43	166	166	328	559

Installing charging hubs in highly populated areas, as well as along corridors that are currently lacking charging infrastructure, could ease some of the qualms that drivers and fleets have in terms of PEV range. A benefit of MD/HD electrification, in this respect, is that most fueling already occurs in a centralized location. Super-fast charging equipment is also being developed, with power outputs ranging from 100 kW to 500 kW, compared to the 1-19 kW range of Level 1 and Level 2 EVSE.[253] That said, the impacts that these charge hubs and super-fast chargers may will have on the electricity grid must be considered.[253] Additionally, there is a need to develop standards for MD/HD charging equipment. SAE has convened a MD/HD charging task force to develop standards for MD/HD EVSE. Standards currently under development include SAE J3068 and SAE 53105.[255] Standardizing charging infrastructure will help ensure that MD/HD PEVs can charge at any EVSE location without having to worry about compatibility between the charging equipment and the vehicle's on-board charging system.[256]

Recently, EVSE manufacturers, OEMs, and national laboratories alike have been researching innovative ways to increase vehicle range through more efficient and strategically placed charging infrastructure. The most basic of the charging methods is on-route charging, or opportunity charging. Drivers can charge their vehicles as they come across EVSE stations, and perhaps plan their routes around where EVSE is available. For fleet vehicles that operate on fixed routes, chargers can be installed along the route for convenience. Another option is a

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[253] Weiss, J., R. Hledik, M. Hagerty, and W. Gorman, *Electrification: Emerging Opportunities for Utility Growth*, The Brattle Group, 2017.
[254] Jadun et al., 2017
[255] McGee, R., *SAE Medium/Heavy Duty Task Force Update*, presentation, 2017.
[256] IEA, 2017a

combination of on-route and overnight charging. As mentioned previously, Foothill Transit charged its BEBs both between routes using DC fast inductive chargers and overnight using conductive chargers to maximize efficiency in vehicle charging and to allow the BEBs to maintain adequate states of charge for regular operation.[257] From interviews with BEB manufacturers, the trend and demand for BEBs is moving away from fast in-route charging and towards overnight depot charging, although there will still be a market for in-route and opportunity charging to extend range if needed.

Electrified road systems (ERS), or eHighways may be a possible near- to mid-term solution to the range limitations of heavy-duty electric vehicles.[258] ERS allow vehicles to charge while they are driving, either through a conductive overhead catenary system or via inductive charging equipment installed in the road below the vehicle. This technology could eliminate the need for larger vehicle batteries and address the lack of available charging equipment (or EVSE), two large setbacks to MD/HD electrification.[259] They can also be installed on particularly steep routes and assist vehicles that carry heavy payloads, both of which can reduce vehicle range.[258]

Conductive overhead catenary systems for plug-in hybrid electric heavy-duty trucks are currently in the demonstration phase. Of note, Siemens has been demonstrating eHighway overhead catenary systems in California, Germany, and Sweden. The system is compatible with parallel-hybrid, serial-hybrid, and full electric trucks.[260] BETs can easily connect and disconnect from the catenary system when needed without major modifications to existing vehicle technologies.[261] Siemens' overhead catenary demonstration in Germany found that the systems can actually smooth the electricity load as compared to conventional "opportunity" vehicle charging. The load profile for the ERS overhead catenary system was low and consistent over the test period, compared to the load profile for conventional PEV charging which was relatively low on some days of the week but very high on others (Figure V-1).[260] The eHighway did not disrupt the flow of regular traffic much.[261] In the near term, overhead catenary systems are feasible for shuttle and mine transport. In the long term, long haul trucking is a feasible

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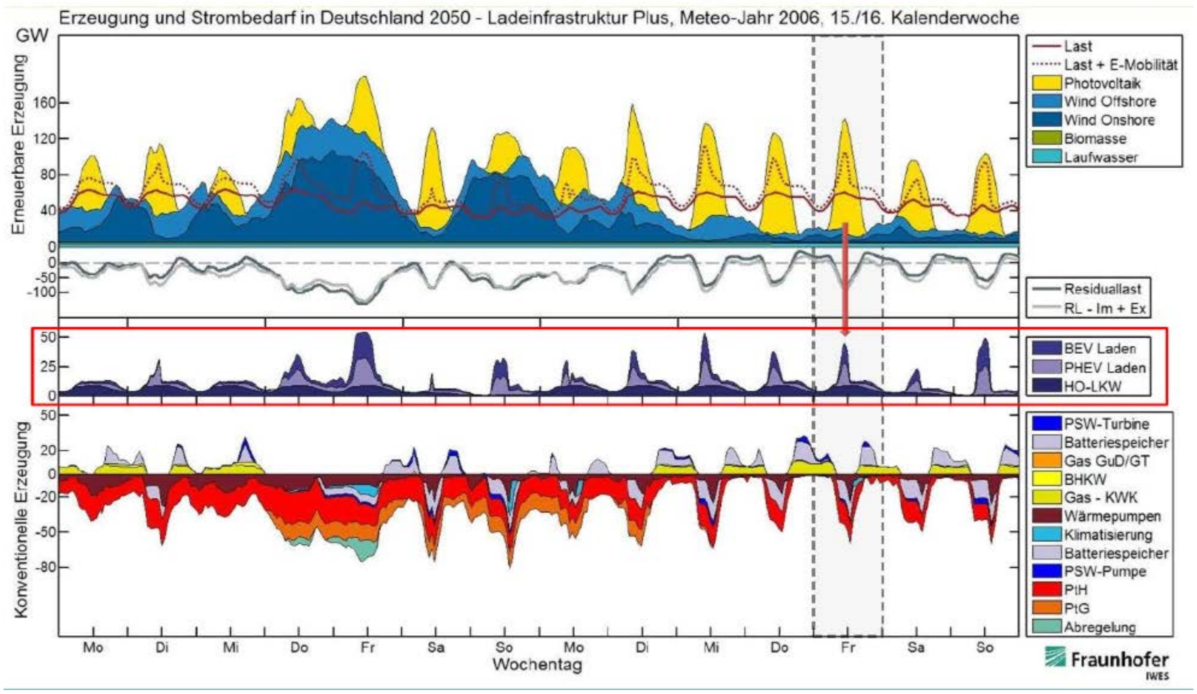
[257] Eudy and Jeffers, 2017
[258] California Cleaner Freight Coalition, 2017
[259] IEA, 2017a
[260] Siemens, *eHighway: Electrified Heavy Duty Road Transport*, presentation, 2017.
[261] Wästljung, U., *Electrification – One Road Towards Sustainable Transport Solutions,* presentation, nd.

application.[260] Volvo has also been testing conductive charging methods, including installing metal bars in the road and overhead catenary systems.[258]

Figure V-1. Electricity Load Profile by Energy Source, Charging System, and Production Method for Siemens eHighway Demo in Germany[260]



Inductive ERS involves the installation of inductive coils in the road and receiving coils in the actual vehicle itself.[262] There are a few demonstrations for inductive ERS as well. For example, Swedish OEM Scania is testing wireless charging routes for urban BEBs and heavy-duty trucks.[263] Although the ease with which vehicles can charge using inductive ERS is a benefit, there are also a number of limitations to the technology that should be taken into account. In particular, inductive ERS is less efficient in charging the vehicle than conventional vehicle charging. In addition, the installation of inductive ERS requires more alterations to existing infrastructure than conductive ERS and is, in general, more complex.[262] Both ERS technologies can help advance MD/HD electrification. Siemens compared the efficiency, range, and cost per kilometer of ERS, PEV batteries, hydrogen, and CNG and found that ERS is the most efficient and is the least expensive option (Figure V-2).[264]

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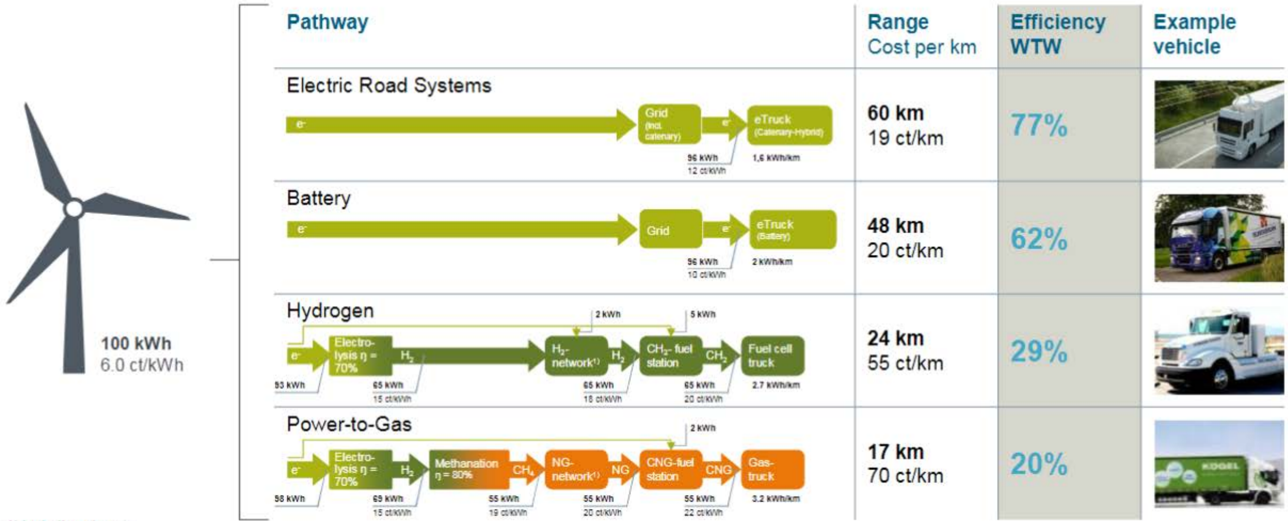
[262] IEA, 2017a
[263] California Cleaner Freight Coalition, 2017
[264] Siemens, 2017

Figure V-2. Siemens' Range and Efficiency Comparison of Various Vehicle Fuels[264]



1) Including storage
Source: German Ministry of Environment

Overall, the publications reviewed emphasized the importance of considering the impact that implementing EVSE and ERS will have on the electricity grid. Integrating renewable energy into the mix may be able to alleviate some of the stress that the increasing deployment of charging technologies will have on electricity load by matching load increases during the day with likely daytime charging of MD/HD BEVs.[264,265] In addition, the ERS should cover a significant portion of the vehicle's route—anywhere from 20% to 50% of the distance that the vehicle will travel.[266]

2. Charging Technology Cost

The cost of charging infrastructure, including trenching and upgrading the distribution system, is often seen as a barrier – or, at the very least, an unknown – to MD/HD BEV deployment.[267] In general, little is known about the utility distribution system implications for large-scale MD/HD BEV deployment, which could have significant impacts on overall infrastructure costs. In addition, several publications call for the standardization of charging infrastructure in order to reduce costs through increased volume and scale.

Table V-2 summarizes charging infrastructure costs, which range between $1,000 and $350,000 for stationary chargers, and up to $6,000,000 per mile for catenary and in-road charging. The high upfront cost of catenary, electric road, and in-road charging systems make them most suitable for heavily traveled corridors, but they can result in lower vehicle costs because of a smaller battery can be used.[268] Siemens own review of its electrified road system compared to other technologies indicated that the total accumulated costs through 2050 of an electrified road system could be about half that of internal combustion engine vehicles, more

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[265] IEA, 2017a
[266] Nylander, A., Electric Road Systems - A Strategic Perspective, presentation, Swedish Transport Administration, nd.
[267] CALSTART, 2015
[268] Moultak et al., 2017

than half the cost of LNG vehicles, and nearly a third of the cost of hydrogen fuel cell vehicles.[269]

Installation costs, which can vary dramatically ($17,000 to $200,000) based on the amount of trenching and electrical service upgrades necessary, and maintenance costs (up to $18,000 per year) are also included, where available.

Table V-2. Charging Infrastructure Costs Cited in the Literature

Year	Measure	Cost	Additional Considerations	Source
2013	50 kw wireless charger	$350,000	Equivalent to $7 per watt	270
2015	Charging infrastructure	$1,000-$350,000		271
2015	Level 2	$2,000-$6,000	Maintenance is $300 per year; trenching is $25-$100 per foot	271
2015	Level 3	$50,000+	Maintenance is $1,000-$2,000 per year; trenching is $25-$100 per foot	271
2015	16.5 kw (220v/75A)	$1,000-$3,000	Installation is $17,000-$32,000	272
2015	70 kW (208 VAC/200A)	$5,000-$10,000	Installation is $20,000-$75,000	272
2015	450 kW (480VAC/640A)	$350,000	Installation is $150,000-$200,000	272
2015	Catenary power (per mile)	$1,300,000 - $6,000,000		273
2015	In-road power (per mile)	$4,000,000 - $6,000,000		273
2016	Proterra depot charger	$50,000	Maintenance is $500 per year	274
2016	Proterra on-road charger	$349,000	Maintenance is $13,000 per year	274
2016	On-route charger installation	$250,000		274
2016	250kW WAVE wireless charger	$286,000	Installation is $220,000; receiver is $103,000	274
2017	200 kw	$400,000	Equivalent to $2 per watt	270
2017	In-depot charger	$50,000		275
2017	Two 500kW Eaton overhead fast chargers	$665,000	Maintenance on chargers is $1,500 per month	275

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[269] Siemens, 2017
[270] Chandler et al., 2017
[271] CARB, 2015d
[272] CALSTART, 2015
[273] ICF, 2015
[274] CARB, 2017b
[275] Eudy and Jeffers, 2017

Year	Measure	Cost	Additional Considerations	Source
2017	Electric road systems, per lane-km (installation)	$1,000,000+	Could come down by half in the future	[276]
2017	Inductive charging on new roads ($/km)	$800,000		[276]
2017	Inductive charging on existing roads ($/km)	$3,100,000		[277]
2017	Infrastructure upgrades ($/bus)	$20,000-$75,000	Depends on site conditions, charging strategy, number of chargers, and other factors	[274]
2017	Catenary power (per km)	$800,000 - $3,800,000	Annual operation and maintenance is 1-2.5% of the initial capital cost	[278]
2017	In-road (per km)	$2,500,000 - $4,000,000	Annual operation and maintenance is 1% of the initial capital cost	[278]

In its Electrification Futures Study, NREL assumes that the costs of charging equipment will remain constant over time, in part because of the lack of reliable projections in the literature, but also due to the “relative maturity” of the technology. The authors explain, “Costs for the EVSE itself are generally assumed to decline, but total costs also depend on future installation costs (DOE 2015d), a significant and uncertain portion of which depends on potentially divergent trends such as learning from experience, regulatory changes, and favorability of sites.” Table V-3 shows projected costs per vehicle of new and replacement charging infrastructure for BEBs, MD BETs, and HD BETs based on NREL’s slow, moderate, and rapid advancement scenarios. It includes both new and replacement costs. The initial purchase is expected to be higher than the replacement because most installation costs (e.g., trenching for new electrical service) are only necessary once. While not included in this table, NREL projects catenary charging infrastructure costs to be nearly $35,000 per HD vehicle, assuming large-scale deployment.[279]

Table V-3. NREL’s Projected Charging Infrastructure Costs per Vehicle for BEVs[279]

	Slow Advancement		Moderate Advancement		Rapid Advancement	
Vehicle Type	New	Replace	New	Replace	New	Replace
BEB	$97,618	$91,097	$45,555	$42,512	$12,424	$11,594
MD BET	$34,556	$25,051	$27,645	$20,041	$9,215	$6,680
HD BET	$136,665	$127,536	$56,944	$53,140	$25,308	$23,618

Table V-4 shows the charging infrastructure collected during interviews with MD/HD manufacturers for this literature review.

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[276] IEA, 2017a
[277] IEA, 2017a
[278] Moultak et al., 2017
[279] Jadun et al., 2017

Table V-4. Charging Infrastructure Costs from Interviews

Vehicle Manufacturer	Charger Type	Cost	Comments/ Additional Considerations
BYD	40kW	$2,500	[280]
BYD	80kW	$8,000	Essentially two 40kW chargers together[280]
BYD	100KW	$20,000	[280]
BYD	200kW	$30,000	Mainly for yard hostlers and coach/articulated buses[280]
Proterra	50-75kW	$40,000 - $50,000	Depot charging; J1772 Combined Charging System (CCS) [281]
Proterra	Up to 400kW	$350,000	Overhead charging; $25,000 - $500,000 installation cost[281]
Motiv	Level 2	$3,900	Clipper Creek, CS100 three phase[282]

Tesla does not have costs available yet for their charging infrastructure. Their base level charging for overnight charging will be 125 kW, similar the currently level of charging available at existing supercharger stations. Tesla is considering in-route or truck stop charging around 1 MW to match the use case of fleet depot or truck stop charging.[283]

VI. Emissions

Under business as usual with ICE vehicles, emissions from MD/HD vehicles are expected to increase as more of them are placed on the road.[284] Demand for goods movement is expected to grow across California, with freight truck VMT estimated to increase 80% by 2035 from 2008 levels in Southern California, and by 60% from 2007 levels by 2040 in the San Joaquin Valley region.[285,286] Many publications emphasize that California cannot reach its emissions targets without the increasing deployment of zero emission vehicles.[287] The emissions impacts of electricity, natural gas, and diesel all depend on tailpipe (i.e., in-use) emissions, the feedstocks used to produce the fuels, and the efficiency of the vehicle technology. BEVs have zero in-use vehicle emissions. On a WTW basis, PEVs also demonstrate both GHG and air pollutant emissions reductions compared to natural gas and diesel vehicles. In fact, while efficiency improvements in conventional diesel vehicle technology can reduce life cycle carbon dioxide emissions by about 40%, electric drive technology powered by renewable sources can improve vehicle life cycle emissions by over 80%.[288] BEVs are zero-emission when referring to tail pipe

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[280] Z. Kahn and R. Schenker, BYD, personal communication, February 9, 2018.
[281] K. Leacock, Proterra, personal communication, February 9, 2018.
[282] U. Nagrani, Motiv, personal communication, February 7, 2018.
[283] D. Witt, Tesla, personal communication, April 16, 2018.
[284] Moultak et al., 2017
[285] Southern California Association of Governments, *On the Move: Southern California Delivers the Goods*, 2012.
[286] *San Joaquin Valley Interregional Goods Movement Plan*, Cambridge Systematics, Inc., The Tioga Group, Inc., Fehr & Peers, and Jock O'Connell, developed for San Joaquin Valley Regional Transportation Planning Agencies, 2013.
[287] The American Lung Association in California, *The Road to Clean Air: Public Health and Global Warming Benefits of Advanced Clean Car Standards,* 2011.
[288] Moultak et al., 2017

emissions. Emissions associated with producing electricity can also be zero when using renewable energy.[289]

1. Electric Vehicle Emissions

BEVs emit zero direct tailpipe emissions. On a well-to-wheels (WTW) basis, BEV GHG and air pollutant emissions depend on the electricity grid mix, as well as emissions from battery manufacturing. Even with the national average electricity grid mix, a majority of the literature reviewed estimates that electrified vehicles will result in GHG, NOx, and PM emissions reductions compared to conventional diesel and fossil natural gas.[290] In fact, according to EPRI and NRDC, carbon dioxide (CO_2), sulfur dioxide (SO_2), and NOx emissions from the United States grid actually decreased from 2003 to 2013, while electricity generation increased by 6%. Many electricity grids across the country have improved their generation efficiency and emissions levels at a faster rate than conventional vehicle emissions have improved. On a national level, EPRI and NRDC found the share of electricity produced by renewable energy sources is increasing.[291]

The same EPRI and NRDC analysis found that, in 2013, a PEV powered by the average United States electricity mix has an energy conversion efficiency of 61 miles per gasoline gallon equivalent (mpgge). This value ranges from 46 mpgge to 251 mpgge, depending on geographic region.[292] The estimated energy conversion efficiency and CO_2 intensities of electricity generation in regions across the United States can be found below (Table VI-1and Figure VI-1).[292]

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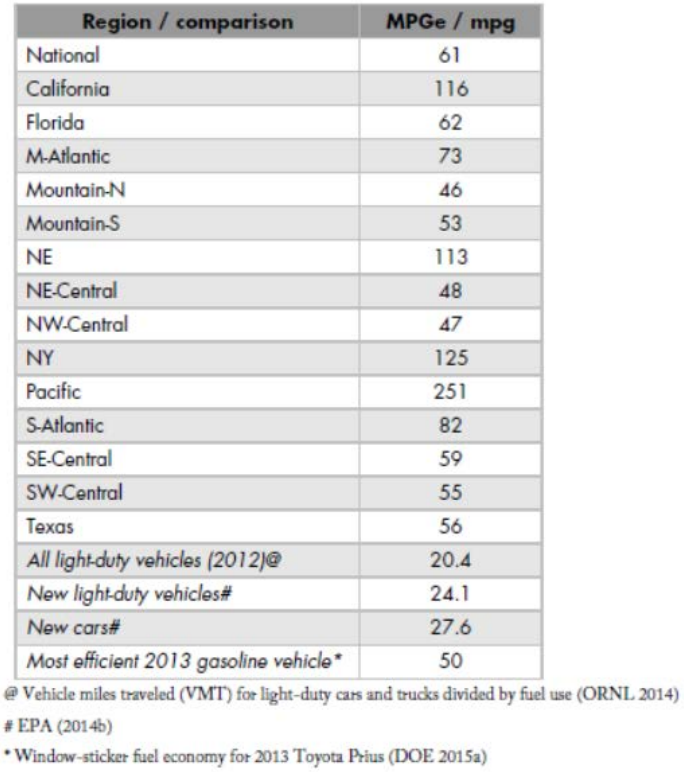
[289] CARB, 2015f
[290] CARB, 2017b
[291] EPRI and NRDC, 2015
[292] EPRI and NRDC, 2015

Table VI-1. PEV Energy Conversion Efficiency Estimates (mpgge) by Region[267]



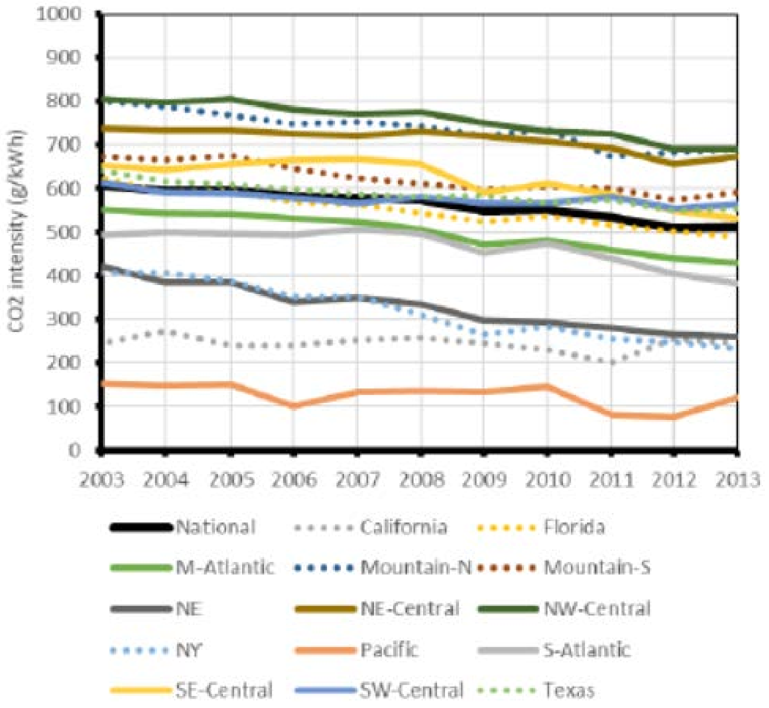
Region / comparison	MPGe / mpg
National	61
California	116
Florida	62
M-Atlantic	73
Mountain-N	46
Mountain-S	53
NE	113
NE-Central	48
NW-Central	47
NY	125
Pacific	251
S-Atlantic	82
SE-Central	59
SW-Central	55
Texas	56
All light-duty vehicles (2012)@	20.4
New light-duty vehicles#	24.1
New cars#	27.6
*Most efficient 2013 gasoline vehicle**	50

@ Vehicle miles traveled (VMT) for light-duty cars and trucks divided by fuel use (ORNL 2014)

EPA (2014b)

* Window-sticker fuel economy for 2013 Toyota Prius (DOE 2015a)

Figure VI-1. Carbon Intensity of Electricity Generation by Region[267]



The extent of emissions reductions from electrification varied by resource. It is important to note that some publications evaluated emissions from specific vehicle categories, while others addressed emissions from all MD/HD electric vehicles. In addition, the granularity of the emissions impact data varied significantly between publications. Some publications provided exact quantitative values for emissions differences between electricity and other fuels, while others simply provided qualitative analyses about the relative emissions of each fuel.

According to UCS, high PM emitting feedstocks in electricity generation are biomass and coal-fired power plants. In California, biomass and coal comprise only 3% and 7%, respectively, of California's electricity generation mix. In fact, California has committed to phasing out coal from electricity generation in the state entirely by 2026. While California's current electricity generation mix results in well-to-pump emission benefits for BEVs compared to ICE vehicles, it is expected that air pollutant emissions will decrease even more as California's grid moves towards more renewable electricity generation sources.[293]

CCFC and NRDC found that, taking into account WTW emissions, MD/HD electrification can reduce GHG, NOx, and PM emissions by 90% or more compared to ICE vehicles.[294,295] NRDC's estimate considered battery electric urban freight trucks traveling 80 miles or less per day, while CCFC considered many different MD/HD freight vocations. CCFC's 90% emissions reduction estimate is for MD/HD freight electric vehicles fueled by CARB's estimate of the California electricity mix by 2020, which assumes a higher percentage of renewables than the U.S. average. NRDC's estimate was calculated for the states of New York and New Jersey, which have electricity mixes of primarily natural gas and nuclear power. Based on the current average electricity mix in the United States, NRDC found that total GHG, NOx, and PM emissions have the potential to decrease by 70%.[295]

As for transit buses, UCS calculated that, compared to a conventional diesel bus, with California's current electricity grid mix of 50% natural gas, 25% renewable energy, 10% nuclear energy, 8% hydropower, and 7% coal, WTW GHG emissions for a BEB is 74% lower. Assuming a 50% renewable and 50% natural gas electricity mix, UCS estimates a GHG emissions reduction of 80% compared to conventional diesel buses.[293] UCS developed a number of figures to summarize these findings, provided below (Figure VI-2 and Figure VI-3).

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[293] Chandler et al., 2017
[294] California Cleaner Freight Coalition, 2014
[295] NRDC, *National Freight Pathways: Moving Toward a Cleaner System to Reduce Emissions, Improve Air Quality, and Create Healthier Communities*, 2015.

Figure VI-2. UCS-Estimated WTW GHG Emissions from Various Fuel Pathways[293]

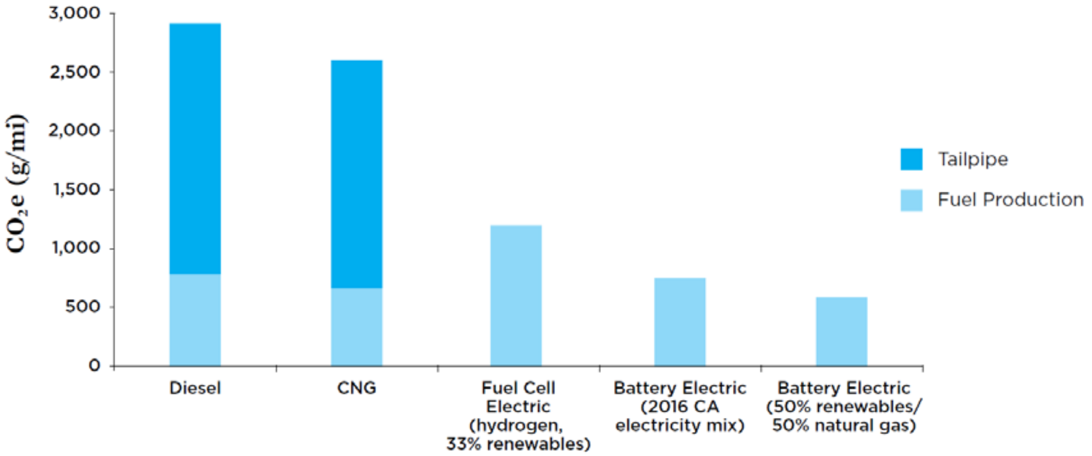
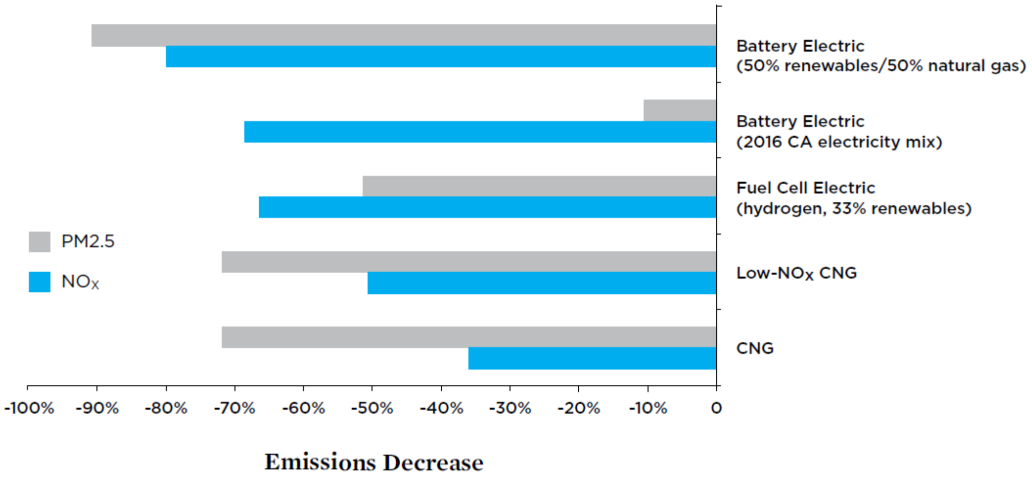


Figure VI-3. UCS-Estimated WTW Air Pollutant Emissions from Various Fuel Pathways[293]



Compared to CNG-powered buses, WTW NOx emissions are also estimated to be lower for BEBs—even for CNG buses certified to California's optional low NOx standards.[296] Another estimate finds that BEBs operating on electricity from a natural gas power plant have lower WTW GHG emissions than a conventional natural gas bus.[297] In addition, one publication stated that a BEB running on electricity from a natural gas power plant can travel up to twice as far as a conventional natural gas bus operating on the same amount of natural gas.[298] It is estimated that electric trucks and buses can reduce GHG emissions by 36% compared to RNG-powered vehicles where the RNG is sourced from landfills.[299]

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[296] Chandler et al., 2017
[297] Chandler et al., 2017
[298] CARB, 2017b
[299] As the Innovative Clean Transit Discussion Document notes, LCFS program staff is proposing to increase the energy efficiency ratio (EER) for heavy-duty battery-electric vehicles from 4.2 to 5.0 based on new data for battery electric trucks and buses. Per the most recent draft updated on 11/08/2017, the carbon intensity of an electric bus would be valued at 19.70 gCO2e/MJ. California average grid electricity supplied to electric vehicles: 98.49 gCO2e/MJ and Energy Economy Ratios (EER) for heavy-duty battery-electric vehicles: 5.0, 98.49/5.0 = 19.70 gCO2e/MJ.

The emissions benefits are less clear cut when it comes to MD/HD plug-in hybrid and hybrid electric vehicles. According to CARB, hybrid electric vehicle (HEV) systems can decrease carbon dioxide (CO_2) emissions, as less fuel is consumed during vehicle operation compared to conventional vehicles. However, NOx emissions impacts depend on the hybrid system. A study conducted by Kittelson et al. in 2015 concluded that the hybrid electric system must be well integrated and utilized in the optimal duty cycle to result in NOx emissions reductions compared to ICE vehicles.[300] Another study carried out by NREL found that NOx emissions actually increased in heavy-duty hybrid vehicles compared to conventional vehicles.[300]

Table VI-2 summarizes the vehicle emissions findings from each of the publications that were reviewed.

Table VI-2. Emissions Comparisons Cited in the Literature

Resource	Vehicle Category	Compared to Diesel	Compared to Natural Gas	Compared to Other Fuels*	Electricity Mix
NRDC, 2015	MD/HD Urban (80 miles or less) Freight EVs	GHG, NOx, and PM emissions reduction of >70%	GHG, NOx, and PM emissions reduction of >70%		Average U.S. electricity mix
		GHG, NOx, and PM emissions reduction of up to 90%	GHG, NOx, and PM emissions reduction of up to 90%		Primarily natural gas and nuclear power; 3-4% coal
CCFC, 2014	MD/HD Freight EVs			GHG, NOx, and PM reduction of 90% or more	California electricity mix by 2020
Goldsmith, 2017	Electric Trucks and Buses		GHG emissions reduction of 36% compared to RNG		
Moultak et. al., 2017	Heavy-Duty PEVs	Life cycle CO_2 emissions reduction of 80%			Renewable energy
	Heavy-Duty PEVs with Overhead Catenary	Life cycle CO_2 emissions reduction of 48%			Renewable energy
CARB, November 2015e	Heavy-Duty PHEVs			Tailpipe NOx emissions impacts are inconclusive or could increase. Tailpipe CO_2 emissions are reduced.	
Wästljung, nd	Heavy-Duty Hybrid Electric Truck with Overhead Catenary	CO_2 emissions reduction of 90%			Region Gävleborg electricity mix

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[300] CARB, 2015e

Resource	Vehicle Category	Compared to Diesel	Compared to Natural Gas	Compared to Other Fuels*	Electricity Mix
IEA, 2017a	Heavy-Duty Plug-In Electric Truck with Overhead Catenary			Significantly lower emissions	
Chandler et al., 2017	BEBs	GHG emissions reduction of 74%	NOx and PM emissions reductions		50% natural gas, 25% renewable energy, 10% nuclear energy, 8% hydropower, and 7% coal
		GHG emissions reduction of >80%			50% natural gas, 50% renewable energy
CARB, 2017b	BEBs	GHG, NOx, and PM emissions reductions	GHG, NOx, and PM emissions reductions, including compared to RNG		Average U.S. electricity mix

*Other fuels include any fuel options not specified by the publication (e.g., "conventional fuels"). This category is populated for studies that did not explicitly specify the comparison fuels.

An additional factor to consider is the impact of battery production on emissions. Of the literature reviewed, CARB's *California's Advanced Clean Cars Midterm Review* found that while vehicle batteries require a significant amount of energy to produce, the emissions resulting from battery production are compensated for by PEV tailpipe emissions savings. In light of this finding, the WTW emissions impacts of PEVs are estimated to be significantly lower than for conventional vehicles, even when considering battery production impacts. That said, to maintain adequate range for larger vehicles with current technology, the batteries will need to be bigger. This could result in higher emissions from battery production. Vehicles with shorter ranges could be produced instead, with drivers charging the vehicle more often, but many fleets are interested in longer range PEVs without the frequent fueling inconvenience.[301]

2. Natural Gas Vehicle Emissions

The literature reviewed emphasized the many benefits of NGVs and their role in meeting California's emissions and public health goals. In 2015, CARB predicted that NGVs will play a significant role in helping to reduce emissions from California's heavy-duty vehicle sector and to meet California's emissions targets overall.[302] There are around 65,000 MD/HD NGVs in operation in the United States. These vehicles consumed the equivalent of 400 million gallons of diesel annually, or less than 1% of the diesel used each year.[303] California NGVs consumed at least 144 million diesel gallon equivalents in 2016.[304] California has a number of programs in

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[301] CARB, 2017a
[302] CARB, 2015b
[303] GNA, 2016
[304] CARB, Data Dashboard: 2011-2016 Performance of the Low Carbon Fuel Standard

place to encourage the use of natural gas as a vehicle fuel, including by incentivizing the purchase of heavy-duty NGVs and the installation of natural gas fueling infrastructure.[302]

Like with electricity, the resources that were reviewed evaluated the WTW emissions of natural gas. Specifically, the potential for GHG emissions during natural gas production, distribution, and storage, as well as GHG leakage from the vehicle itself. Compared to conventional diesel, natural gas offers air pollution benefits. Heavy-duty natural gas engines have consistently certified to EPA's 2010 NOx emissions target of 0.2 g/bhp-hr, and a handful of natural gas engines have been certified to CARB's optional low NOx standards. Additional GHG emissions reductions can be realized by producing natural gas with renewable feedstocks, such as landfill gas, municipal solid waste, or dairy waste. On a WTW basis, a majority of the publications reviewed cited GHG emissions reductions from MD/HD PEVs compared to NGVs operating on conventional natural gas. Estimated GHG emissions from PEVs compared to NGVs running on RNG varied by resource.[302]

NGVs offer GHG and air pollutant emissions benefits compared to conventional diesel vehicles. Gladstein, Neandross & Associates (GNA) and CARB attribute the NOx emissions benefits from NGVs, in part, to NGVs ability to operate in cold start and low temperature, speed, and load operations without NOx emissions control issues.[305,306]It is often more difficult to achieve both low GHG emissions and low NOx emissions at low speed, temperature, and load operations with diesel vehicles.[307] GNA estimated the carbon intensities (CI) in grams of CO_2 per megajoule (gCO_2/megajoule), of conventional diesel, natural gas, and ZEV fuel pathways (Figure VI-4 and Table VI-3). GNA found that fossil natural gas pathways have more than twice the carbon intensity of electricity and gaseous hydrogen, while RNG used in engines certified to the 0.2g/bhp-hr NOx emissions standard can reduce GHG emissions compared to ZEV pathways.[306] The lowest carbon intensity pathway currently certified in the LCFS program is for dairy waste to RNG with a carbon intensity of -254 g/MJ.

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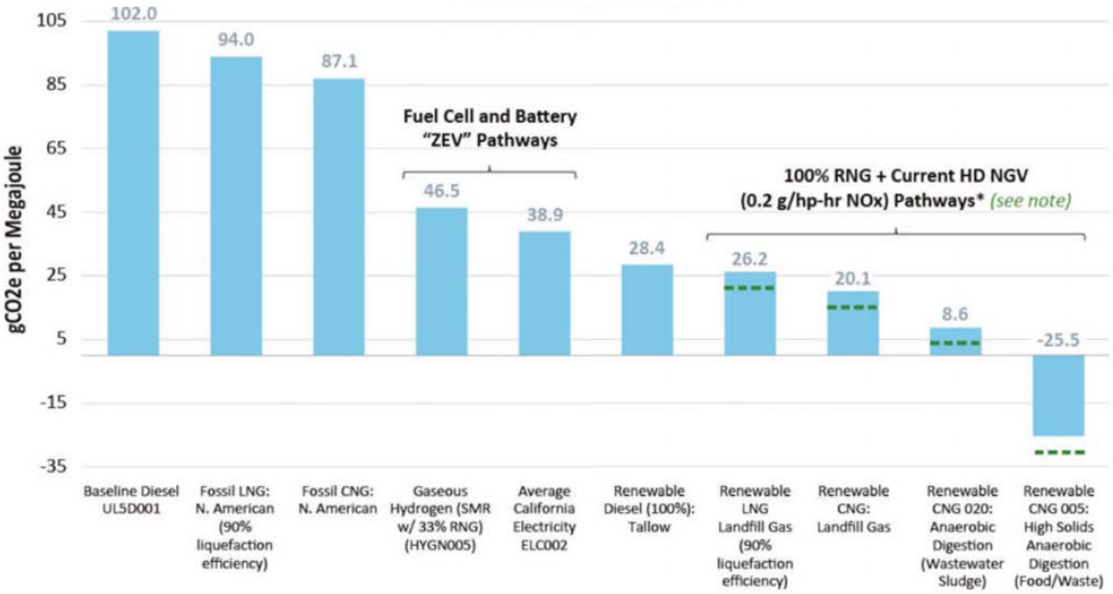
[305] CARB, 2015b
[306] GNA, 2016
[307] CARB, September 2015c

Figure VI-4. GNA-Estimated Carbon Intensities for Various Fuel Pathways Based on CA-GREET 2.0[306]



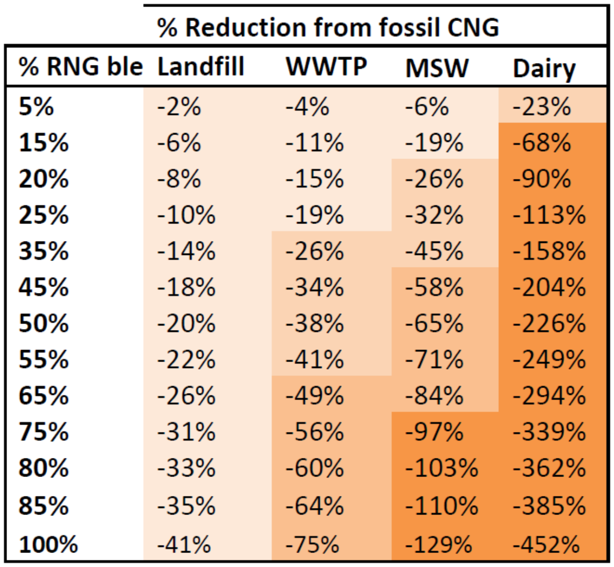
- - - - * **Note:** using the new "NZ" NG engine (0.02 g/hp-hr) **will further reduce the CI scores of these RNG pathways by about 4 gCO_2e/MJ** (closed crankcase ventilation reduces methane by 70%).

Table VI-3. GNA-Estimated Carbon Intensities for Various Fuel Pathways Based on CA-GREET 2.0[306]

Heavy-Duty Transportation Fuel Pathway	CI Value (includes Indirect Land Use and EER)	CI Value Relative to Baseline Diesel
Baseline Diesel (Ultra Low Sulfur)	102.01	–
Gaseous Hydrogen (SMR w/ 33% RNG)	46.50	-54.4%
California Electricity (Average grid mix)	38.9	-61.8%
Renewable Diesel (100%) from Tallow	28.4	-72.1%
Renewable LNG (100%), (Landfill Gas, 90% Liquefaction Efficiency)	26.2	-74.3%
Renewable CNG (100%), (Landfill Gas)	20.1	-80.3%
Renewable CNG (100%), (Anaerobic Digestion of Wastewater Sludge)	8.6	-91.6%
Renewable CNG (100%), (High Solids Anaerobic Digestion of Food / Waste)	-25.50	-125.0%
Source: California Air Resources Board, CA-GREET 2.0 2015		

Conventional natural gas can also be blended with RNG to reduce the fuel's CI. The higher the blend of RNG, the higher the expected CI reduction. Depending on the feedstock, CI reduction can exceed 100% (Table VI-4).[308]

Table VI-4. Percent Carbon Intensity Reduction by RNG Blend[308]



	% Reduction from fossil CNG			
% RNG ble	**Landfill**	**WWTP**	**MSW**	**Dairy**
5%	-2%	-4%	-6%	-23%
15%	-6%	-11%	-19%	-68%
20%	-8%	-15%	-26%	-90%
25%	-10%	-19%	-32%	-113%
35%	-14%	-26%	-45%	-158%
45%	-18%	-34%	-58%	-204%
50%	-20%	-38%	-65%	-226%
55%	-22%	-41%	-71%	-249%
65%	-26%	-49%	-84%	-294%
75%	-31%	-56%	-97%	-339%
80%	-33%	-60%	-103%	-362%
85%	-35%	-64%	-110%	-385%
100%	-41%	-75%	-129%	-452%

Dairy and municipal solid waste have the potential to reduce CI to the greatest extent out of the feedstocks listed above.[308] It should be noted, however, that natural gas heavy-duty vehicles—whether it is fossil or renewable natural gas—have higher ammonia emissions rates than diesel vehicles; [309] and ammonia is a precursor to secondary particulate formation.[310]

As mentioned previously, there are a number of heavy-duty natural gas engines that certify to EPA's 0.2 g/bhp-hr emissions standard. CARB's evaluation of in-use emissions for natural gas, diesel hybrid, and diesel engines found that natural gas engines typically met EPA's NOx emissions standard more reliably than their conventional diesel and diesel hybrid counterparts (Figure VI-5).[311]

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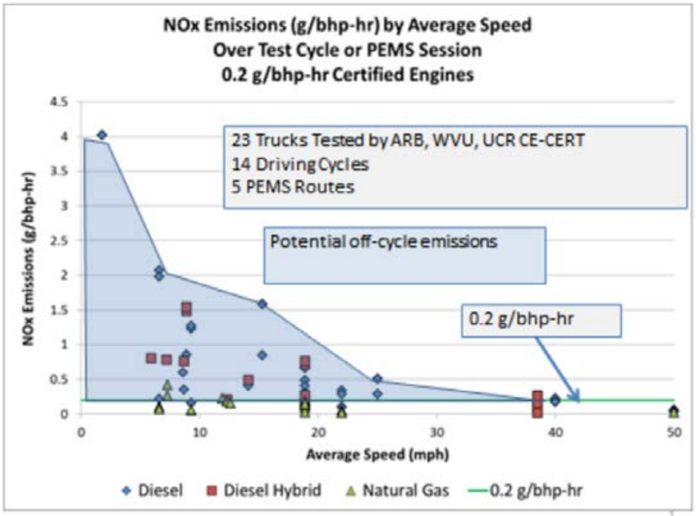
[308] Jaffe, 2017a

[309] Thiruvengadam, A. et al, Unregulated greenhouse gas and ammonia emissions from current technology heavy-duty vehicles, Journal of the Air & Waste Management Association, 66:11, 1045-1060, DOI: 10.1080/10962247.2016.1158751.

[310] Jaffe et al., 2017b

[311] CARB, September 2015b

Figure VI-5. Comparison of In-Use Exhaust NOx Emissions by Vehicle Type[311]



In addition to meeting EPA's 2010 NOx standard, Cummins Westport has certified its 8.9 L and 11.9 L natural gas engines to CARB's optional low NOx standard of 0.02 g/bhp-hr and its 6.7 L natural gas engine to CARB's optional low NOx standard of 0.1 g/bhp-hr.[312] It is also important to note that more recently developed natural gas engines have certified from 25% to 75% below this standard in order to account for any emissions fluctuations that may occur during testing and operation. Diesel engines, on the other hand, typically only certify 10% to 60% lower than the actual NOx standard.[313] As such, NGVs have the potential to decrease NOx emissions even further than conventional diesel vehicles, even with engines that certify to meet the same EPA emissions standards.

3. Diesel Vehicle Emissions

In the South Coast air basin, NOx emissions from diesel trucks are around 29% of all NOx in the area.[314] In addition, in the San Joaquin valley, diesel trucks emissions are responsible for 40% of all NOx emissions.[315] There has yet to be a diesel engine that is certified to CARB's optional NOx emissions standard for heavy-duty vehicle engines of 0.02 g-bhp/hr. CARB in 2015 expected that they may be ready for deployment in mid-2020.[316] One of the primary barriers to reducing both GHG and NOx emissions from heavy-duty diesel vehicles is their operational issues in cold start, low speed, and low load operations. Without additional engine controls, either GHG or NOx emissions usually increase in these situations. However, CARB proposes raising exhaust temperatures, advanced catalysts with more NOx control, and NOx storage catalysts as a few of the solutions.[316] CARB modeled the extent to which natural gas engines using emissions reduction technologies such as selective catalytic reduction (SCR), thermal

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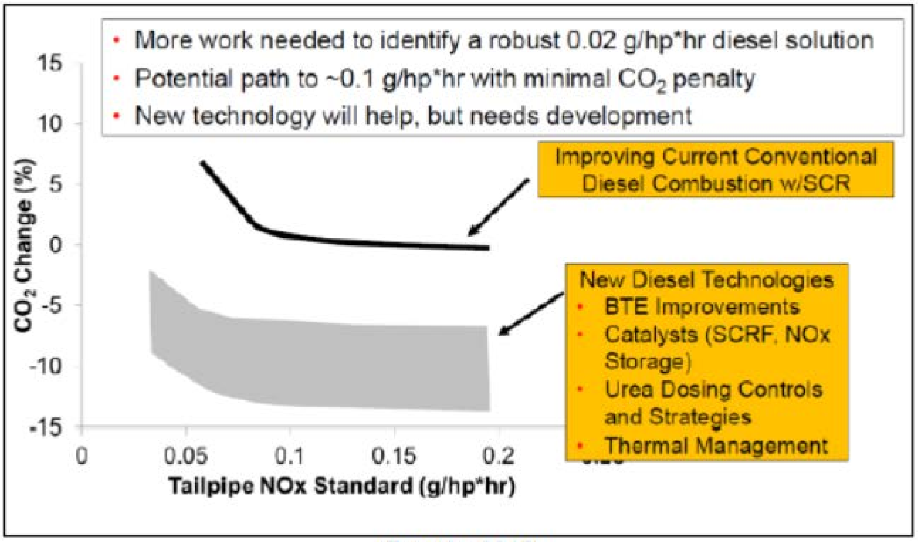
[312] GNA, 2016
[313] CARB, September 2015b
[314] SCAQMD, 2014
[315] CARB, 2013
[316] CARB, 2015c

management, and brake thermal efficiency (BTE) improvements can lower CO_2 and NOx emissions (Figure VI-6). Emissions reductions are possible, but further advancements are needed to reach CARB’s optional low NOx and other emissions standards.[317]

Figure VI-6. Potential GHG and NOx Emissions Reductions from New Engine Technologies[317]



(Eckerle, 2015)

While emissions reductions certainly are possible with diesel vehicles, the timing of implementing the technology may not keep pace with the growth of the number of heavy-duty trucks. In other words, the rate at which fleets and drivers switch from conventional fuels to cleaner diesel or natural gas engines must increase to meet the rate of the growth of the heavy-duty population to truly make a difference in reducing vehicle emissions.[318]

4. Future Emissions Projections

It is expected that the number of MD/HD vehicles on the road will increase in the next few decades.[319,320] In California, specifically, truck vehicle miles traveled are predicted to increase by 50% between 2010 and 2050.[320] Of the literature that estimated the emissions impacts of MD/HD vehicles in the future, all suggest the need for the increased deployment of BEVs. Some projections estimate that significant emissions reductions cannot be made in the near future without an increase in the use of other zero and low emission fuels, including hydrogen, natural gas, and biodiesel. The rate of adoption of battery and fuel cell technologies directly affects the role liquid biofuels and natural gas/RNG will need to play to achieve fuel future reduction requirements. Studies also emphasized the need to decarbonize the electricity grid. One prediction estimates that the electricity mix in North America will become increasingly dominated by renewable energy sources, with over half of its electricity sourced from wind or solar by 2050.[319]

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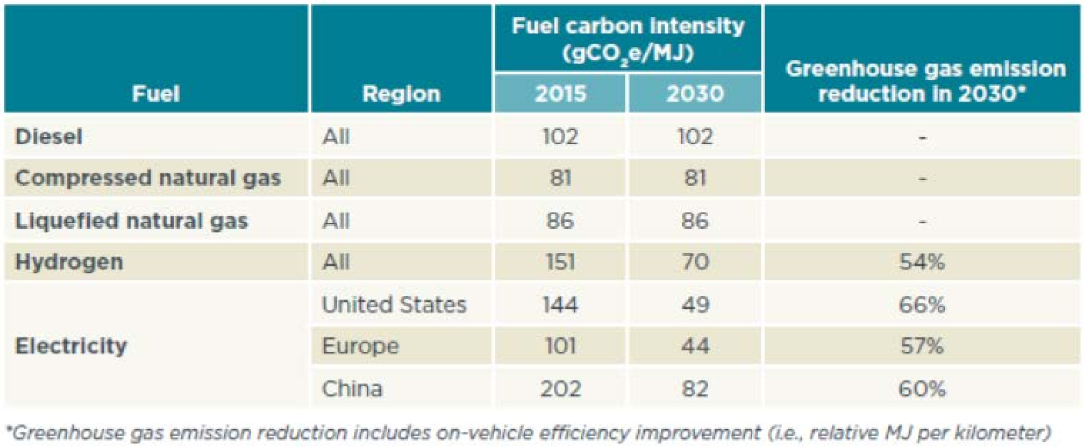
[317] CARB, 2015c
[318] Chandler et al., 2017
[319] DNV GL, 2017
[320] Fulton and Miller, 2015

Many publications have developed methodologies to predict the carbon intensities of various vehicle fuels. Moultak et al. predicts that the carbon intensity of electricity in the United States can decrease by 66% from 2015 to 2030 (Table VI-5). It also estimates that PEVs utilizing an overhead catenary system can reduce life cycle CO_2 emissions by 48% compared to conventional diesel vehicles, compared to hydrogen fuel cell vehicles which can reduce CO_2 emissions by 10%. Additionally, diesel and fossil natural gas CO_2 emissions are expected to be fairly similar from 2015 through 2030 (Figure VI-7).[321]

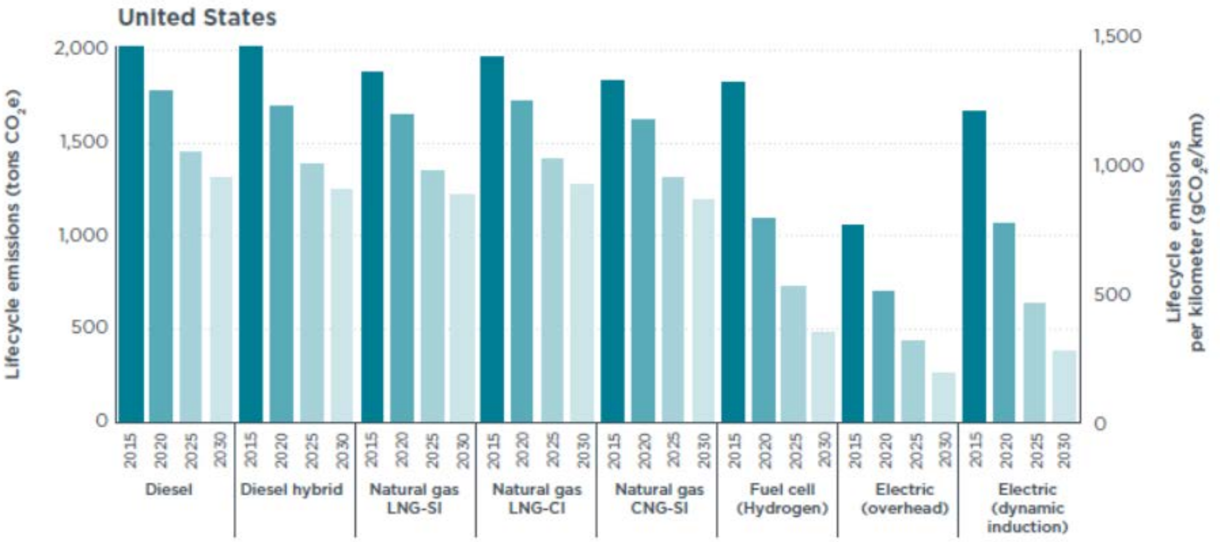
Table VI-5. Projected Carbon Intensities (gCO_2e/MJ) of Various Fuels, 2015-2030[321]



Fuel	Region	Fuel carbon intensity (gCO_2e/MJ) 2015	Fuel carbon intensity (gCO_2e/MJ) 2030	Greenhouse gas emission reduction in 2030*
Diesel	All	102	102	-
Compressed natural gas	All	81	81	-
Liquefied natural gas	All	86	86	-
Hydrogen	All	151	70	54%
Electricity	United States	144	49	66%
	Europe	101	44	57%
	China	202	82	60%

**Greenhouse gas emission reduction includes on-vehicle efficiency improvement (i.e., relative MJ per kilometer)*

Figure VI-7. Estimated Life Cycle Carbon Emissions by Fuel Pathway[321]



A number of scenarios have been developed to predict the level of BEV and other low emission vehicle deployment that will be required to reduce emissions significantly from MD/HD vehicles. Two of such models were created at UC Davis, both of which evaluate the role of biofuels in combination with ZEVs in reducing GHG emissions in California. The first is based on the Paris

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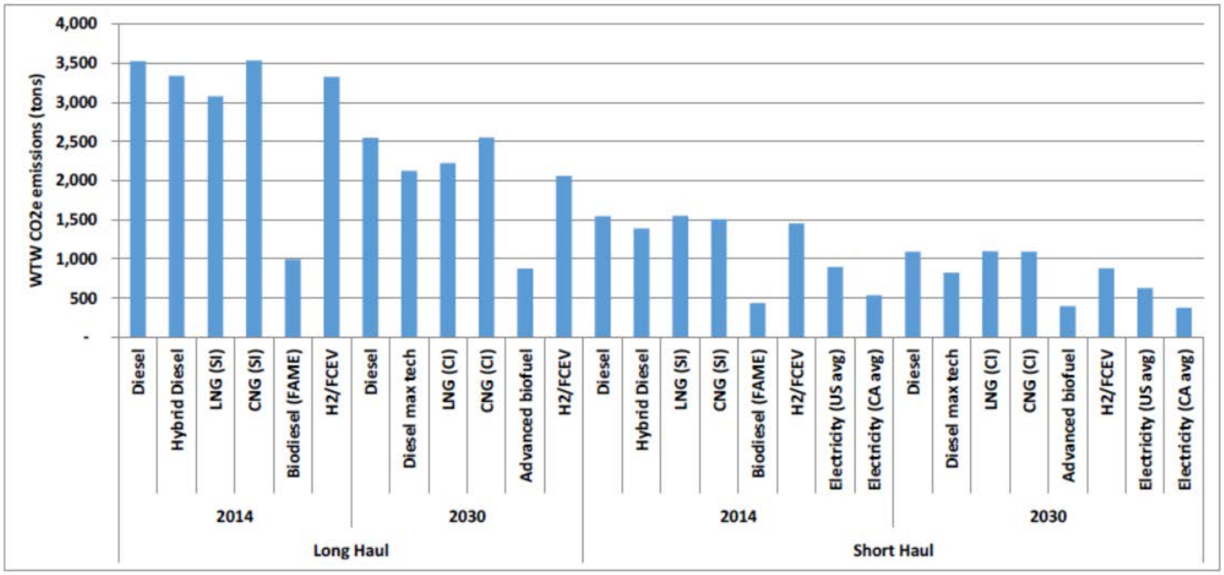
[321] Moultak et al., 2017

Agreement, assuming that California should achieve an 80% reduction in GHG emissions by 2050. The model also assumed that the CI of both the U.S. and California electricity mixes are higher than natural gas on a WTW basis, but that WTW emissions over the lifetime of a BEV are significantly lower than that of a NGV (Figure VI-8).[322]

Figure VI-8. Life Cycle GHG Emissions for Long and Short Haul Trucks by Fuel Pathway[322]



The baseline scenario assumes that reductions in emissions will be achieved primarily through technology improvements. The study estimated that, in order to achieve an 80% GHG emissions reduction by 2050 primarily through the deployment of ZEVs, there must be aggressive ZEV sales by 2025 and exclusively ZEV sales by 2040. This would allow time for California's fleet of vehicles to consist of primarily ZEVs by 2050 (Figure VI-9 and Figure VI-10).[323]

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[322] Fulton and Miller, 2015
[323] Fulton and Miller, 2015

Figure VI-9. Estimated MD/HD Truck GHG Emissions for Baseline Scenario by Fuel and Vehicle Type[323]

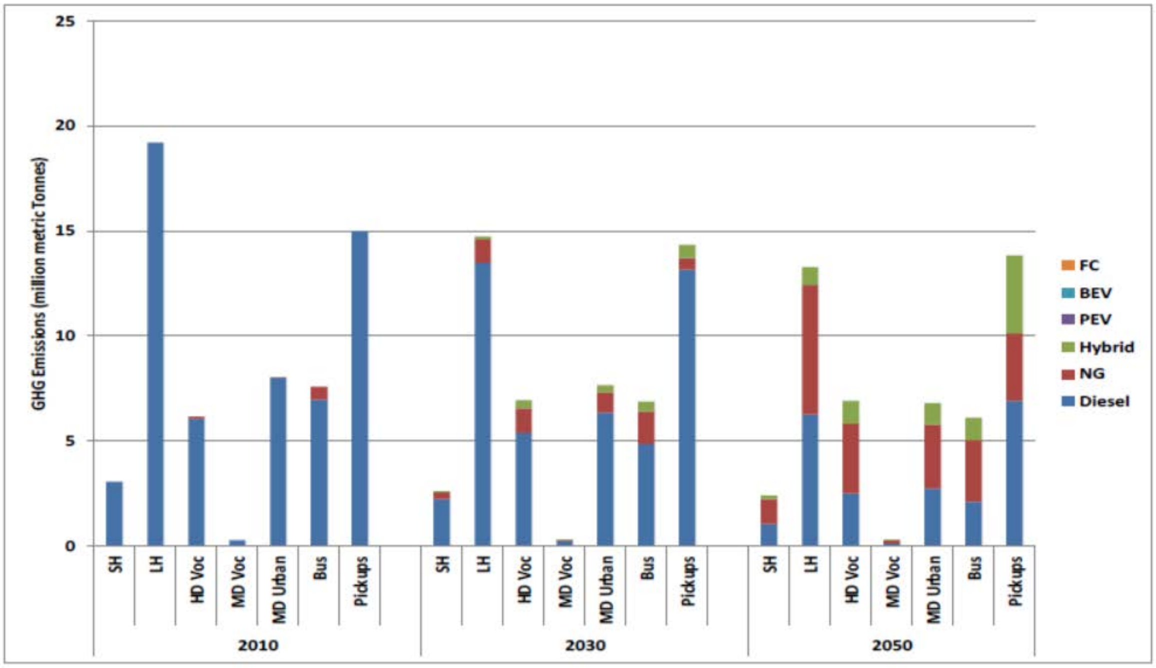
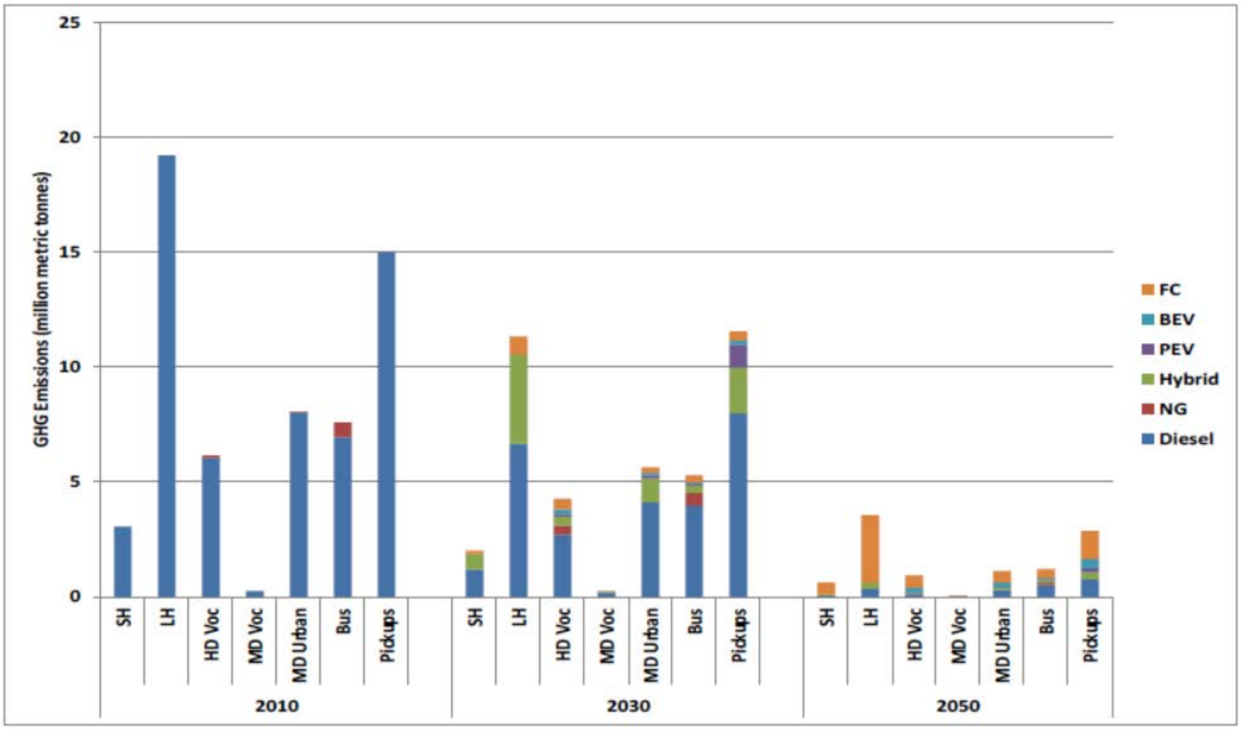


Figure VI-10. Estimated MD/HD Truck GHG Emissions for 80-by-50 Scenario by Fuel and Vehicle Type[323]



This study concluded that a mix of fuels should be utilized to achieve the 80-by-50 goal, including biofuels, hydrogen, and electricity (to a lesser extent). Achieving these emissions reductions through the deployment of ZEVs alone is unlikely.[324]

The other UC Davis model was used to evaluate four different scenarios based on the market share that ZEVs will comprise by 2050 to see whether the level of emissions reductions would be sufficient to achieve the Paris Agreement 80-by-50 goal. The four scenarios include business as usual (BAU), a 25% ZEV market share by 2050 (scenario 1a), a 25% ZEV market share by 2050 with a low refueling time (scenario 1b), and a 50% ZEV market share by 2050 (scenario 2). The model was also run for the 25% ZEV market share scenarios (1a and 1b) under a “high biofuels” assumption, in which 50% of conventional fuel used is renewable diesel by 2050. The model calculated that GHG emissions reductions from the four different scenarios are as follows (Table VI-6 and Table VI-7):[325]

Table VI-6. Estimated GHG Emissions Reductions and Cost Efficiency by ZEV Market Share Scenario (excluding BAU)[325]

ZEV scenario	Investment (billions $)	GHG reductions (ktonne CO_2e)	Cost efficiency ($/tonne)
1a	8.9	13.8	648
1b	6.9	13.8	297
1a with high biofuels	8.9	30.0	501
1b with high biofuels	6.9	30.0	230
2	42.9	32.0	1,339

Table VI-7. Estimated GHG Emissions Reductions (%) by ZEV Market Share Scenario[325]

Scenario	GHG reductions (%) from 2010 by 2050
BAU	10
ZEV scenario 1	22
ZEV scenario 1 with high biofuels	45
ZEV scenario 2	46

The emissions reductions resulting from these four scenarios did not come close to the 80% reduction needed by 2050. It was concluded that a better understanding of fleet purchasing decisions is needed to increase ZEV market share. In addition, efforts should be made to increase fleet exposure to ZEV technology to reduce the perceived risk of the technology. Also, this study shows that a combination of fuels and technologies, not just one technology alone, have the potential to achieve the greatest reductions at the lowest costs. [325]

A study conducted my McCollum et al. estimated that GHG emissions from the heavy-duty vehicle sector would increase by 175% of 1990 levels by 2050 if not curbed by advanced vehicle technology improvements. After evaluating three different scenarios (efficient biofuels, electric drive, and multi-strategy), McCollum et al. concluded that emissions reductions of over 50% are achievable if 5% of total VMT are electric and 28% are hydrogen and the balance a split of conventional fuels and biofuels. The multi-strategy scenario estimated that an 80% reduction in GHGs is possible if conventional fuel VMT were eliminated completely and only biofuels, hydrogen, and electricity are utilized. Like Fulton and Miller, McCollum et al. emphasizes the need for other fuels in addition to electricity to reduce vehicle emissions.[324]

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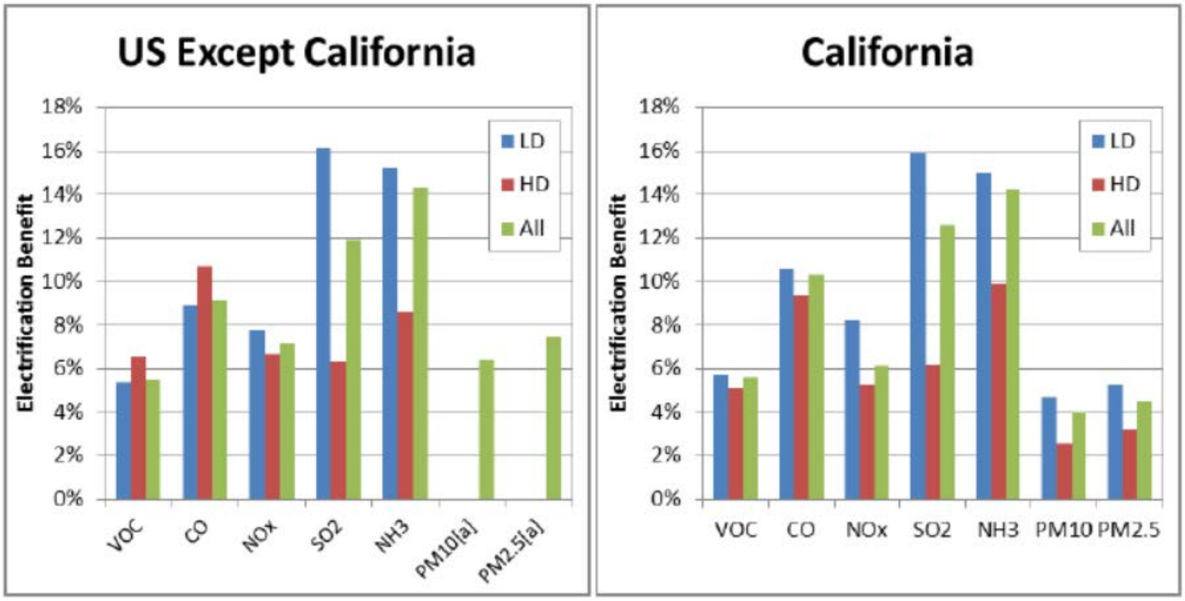
[324] Fulton and Miller, 2015

[325] Miller et al., 2017

The California PATHWAYS analysis estimates the level of emissions reductions that can be achieved by 2030 through the deployment of zero and near-zero emission vehicles of all vehicle classes. It evaluates the impacts of deploying anywhere from 3 to 8 million ZEV and PHEVs by 2030. The analysis found that it is possible to arrive at a 26% to 38% reduction in GHG emissions by 2030 compared to 1990 levels through ZEV and PHEV deployment. This emissions reduction would require a transition of the California vehicle fleet from conventional fuels to ZEVs, as well as the decarbonization of the electricity grid.[326]

EPRI and NRDC also developed projections for the impact of PEVs on emissions. These projections were based on two different scenarios: a base case and an electrification case. The base case assumes that no additional PEVs are purchased from 2015 on. The electrification case assumes that PEV market share increases by 1% annually from 2015 through 2020, exceeds 50% of the vehicle market share after 2030, and levels off at 67% of the vehicle market share in 2045. The emissions benefits of the electrification scenario by 2030 are significant for both light-duty and heavy-duty vehicles (Figure VI-11).[327]

Figure VI-11. Estimated Emissions Benefits of Electrification by Vehicle Class[328]



*PM10 and PM2.5 emissions are not available by vehicle class.

Due to reductions in ozone-forming emissions, EPRI and NRDC also expect atmospheric ozone benefits from electrification in many parts of the country through 2030 compared to the base case scenario (Figure VI-12).[328]

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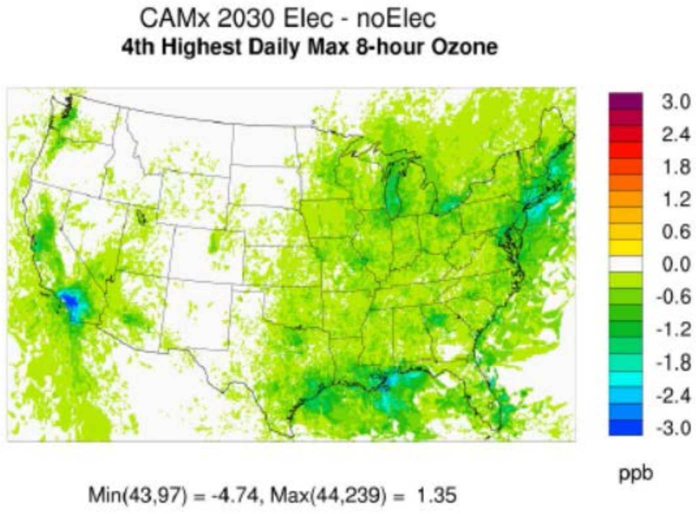
[326] Energy + Environmental Economics, 2015

[327] EPRI and NRDC, 2015

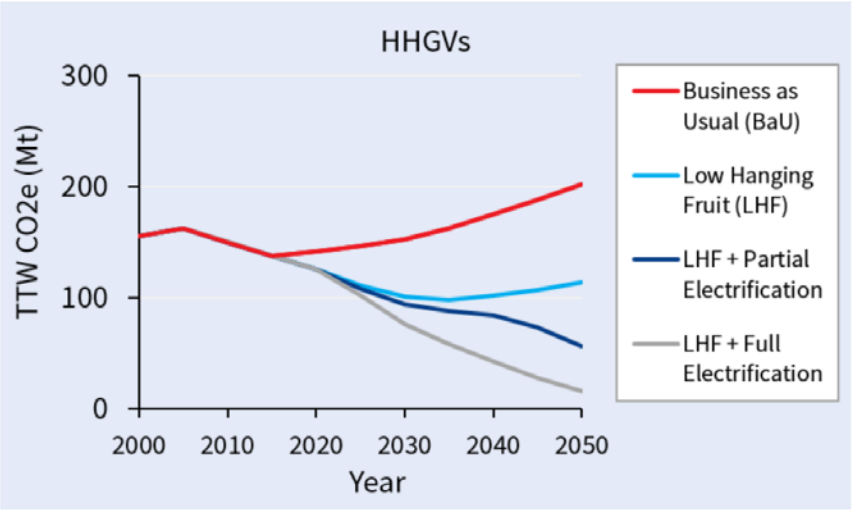
[328] EPRI and NRDC, 2015

Figure VI-12. Projected Difference in Fourth Highest Daily Maximum Atmospheric Ozone Levels between Base Case and Electrification Case, 2030[328]



Lastly, Transport and Environment developed four different scenarios to evaluate the steps it would take to decarbonize the freight sector in Europe completely by 2050 (Figure VI-13). The four scenarios included business as usual, low hanging fruit (LHF; i.e., modest technology improvements), LHF and partial electrification (i.e., technology improvements and deployment of overhead catenary lines on main highways), and LHF and full electrification (i.e., technology improvements and electrification of all heavy-duty vehicles). The study also assumes an increasing amount of renewable electricity. Transport and Environment concluded that, even with complete decarbonization of the electricity grid and all BEV vehicle sales by 2050, it would take time for the vehicle fleet to completely transition over to BEVs.[329]

Figure VI-13. Tank-to-Wheels (TTW) GHG Emissions by Scenario[329]



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[329] Transport and Environment, 2017a

Based on the models evaluated in this literature review, it can be concluded that significant reductions in MD/HD vehicle emissions require time and aggressive ZEV and low emission vehicle deployment strategies. However, it is not only the deployment of MD/HD PEVs that will decrease emissions—grid decarbonization is necessary as well. Efforts to decarbonize the grid thus far have been important and will continue to contribute to emissions reductions from electricity generation in the future.

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