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Public Interest Energy Research (PIER) Program

DRAFT FINAL PROJECT REPORT

CALHEAT RESEARCH AND MARKET TRANSFORMATION ROADMAP FOR MEDIUM- AND HEAVY-DUTY TRUCKS

Prepared for: California Energy Commission

Prepared by: California Hybrid, Efficient and Advanced Truck Research Center

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks is the final report for the CalHEAT Project, Phases 1 through 3 (contract number 500-09-019), conducted by CALSTART. The information from this project contributes to PIER's Transportation Program.

The California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) was established by the California Energy Commission in 2010 as a project operated by CALSTART to research, plan, support commercialization and demonstrate truck technologies that will help California meet environmental policies mandated through 2050.

The Roadmap describes the objective, approach, results and conclusions of the work done from 2010 through 2012 to identify near-term action items for the period from 2013 through 2020 to reduce petroleum use and greenhouse gas and particulate emissions from medium- and heavy-duty trucks.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

The California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) was established by the California Energy Commission in 2010. It is operated by CALSTART to perform research into planning, commercializing, and demonstrating truck technologies for more fuel-efficient medium- and heavy-duty vehicles and to reduce emissions. The role of the research center is to coordinate the development of a *Research and Market Transformation Roadmap* to deliver clear actionable steps to help meet or exceed the 2020 goals for California in petroleum reduction, carbon reduction, and air quality standards, and identify longer term goals through 2050. Medium- and heavy-duty trucks account for 9% of greenhouse gases in California, and approximately 20% of fuel consumption. Improvements in efficiency or reduction of petroleum use by trucks provide a substantial opportunity to reduce emissions. CalHEAT has identified 66 action items in the Roadmap, grouped under Electrification and Engine & Driveline efficiencies, to help mitigate emissions or improve efficiency. Clearly defined, achievable "stepping stones" provide a pathway through successive stages of technology development and adoption across multiple technology categories and vehicle platforms. CalHEAT has collaborated in the development of this Roadmap with the State's Air Resources Board, Energy Commission, Air Quality Management Districts, the U.S. Department of Energy, U.S. Environmental Protection Agency, and nationally-recognized medium- and heavy-duty truck associations, manufacturers, and experts. By 2050, implementation of advanced truck technologies through Roadmap action items could result in a reduction of more than 40 Million Metric Tons of carbon dioxide equivalent emissions compared to existing technology, referred to as "Business as Usual". NOx is projected to drop from 249,000 metric tons/year in 2012 to 67,000 metric tons/year by 2050. Assuming an adoption rate for biofuels of 25%, petroleum consumption by trucks decreases from 3.5 billion gallons per year in 2012 to 1.5 billion gallons per year by 2050.

Keywords: Air quality, California Energy Commission, CalHEAT, goods movement, greenhouse gas emissions, low-emission trucks, medium- and heavy-duty trucks

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

The California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) was established by the California Energy Commission in 2010 as a project operated by CALSTART to research, plan, and support commercialization and demonstrate truck technologies that will help California meet environmental policies mandated through 2050.

The role of the research center is to coordinate the development of a *Research and Market Transformation Roadmap* to deliver clear, actionable steps to help meet or exceed the 2020 goals for California in petroleum reduction, carbon reduction, and air quality standards, and set up a Roadmap for longer term goals. Medium-duty vehicles (MDV) and heavy-duty vehicles (HDV) account for 9% of greenhouse gases in California, and approximately 20% of fuel used. Improvements in efficiency or reduction of petroleum use by trucks provide a substantial opportunity to reduce emissions.

Regulatory Context and Purpose

The State of California has passed regulations that establish emission reduction targets. The primary driver is AB 32 – The California Global Warming Solutions Act of 2006. AB 32 was signed into law with the goal of reducing 2020 greenhouse gas emissions to year 1990 levels by 2020, and to meet more stringent ongoing environmental policies through 2050. The regulations require a reduction of nearly 30% from the projected 2020 levels if no changes occurred, referred to as "Business as Usual," and a reduction of 15% from 2009 levels.

In addition to AB 32, there are a number of overlapping State and Federal regulations aimed at decreasing emissions of greenhouse gases and particulate matter, improving air-quality, increasing biofuel use, decreasing petroleum use and more.

At the State level, the primary additional relevant regulations include AB 1007, which requires the preparation of a state alternative fuel plan; AB 2076, which sets specific goals for State reduction of petroleum use; a Statewide Truck and Bus Regulation, which mandates reduced emissions of diesel particulate matter, oxides of nitrogen, greenhouse gases and other pollutants from diesel-fueled vehicles; and a Diesel Risk Reduction Plan, intended to reduce the public's risk exposure to diesel particulate matter by 80 percent by 2020 from 2000 levels.

In addition, Federal regulations include fuel economy and carbon emission requirements that will be applied to new medium- and heavy-duty trucks starting in 2014 that will drive emissions reductions and efficiency improvements.

CalHEAT Truck Classification and Baseline Report

As the first step in the development of this Roadmap, CalHEAT performed a California Truck Inventory Study to better understand the various types of trucks used in California, their relative populations, and how they are used. The analysis included nearly 1.5 million commercial medium- and heavy-duty trucks, grouped by weight and application, to establish a baseline inventory and determine fuel use and potential for efficiency and emissions improvements.

CalHEAT Technology Roadmap Summary and Recommendations

CalHEAT has identified 66 action items in the Roadmap to help mitigate emissions or improve efficiency. These clearly defined, achievable "stepping stones" provide a pathway through successive stages of technology development and adoption across multiple technology categories and vehicle platforms. The action items focus on 13 technology strategies grouped broadly under electrification and engine or driveline efficiency. CalHEAT collaborated in the development of this Roadmap with the State's Air Resources Board, Energy Commission, Air Quality Management Districts, the U.S. Department of Energy, U.S. Environmental Protection Agency and nationally-recognized medium- and heavy-duty truck associations, manufacturers, and experts. With implementation of the 66 action items, the *Research and Market Transformation Roadmap* projects a reduction in 2050 of more than 40 Million Metric Tons of carbon dioxide equivalent emissions per year compared to existing technology, referred to hereafter as "Business as Usual." Truck-related petroleum use is projected to decrease from 3.6 billion gallons per year in 2012 to 1.5 billion gallons per year in 2050, a decrease of 58%, or more than 2 billion gallons per year, compared to Business as Usual. Nitrous oxide emissions are projected to decrease by 73% from 249,000 metric tons/year in 2012 to 66,000 metric tons/year by 2050, accomplished through increases in mileage per gallon and from adoption of NOx reduction technologies.

CHAPTER 1: Introduction and Summary

California Policy Context

Medium- and heavy-duty vehicles are critical to California's economy yet they are a major concern in relation to petroleum use and carbon dioxide emissions. These vehicles contribute 9% of California greenhouse gas (GHG) emissions and consume 20% of the total fuels used in California fleets[1]. GHG from trucks increased by 77% from 1990-2006, a growth rate three times greater in medium- and heavy-duty trucks than light-duty vehicles during that period. The California Energy Commission predicts a 42% increase in the use of diesel fuel by 2030[2]. Diesel is a primary fuel for medium- and heavy-duty vehicles. The U.S. Department of Energy (DOE) predicts that the percentage of transportation GHGs that come from freight trucks will continue to grow, estimating a (national) shift from 17.4% in 2007 to 20.7% in 2030.[3]

AB 32 – The California Global Warming Solutions Act

The State of California has passed regulations that establish emission reduction targets. The primary driver is AB 32 – The California Global Warming Solutions Act of 2006. AB 32 was signed into law with the goal of reducing greenhouse gas emissions to year 1990 levels by 2020, and to meet more stringent ongoing environmental policies through 2050, as shown in Figure 1, page 4). The regulations require a reduction of nearly 16% from the projected 2020 levels if no changes occurred, referred to as "Business as Usual," and a reduction of6% from 2010 levels.[4] Another aspect of AB 32 includes the Low Carbon Fuel Standard, which is intended to reduce carbon intensity of transportation fuels by at least 10% by 2020, leading to a reduction of 15 Million Metric Tons of CO_2 equivalents ($MMTCO_2e$) by 2020. Recommended reductions relevant to trucks identified in the AB 32 Scoping Plan are shown in Table 1, page 4.

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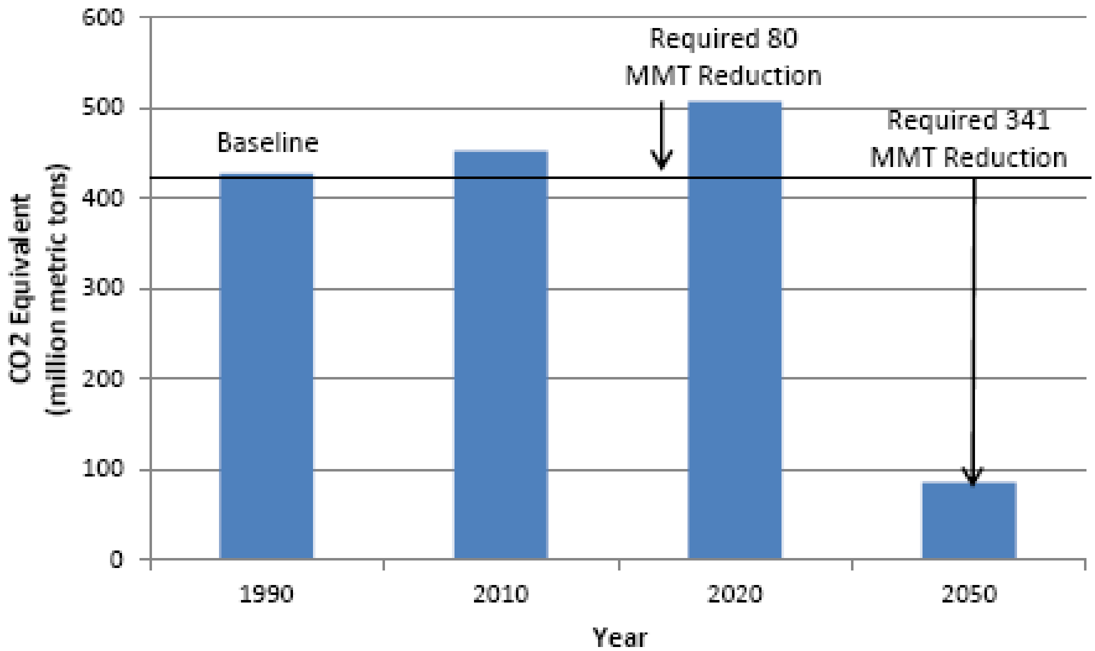
[1] California DOT, ***2008 California Motor Vehicle Stock, Travel and Fuel Forecast***, 2008.

[2] http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf

[3] U.S. Department of Transportation, ***Transportation's Role in Reducing U.S. Greenhouse Gas Emissions***, 2010.

[4] California Air Resource Board, ***AB 32 Climate Change Scoping Plan***, December 2008. < http://www.arb.ca.gov/cc/scopingplan/document/scopingplandocument.htm>

Figure 1: California Greenhouse Gas Reduction Goals (Mobile and Stationary Sources)



CO_2 equivalent emission reduction targets mandated by AB 32 – The California Global Warming Solutions Act of 2006 with the goal of reducing 2020 greenhouse gas emissions to 1990 levels and to meet more stringent ongoing environmental policies through 2050.

California Air Resources Board Climate Change Scoping Plan

Table 1: AB 32 Scoping Plan Reduction Measures Relevant to Trucks

Recommended Reduction Measures Relevant to Trucks	**Reductions Counted Toward 2020 Target (MMTCO_2e)**
Low Carbon Fuel Standard – Reduces carbon intensity of transportation fuels by at least 10% by 2020	15
Medium- and Heavy-Duty Vehicle Greenhouse Gas Emission Reduction	0.9
Medium- and Heavy-Duty Vehicle Hybridization	0.5
Goods Movement, Ship Electrification at Ports, System-wide Efficiency Improvements	3.7

AB 32 Scoping Plan measures related to CO_2e emissions from transportation, with reduction targets by 2020. The Low Carbon Fuel Standard reduction targets figure of 15MMTCO_2e includes passenger cars as well as trucks. The Medium- and Heavy-Duty Vehicle Greenhouse Gas Emission Reduction and Medium- and Heavy-Duty Vehicle Hybridization measures are specific to trucks. The reductions shown for Goods Movement, Ship Electrification at Ports and System-wide Efficiency Improvements include reductions from both trucks and ships.

AB 32 Scoping Plan and CalHEAT Vehicle and Technologies Characterization and Baseline Report

Other California Regulations

In addition to AB 32, there are a number of overlapping State and Federal regulations aimed at decreasing emissions of greenhouse gases and particulate matter, improving air-quality, increasing biofuel use, decreasing petroleum use and more.

At the State level, the primary relevant regulations affecting medium- and heavy-duty trucks include:

- AB 1007, in response to which the California Energy Commission (CEC) prepared a state alternative fuel plan in 2007[5]. The plan established goals for alternative fuels penetration rates of 9% by 2012, 11% by 2017, and 26% by 2022.

- AB 2076, in response to which the Energy Commission and the California Air Resources Board prepared and adopted a joint agency report, *Reducing California's Petroleum Dependence*. Included in this report are recommendations to increase the use of alternative fuels to 20% of on-road transportation fuel use by 2020 and 30% by 2030[6].

- Statewide Truck and Bus Regulations, established to reduce emissions of diesel particulate matter (PM), oxides of nitrogen (NOx) and other criteria pollutants, and greenhouse gases from in-use diesel-fueled vehicles[7].

- Diesel Risk Reduction Plan, intended to reduce the public's risk exposure to diesel particulate matter by 80 percent by 2020 from 2000 levels[8].

- Executive Order B-16-2012 establishes the goal of reducing CO_2e from the transportation sector in 2050 to 80% less than 1990 levels. The EO further orders the state to establish benchmarks to achieve widespread use of zero-emission vehicles for public transportation and freight transport by 2020.

[5] State Alternative Fuels Plan, December 2007, CEC-600-2007-011-CMF

[6] ***Reducing California's Petroleum Dependence,*** California Energy Commission and Air Resources Boards, joint agency report, August 200, publication #P600-03-005.

[7] http://www.arb.ca.gov/regact/2008/truckbus08/revfro.pdf

[8] ***Emissions and Health Benefits of Regulation for In-Use Off-Road Diesel Vehicles,*** June 2010 http://www.arb.ca.gov/msprog/ordiesel/documents/OFRDDIESELhealthFS.pdf

Federal Regulations

Federal regulations from the National Highway Traffic Safety Administration (NHTSA) include fuel economy and carbon emission requirements that will be applied to medium- and heavy-duty trucks starting in 2014.9,10 Additionally, Phase 2 NHTSA regulations are likely to be implemented as early as 2019, building upon Phase 1 and incorporating new regulations to encourage use of new cost-effective technologies and more aggressive fuel reduction standards.11 This legislation will have an enormous effect on programs in California. Not only will it set new standards for trucks here, but the cost and expense of making trucks that meet the new standards may impact manufacturers in very significant ways, which may mean that they have fewer resources that can be devoted to California-specific programs. Understanding the impact of this regulation and how it will affect development of new truck technologies was a significant factor in CalHEAT's effort to build an accurate model and Roadmap for the California fleet.

Federal ozone regulations will affect much of California. New rules will drop exposure limits to .060-.070 ppm over 8 hours, phased in over 20 years beginning in 2010.[12] The current limit is .075 ppm,[13] but background and other sources leave very little room for truck emissions. The South Coast Air Quality Management District estimates that changes to meet the new lower ozone levels will require a reduction in oxides of nitrogen (NOx) of 88-91% by 2030.[14] Much ground level ozone is created by a chemical reaction between NOx and volatile organic compounds in the presence of sunlight. Since trucks are significant producers of NOx, it is likely that future ozone regulations will require further restriction on truck NOx production levels.

The Renewable Fuels Standard mandates that the American economy will be using 36 billion gallons of renewable fuel per year in its transportation fuel supply by 2022, with 16 billion gallons coming from advanced cellulosic biofuels that also reduce GHG by at least 60% relative to gasoline.[15]

Significant challenges to improvements in air quality, especially in Southern California and the Central Valley, are related to goods movement. In Southern California, traffic congestion, including that associated with the ports, and the need to reduce ozone and NOx levels, are driving forces for electrification of these vehicles to achieve zero and near zero emissions. The

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[9] http://www.nhtsa.gov/fuel-economy

[10] http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/CAFE_2014-18_Trucks_FactSheet-v1.pdf

[11] ***HD GHG Standards for HTUF***, CALSTART, Sept. 17, 2012.

[12] http://www.epa.gov/glo/fr/20100119.pdf

[13] http://www.aqmd.gov/legal/legalaut.html

[14] Presentation to CALSTART Staff, 2010

[15] USDA, ***A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022***, 2010.

Central Valley, managed by the San Joaquin Air Pollution Control District, is facing a particulate matter problem caused by the significant number of Class 8 tractors and over- the-road line-haul trucks that commute from southern to northern California on the Interstate 5 corridor.

As trucks are significant contributors to greenhouse gas emissions and particulate matter, the AB 32 Scoping Plan outlined specific areas with reduction goals applicable to medium- and heavy-duty trucks, as shown in Table 1, page 4. Although the State outlined reductions were necessary to help meet AB 32 goals, there was still much detail needed to determine how these segment reductions would be met, and to identify gaps and barriers both in market adoption and technology development that stand between the present and these goals.

To address this need, the California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) was established by the CEC within its Public Interest Energy Research (PIER) Program in 2010 to perform research into planning, commercializing and demonstrating truck technologies for efficient medium- and heavy-duty vehicles. The role of the research center during a three-year program is to coordinate the development of an overall *Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks* and facilitate the plan implementation. The strategies and pathways outlined in the Roadmap are intended to deliver clear actionable steps to help meet the 2020 goals for California in petroleum reduction, carbon reduction, and air quality standards, and set up a framework, roadmap and timeline for longer-term goals. CalHEAT has collaborated in the development of this roadmap with the state's Air Resources Board, Energy Commission, Air Quality Management Districts, the U.S. Department of Energy, U.S. Environmental Protection Agency and nationally-recognized medium- and heavy-duty truck associations, manufacturers, and experts.

CEC Guidance: What is the Roadmap?

The purpose of the Roadmap is to lay out an action plan for research, development and market transformation in medium- and heavy-duty trucks and goods movement to deliver clear actionable steps to meet or exceed the 2020 goals for California in petroleum reduction, carbon reduction, and air quality standards. The Roadmap also sets up a framework and timeline to address longer-term goals for carbon reduction and serves as an example that can be applied to other regions in transforming the heavy-duty truck sector. To do so, CalHEAT staff and members have examined varied technologies and strategies that can help meet these goals, and have looked closely at the necessary market and technological gaps that need to be addressed to speed the implementation of needed changes. Their efforts to thoughtfully define pathways and a series of achievable actions to develop and adopt successive next steps across multiple technology categories and vehicle platforms are what set this Roadmap apart from others that define goals without specifics on how to achieve them.

CalHEAT Roadmap Goals

The roadmap outlines specific, actionable steps on the identified technology pathways, with both technology and market milestones, including performance metrics and timeframes along those pathways. Achieving these steps will contribute to the effort to reach California's mandated environmental policy goals.

CO_2e reductions from trucks are mandated by AB 32 and California EO B-16-2012, shown in Table 2, below, to reduce emission levels from 35.7MMT in 2012 to 1990 levels of 29MMT/year by 2020, and further reduce them to 5.8MMT by 2050, a level approximately one-tenth of the projection under a business as usual scenario.

Table 2: California Goals for Truck-Related CO_2e Emissions in MMT by 2050

Year	**1990**	**2012**	**2020**	**2050**
BAU		35.7	40.7	59.7
AB 32 and EO B-16-2012	29.0	35.7	29.0	5.8

Carbon dioxide equivalents in MMT for 1990 and 2012, with projections for 2050, under "Business as Usual" or existing technology and vehicle use, and the truck-related reductions mandated by California AB 32 and Executive Order B-16-2012, to reduce CO_2e to 1990 levels by 2020, with much more stringent reductions by 2050.

California Air Resources Board Climate Change Scoping Plan[16] and California Greenhouse Gas Inventory for 1990[17]

California's legislative target, under AB 2076, is to reduce petroleum use 15% from 2003 levels by 2020._Additionally, AB 1007 establishes goals for alternative fuel penetration rates of 9% by 2012, 11% by 2017, and 26% by 2022. AB 2076 also includes recommendations to increase use of alternative fuels for on-road transportation fuel use by 20% by 2020 and 30% by 2030. A Statewide Truck and Bus Regulation also mandates reduced emissions of diesel particulate matter, oxides of nitrogen, greenhouse gases and other pollutants from diesel-fueled vehicles. A Diesel Risk Reduction Plan is intended to reduce the public's risk exposure to diesel particulate matter by 80 percent by 2020 from 2000 levels. New federal regulations for fuel economy that take effect in 2014 for medium- and heavy-duty trucks will also drive emissions reductions and fuel efficiency improvements.

[16] California Air Resource Board, ***AB 32 Climate Change Scoping Plan***, December 2008.

[17] ***California Greenhouse Gas Inventory***, 1990, page 10, http://www.arb.ca.gov/cc/inventory/1990level/1990level.htm

During the initial term of CalHEAT's CEC-PIER agreement, the research center has focused on the following three goals:

- Development of the research Roadmap described in this report to advance science and technology for medium- and heavy-duty trucks,
- Research and data collection on advanced Class 8 trucks, plug-in trucks, and alternative fuel, high-efficiency hybrid trucks, and
- Technology transfer activities geared to end-users, manufacturers, suppliers and organizations suited to combining technical and commercial capabilities.

Technologies that address one area of concern may have a positive, neutral or negative impact on other areas of concern, so all the regulations noted in the preceding policy section were considered during the development of this Roadmap. The goal of the Roadmap is to find solutions that provide co-benefits: solution pathways that meet and address the overlaps in all these varying regulations and goals, while also addressing market realities.

State of the Industry by CalHEAT Classification

As the first step in the development of this Roadmap, CalHEAT performed a California Truck Inventory Study[18] to better understand the various types of trucks used in California, their relative populations, and how they are used. As the State looks to technologies with the ability to reduce petroleum consumption or emissions, it is imperative to understand that specific technologies may have widely varying impacts depending on a truck's characteristics and how it is used. For example, a box truck used for heavy urban cycles may benefit greatly from hybridization or electrification, whereas a truck used to drive between Los Angeles and San Francisco may benefit more from aerodynamic improvements and light-weighting.

The analysis included nearly 1.5 million trucks, ranging in size from Class 2B to Class 8. This number is based on California registration figures for commercial trucks in the weight category 2B and above, via the Polk database.[19] The vehicle classes included in the inventory are shown in Figure 2 below, grouped both by weight and use. Class 2B pickup trucks and vans registered to individuals were eliminated under the assumption that most, if not all, were non-commercial vehicles.

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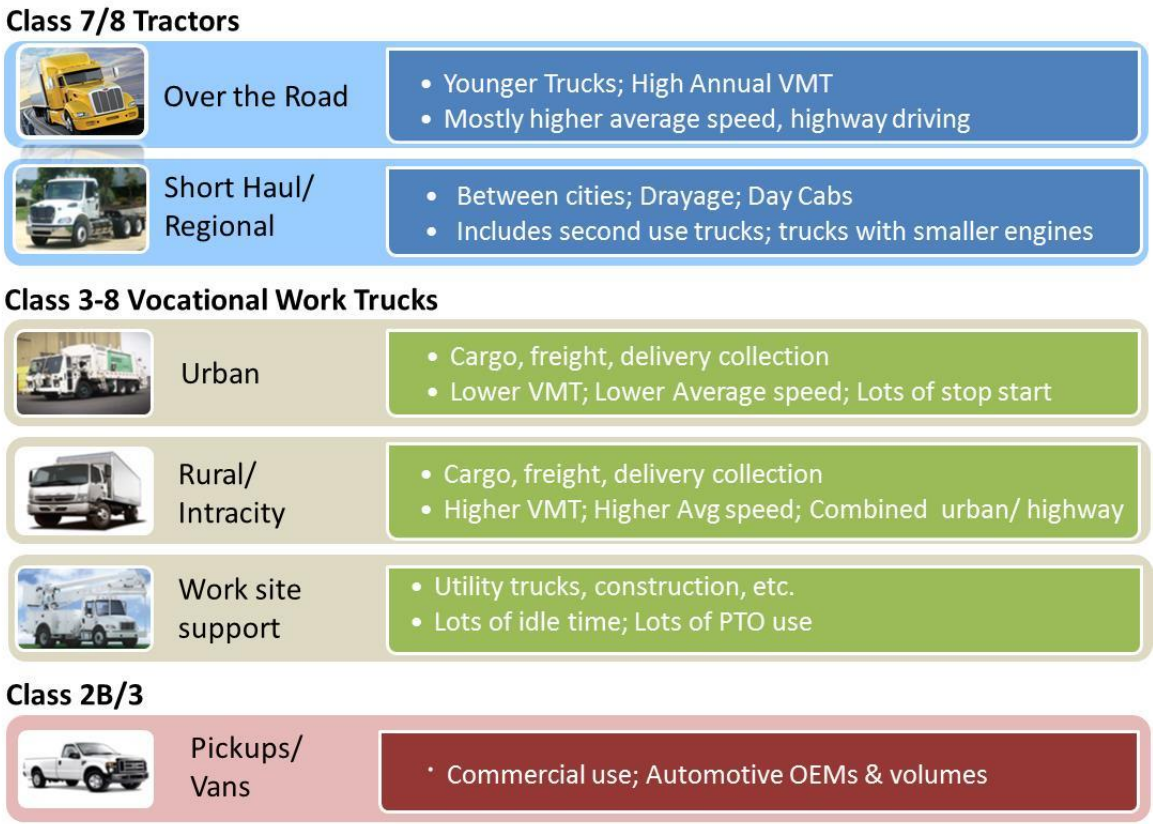
[18] Jennings, Geoff, and Brotherton, Tom. (CalHEAT). ***California Truck Inventory and Impact Study, June, 2012.*** http://www.calstart.org/Projects/CalHEAT/Presentations-and-Publications.aspx

[19] https://www.polk.com/knowledge/reports CalHEAT worked with Polk to create a custom dataset from their database, which covers registered vehicles in CA.

Figure 2: Six Truck Categories Based on Technology Applicability



Truck classifications, by weight and application, in the 2010 CalHEAT Truck Inventory Study.

California Hybrid, Efficient and Advanced Truck Research Center

For the purposes of CalHEAT's Roadmap data, it was apparent that the weight classes were not sufficient to evaluate the impact of technology. With significant input from the CalHEAT Technology Advisory Group and the CalHEAT Advisory Council, six categories were developed. The intent behind the formation of their categories was to group trucks that are used in similar ways, such that it could be assumed that there may be similar impacts from technologies. A Class 4 truck in heavy urban use might see a different percentage improvement from hybridization than a Class 6 truck in similar use would achieve. However, that Class 4 urban truck would be more similar to a Class 6 urban truck than a Class 4 truck primarily used for long distance freeway driving in how it is affected by a given technology.

Table 3, below, shows the 2010 California truck population by application and the contribution to CO_2e emissions both in $MMTCO_2e$ per year and on a percentage basis. Figure 3, page 12, shows relative CO_2e emissions by truck category and miles travelled. Relative NOx emissions, which contribute to the development of ozone, are shown by truck category, truck population and miles traveled in Figure 4, page 13.

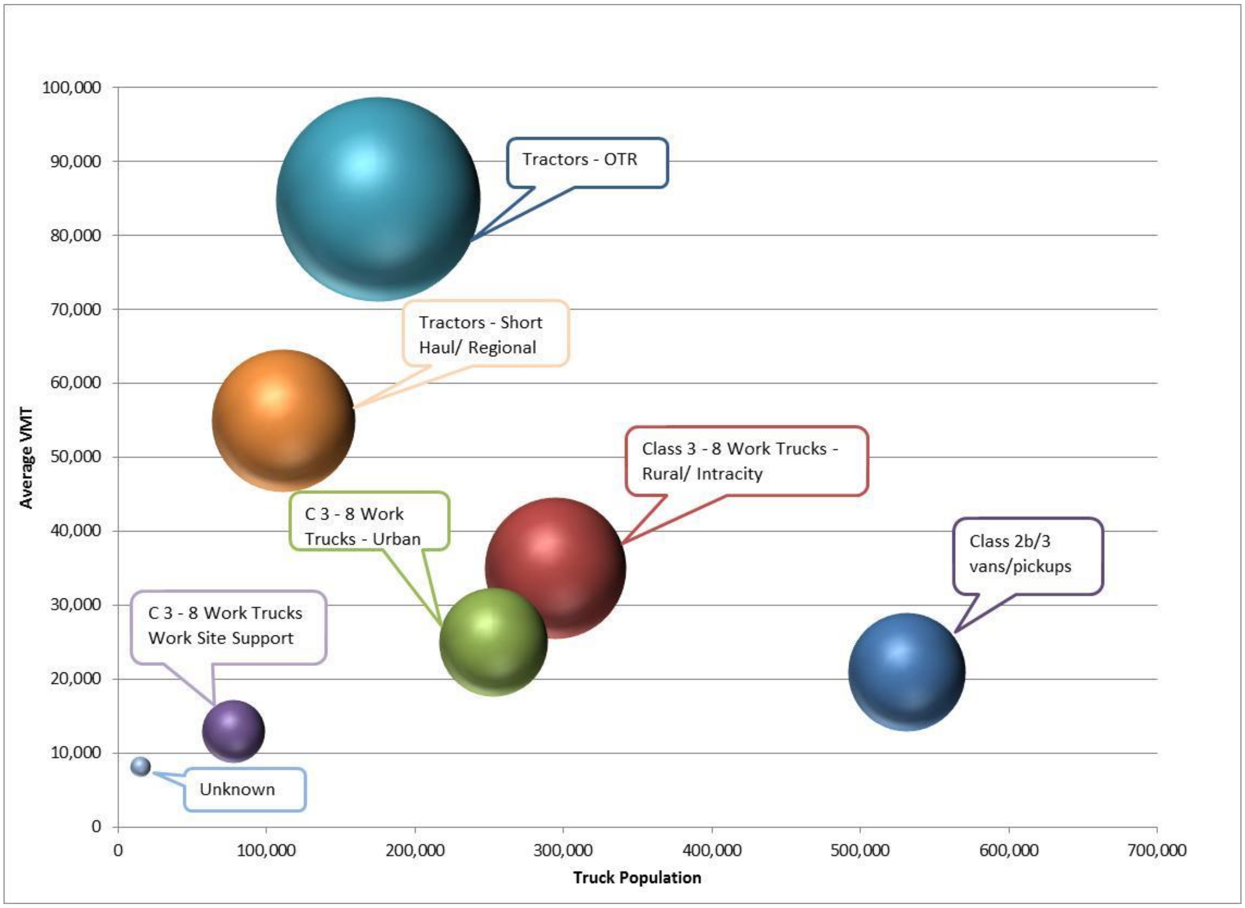
Table 3: Truck Categories, 2010 Populations and CO_2e Emissions

Vehicle Category	Truck Population	% Population	Average VMT	CO_2e (MMT/yr)	%CO_2e
Tractors - OTR	175,000	12%	85,000	12.9	38%
Tractors – Short Haul/Regional	111,000	8%	55,000	6.3	18%
Class 3 – 8 Work - Urban	253,000	17%	25,000	3.6	11%
Class 3 – 8 Work – Rural/Intracity	295,000	20%	35,000	6.1	18%
Class 3 – 8 Work – Work Site	77,000	5%	13,000	0.8	2%
Class 2B/3 vans/pickups	531,000	36%	21,000	4.2	12%
Unknown	15,000	1%	8,192	0.1	0%
Total	1,457,000	100%	34,255	34.0	100%

California truck population by weight class and application, along with average vehicle miles traveled, CO_2 equivalent emissions in MMT/year, the percentage of vehicles by category, and percentage contribution to total truck CO_2e emissions.

California Hybrid, Efficient and Advanced Truck Research Center calculations

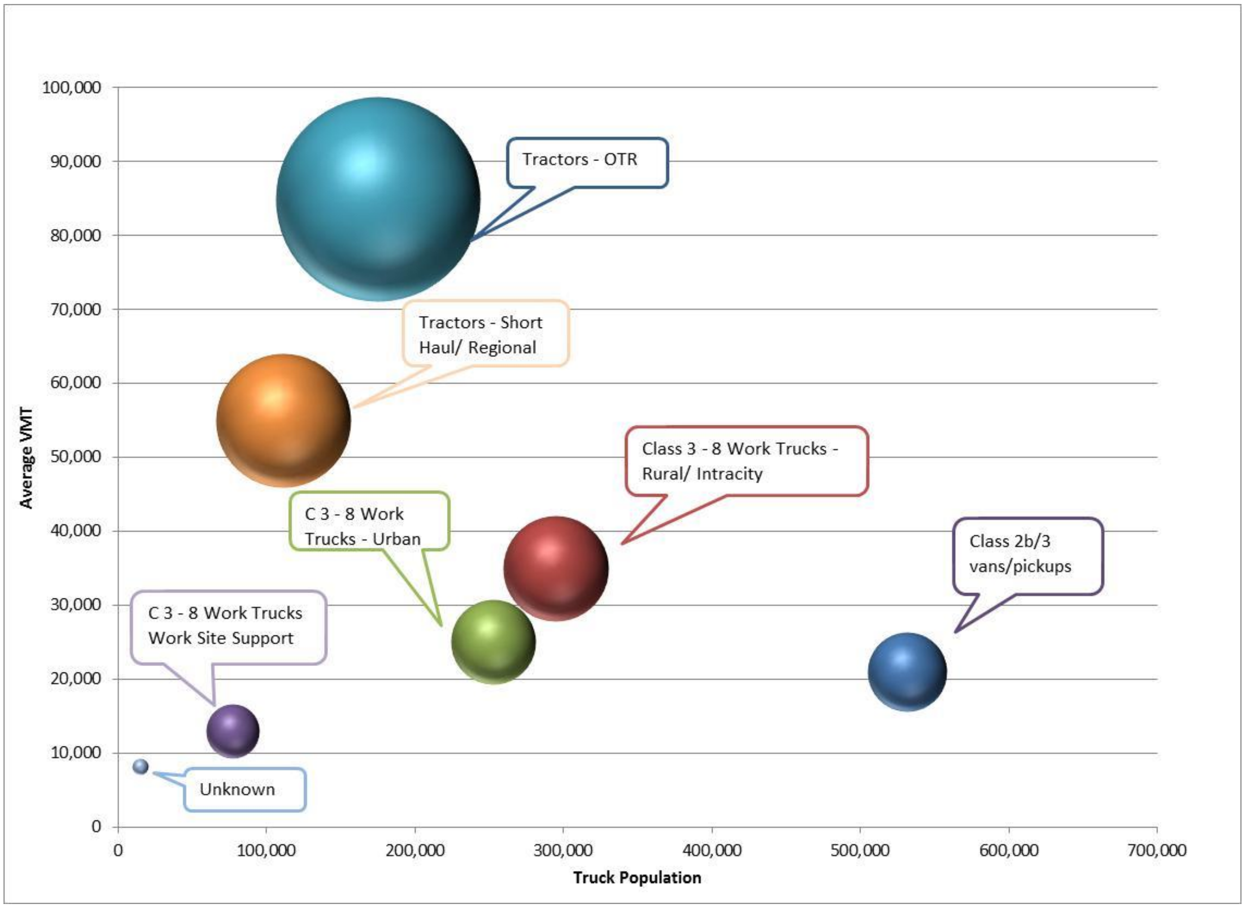
Figure 3: Truck CO_2e, Average Vehicle Miles Traveled and Population by Truck Category



The California truck population analyzed in the 2010 CalHEAT Truck Inventory and Impact Study, shown by CO_2e emissions, truck category and relative population, and annual vehicle miles travelled. The size of each ball represents the CO_2e emissions for the truck category.

California Hybrid, Efficient and Advanced Truck Research Center calculations, and data from Polk Knowledge Base

Figure 4: Relative NOx by Truck Category



The six truck categories in the CalHEAT study shown by truck population, annual vehicle miles travelled and percentage contribution to total truck nitrogen oxide emissions. The size of each ball represents the NOx emissions for the truck category.

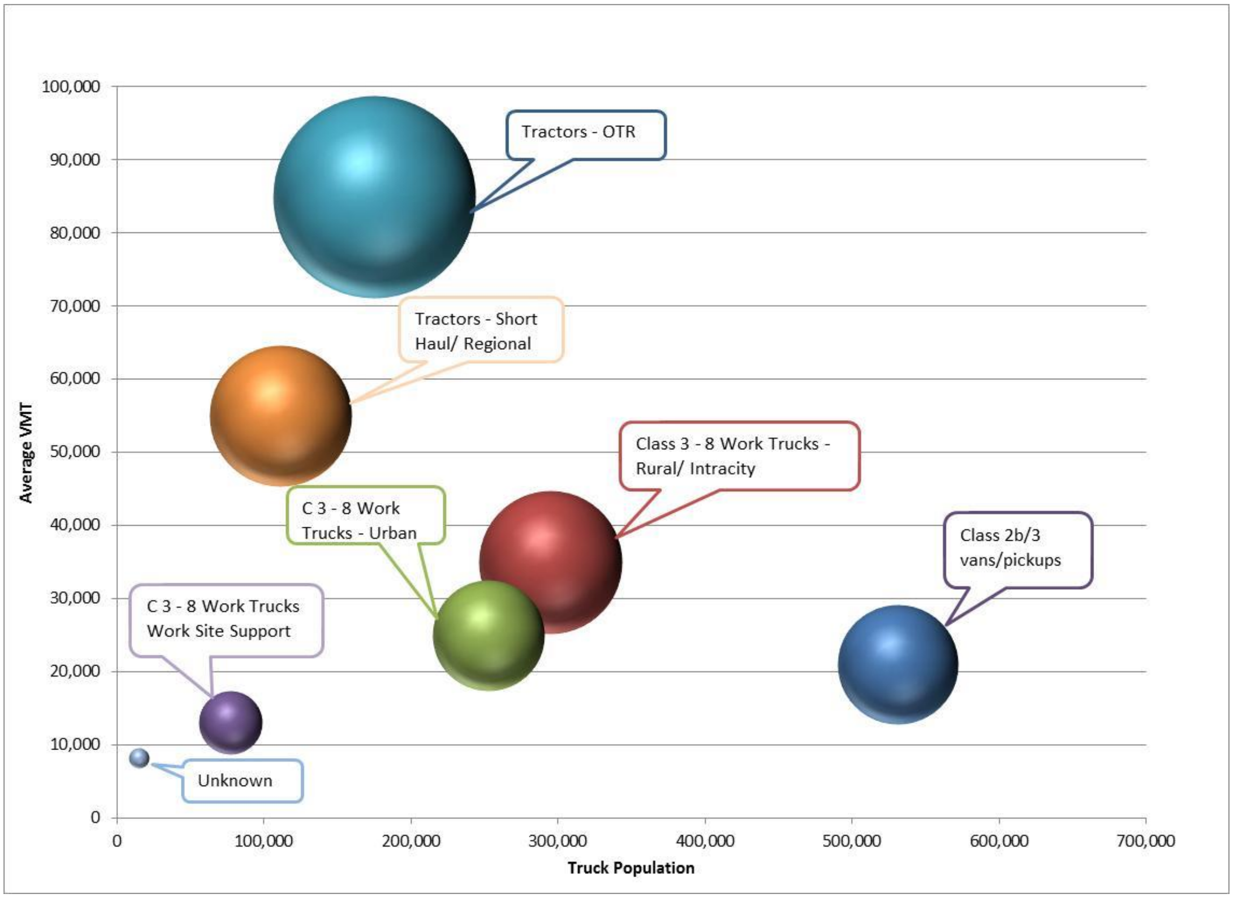
California Hybrid, Efficient and Advanced Truck Research Center calculations

Truck Fuel Use

The medium- and heavy-duty vehicle market uses more diesel than gasoline. This is not because there are more diesel trucks on the road; in fact there are more gasoline vehicles by total number. However, because the heaviest trucks use the most fuel, and are nearly 100% diesel, total diesel fuel use is higher. As one moves up the weight classes, the percentage of vehicles goes from primarily gas on the light duty end to nearly 100% diesel in the heaviest Class 8 segment.

The CEC reports approximately 15 billion gallons of gasoline used in CA in 2008, mostly in light-duty passenger cars and light trucks. This amount is projected to decline annually through 2020. According to the same report, diesel fuel use, in contrast, is estimated at 3.6 billion gallons, and is expected to increase by 1.5% annually during the same period In 2010, trucks accounted for 20% of the petroleum fuels (gasoline and diesel combined) used in California, or a total of approximately 3.5 billion gallons of which 60% was diesel.

Figure 5: Relative Baseline Truck Petroleum Use, 2010



The six truck categories in the CalHEAT study shown by truck population, annual vehicle miles travelled and their relative use of petroleum. The size of each ball represents the percentage of fuel used by trucks in that category.

California Hybrid, Efficient and Advanced Truck Research Center calculations

Technology Roadmap Summary Results

The technology strategies listed below were those identified by CalHEAT staff, its Advisory Council, and Technology Working Groups as the most feasible ways to improve efficiency and reduce emissions in MDV and HDV. The seven [only six in list on next page…] strategies grouped under Electrification and six strategies related to Engine & Driveline comprise the thirteen strategies with 66 specific actions in this Roadmap. The technology strategies and related actions are described in Chapter 2, with supporting information on the actions shown in Appendix B. The six strategies grouped under chassis, body, and roadway systems are also important and will contribute to reduction of fuel use and efficiency improvements. However, they are strategies that are already receiving reasonable attention by the industry. As a result, they are not included in specific action items recommended in this Roadmap. Additionally, investments in infrastructure, clean fuels, and other complementary needs and strategies are not included in this Roadmap.

Technology Strategies

Electrification

- Hybrid Electric
- Electrified Auxiliaries E-Trucks
- Electrified Power Take-off (EPTO)
- Plug-in Hybrid Electric
- Electrified Corridor
- Alternative Fuel Hybrids

Engine and Driveline

- Hydraulic Hybrid
- Optimized Alternative Fuel Engines
- Waste Heat Recovery
- Engine Optimization
- Alternative Power Plants and Combustion Cycles
- Transmission and Driveline Improvements

Chassis, Body, and Roadway Systems

- Light weighting
- Aerodynamics
- Lower Rolling Resistance
- Intelligent Vehicle Technologies, e.g. Forecasting, Adapting
- Corridors and Platooning
- Longer, Heavier Single Trucks

Investment

The projected investment required for the 66 action items included in this Roadmap between 2013 and 2020 totals $434,700,000. These investments continue the ongoing momentum towards California's environmental goals and act as a launch point for cost effective commercial product introductions. The focus of these CalHEAT investments are to assure the development and pilot demonstration of technologies that culminate in providing the fleets with a return on investment of two to four years by 2020.

The CalHEAT investment analysis scenario also assumes the following:

- Aggressive new state and federal regulations by 2020 that motivate manufacturers to produce, and fleets to purchase, large numbers of advanced technology vehicles. These include requirements that drive NOx emission reductions by up to 90% as well as Green House Gas reductions similar in magnitude to those put in place for the light duty vehicle market under CAFE rules.
- Significant parallel investment must be made in:
  - vehicle fueling infrastructure
  - cleaner and renewable fuels
  - advanced technology vehicle component manufacturing and workforce training.
- Economies of scale significantly drive down vehicle technology costs as production volumes increase.
- Fleets accept new technologies as vehicle payback period approaches two years.

Further, these investment projections do not include transformation of California's light-duty vehicles, off-road equipment, marine vessels and locomotive fleets. Significant additional investments and/or regulations to accelerate development and deployment of advanced technology vehicles and equipment could be needed for the South Coast and San Joaquin Valley Air Basins to meet the federal eight-hour ozone standard as required by 2023.

Incentives were developed to jumpstart new technologies, to support fleet adoption and overcome perceived fleet risks. The deployment incentives proposed here are to help build initial volumes to launch points, not to fully fund fleet turnover. Additional incentive investment would likely be needed to reach larger fleet adoption in the long run. Moreover, the total investment need is highly dependent on the specific investment strategy. CalHEAT focuses on early stage R&D in addition to deployment, in order to drive down technology costs and move past the need for purchase incentives. However, California is currently investing almost exclusively in late stage demonstrations and early deployments. A continued focus on late-stage investments would slow technology advancement and increase the amount needed for purchase incentives.

The CalHEAT investment analysis scenario assumes very aggressive fuel economy standards to be set by EPA/NHTSA under phase two of the Greenhouse Gas initiative for heavy duty vehicles. As an example an aggressive fuel economy standard for over the road Class 8 Tractors was projected at a 100% improvement. It is anticipated that the standards would be in place by 2020 and would find support by California for early adoption by 2018. In this manner the suppliers will likely self-invest in the commercialization of cost effective technologies. Without aggressive standards of at least a 50% increase, or delays in these standards, additional investment in incentives would be required to drive market adoption and acceptance.

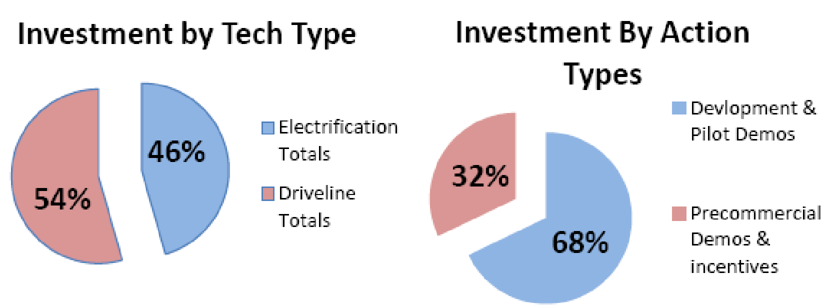
Investment for the major categories Electrification and Engine and Driveline, is shown in "

Figure 6" for two three-year periods from 2013-2016 and 2017-2020. Grouped by action, 68% of the projected investment needed to achieve the emission and efficiency targets would be in development and demonstrations, and 32% would be in deployments and incentives. By strategy, Electrification-related actions comprise 46% of the projected investment, while 54% would be for Engine & Driveline improvements. Chassis, Body, and Roadway Systems improvements have not been in included in this Roadmap, in either the investments shown or as part of the 66 action items because many advances in these areas are already underway by truck manufacturers. In addition these investment do not include any new unidentified actions that are likely to become apparent up to and beyond 2020

Further detail showing projected investment required by specific strategy to achieve the 66 action items is shown in Figure 7, page 17 and Table 4, page 18.

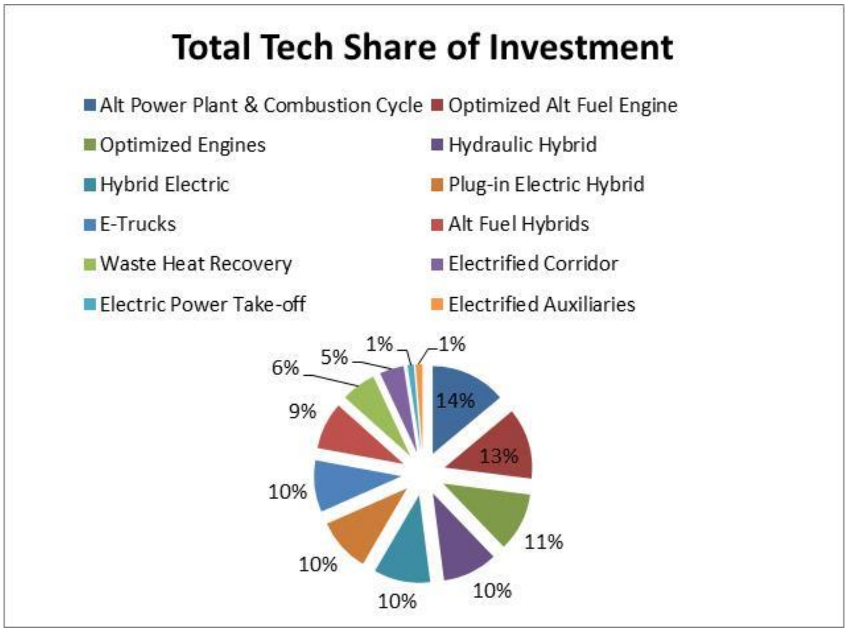
Figure 6: Investment in Actions, 2013-2020

Year	2013-2016	2017-2020	Totals $
Electrification	144,200,000	54,000,000	198,200,000
Engine and Driveline	175,000,000	61,500,000	236,500,000
Totals $	319,200,000	115,500,000	434,700,000



Projected investment by 2020 needed to address the 66 action items identified in the CalHEAT Roadmap.

Figure 7: Investment Portfolio by Strategy



Technology strategies identified by CalHEAT for medium- and heavy-duty trucks to achieve emissions reductions and efficiency improvement objectives by 2020, by strategy, showing percentage of emphasis.

California Hybrid, Efficient and Advanced Truck Research Center calculations

Table 4: Investment Portfolio by Strategy, in Millions

Technology	$ Million	Percentage
Alternative Power Plants and Combustion Cycles	$60.5	14%
Optimized Alternative Fuel Engines	$57.0	13%
Optimized Engines	$47.0	11%
Hybrid Electric	$45.4	10%
Hydraulic Hybrid	$45.4	10%
Plug-in Electric Hybrid	$43.4	10%
E-Trucks	$41.5	10%
Alternative Fuel Hybrids	$37.9	9%
Waste Heat Recovery	$28.0	6%
Electrified Corridor	$19.5	4%
Electric Power Take-off	$5.1	1%

Electrified Auxiliaries	$5.6	1%
Total	$434.7	100%

Projected investment required to accomplish the technology strategies identified by CalHEAT in the Roadmap for medium- and heavy-duty trucks to achieve emissions reductions and efficiency improvement objectives by 2020, shown by millions of dollars and relative percentage, by technology strategy.

California Hybrid, Efficient and Advanced Truck Research Center calculations

Results

The Market and Transformation Roadmap projects a reduction in emissions through advanced truck technologies by 2050 of more than 40 $MMTCO_2e$ emissions compared to existing technology, or "Business as Usual". These projected results are the expected outcome of implementation of the 66 action items in the Roadmap. Table 5, below, summarizes feasibility by CalHEAT truck category of the 13 technology strategies grouped broadly under Electrification and Engine and Driveline Efficiency. Solid circles represent technology strategies anticipated to make noticeable contributions in the corresponding truck category by 2020, half circles represent technology strategies expected to be implementable after 2020 with noticeable results, and the empty circles indicate technology strategies not applicable to the truck category or not expected to offer significant benefits.

Table 5: Promising Technology Pathways by Truck Category

Pathway	Technology	Class 7-8 Urban	Class 8 OTR	C 3 – 8 Work Site	Class 3 – 8 Urban	Class 3 – 8 Rural	Class 2b – 3 Vans/ trucks
Electrification	Hybrid Electric	●	◑	●	●	●	●
	Electrified Auxiliaries	●	●	●	●	◑	●
	E-Trucks	●	○	◑	●	◑	◑
	Electric Power Take-off	○	○	●	○	○	○
	Plug-in Hybrids	●	○	●	●	●	●
	Electrified Corridor	●	○	○	◑	○	○
	AF Hybrid	●	◑	◑	●	●	◑
Engine and Driveline	Hydraulic Hybrid	◑	○	○	●	●	●
	Optimized AF Engine	●	●	●	●	●	●
	Waste Heat Recovery	●	●	○	●	◑	◑
	Engine Optimization	●	●	●	●	●	●
	Alternative Power Plants & Combustion Cycles	●	●	◑	◑	◑	◑
	Transmission and Driveline	●	●	●	●	●	●

The 13 technology strategies deemed most feasible by the CalHEAT research are shown in this chart. Solid circles represent the technologies in the Roadmap that are expected to contribute to noticeable CO_2e reductions by 2020. Half circles represent technologies expected to be implementable after 2020 with noticeable results. The empty circles indicate technologies not expected to offer significant results in that truck category.

California Hybrid, Efficient and Advanced Truck Center Research

The technology evaluation groupings below were the initial technology pathways considered to have the greatest potential for reducing emissions and fuel use, and led to the selection of the 13 technology strategies identified in the Roadmap. These evaluation groups have been used in some of the long-term projections, including the Technology Adoption Charts shown in Category , page 27 and Figure 14: Technology Adoption all Truck Categories, page 28.

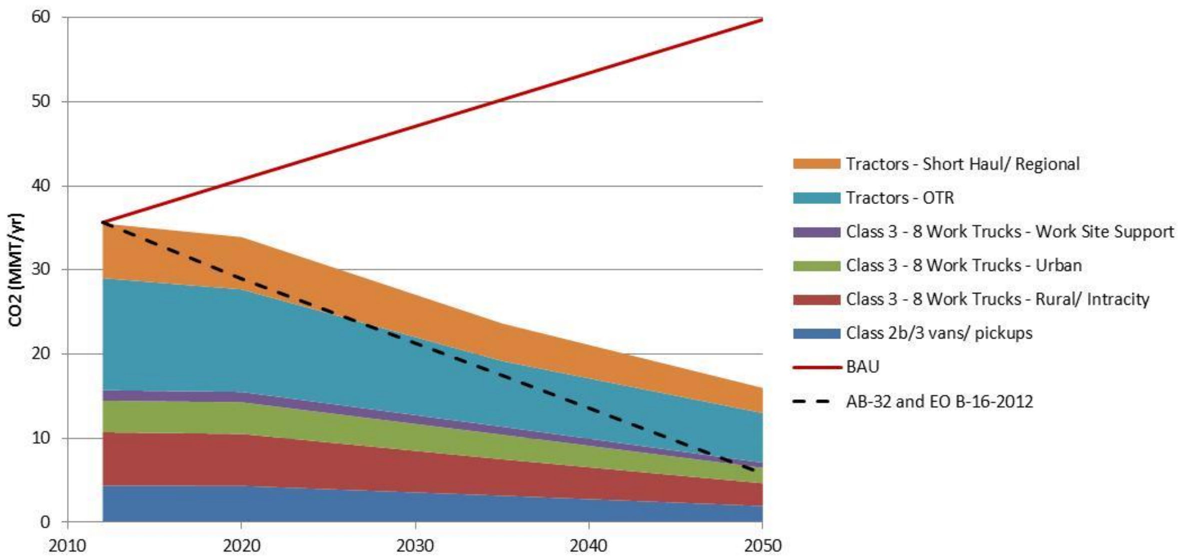
Technology Evaluation Grouping

Baseline	Waste Heat Recovery Engine Optimization Transmission and Driveline Improvements Light-weighting Aerodynamics Lower Rolling Resistance Intelligent Vehicle Technologies, e.g. Forecasting and Adapting Corridors and Platooning Longer, Heavier Single Trucks
New Combustion	Alternative Power Plants and Combustion Cycles
Fuel Cells	Alternative Power Plants/Alternative Fuels
Hydraulic	Hydraulic Hybrid
HEV	Hybrid Electric Electrified Auxiliaries Electrified Power Take-off (EPTO)
xEV	E-Trucks Plug-in Hybrid Electric Electrified Corridors

CO_2e Reduction from the CalHEAT Roadmap

Through implementation of the 66 action items identified in this Roadmap, a reduction of approximately 5 $MMTCO_2e$ can be achieved by 2020 from the "Business as Usual" projected level without these changes, and a reduction of over 40 $MMTCO_2e$ could be achieved by 2050. Figure 8, below, shows the impact by CalHEAT vehicle category compared to "Business as Usual." The Roadmap reductions are based on technology improvements to increase mileage or reduce fuel consumption, including increased adoption of hybrids and E-Trucks. The model is based on a 25% adoption rate of biofuels by 2050. The descending line shows the targeted reduction called for by AB 32 and EO B-16-2013. The gap between the projected reduction and the Roadmap reductions could be met by a higher rate of adoption of biofuels.

Figure 8: CO_2e Reduction from Roadmap



The combined impact of the 66 Actions included in the CalHEAT Roadmap as projected to reduce CO2 equivalent emissions by 2050. Reduction is shown for each of the six CalHEAT truck categories defined in the Roadmap by size and application. The ascending line for "Business as Usual" shows projected emissions without the Roadmap Actions. The dashed line shows the reduction goals set by AB 32 and EO B-16-2012.

California Hybrid, Efficient and Advanced Truck Research

Fuel-Related Reductions

Use of biofuels and decarbonization of electricity and hydrogen used in fuel cells are expected to account for a portion of the projected CO_2 reduction from the Roadmap actions, as shown in Figure 9, below. Increased use of diesel biofuel is projected in the Roadmap as one of the ways to reduce carbon and petroleum-based fuels. Although most gasoline sold in California is currently 10% ethanol, only a very small percentage of today's diesel fuel includes biodiesel. The CalHEAT model is based on an assumption of increased use of biodiesel to 5% by 2020, which is expected to be achieved by blending biodiesel with petroleum-based diesel. The model assumes an increase to 20% biodiesel by 2035. These assumptions were developed in part on the Air Resources Board Advanced Biofuel Market Report 2011 which details expected increases in availability of biodiesel through 2015. [20] Biofuels give off approximately the same amount of CO_2 as petroleum based fuels during combustion. However, they reduce the net amount of carbon in the air because the plants from which the biofuels are derived use CO_2 as the carbon source for the complex oil molecules in which the plant stores energy.

Electricity decarbonization is another way to reduce carbon impact, by changing the source of energy used to generate power to more renewable sources. The fuel curve assumptions used in the model are based on 30% renewable sources of energy for power generation by 2020, based on targets established in 2006 by AB 32. The fuel curves in the Roadmap also assume an increase to 95% renewable sources of energy for generation of electricity by 2050, based on a published model used to analyze the potential for electricity decarbonization.[21]

Hydrogen decarbonization, a way to extract hydrogen in a usable form from renewable sources, is expected to become cost-effective in the future as an energy source in fuel cells. As a result, it is projected to make a contribution in carbon reduction beginning in 2020, and continue through 2050. The Roadmap model assumes that 33% of hydrogen will be from solar-generated electrolysis or renewable natural gas through 2035. After 2035, the curve follows that used for electricity. For additional information on assumptions used and how the Roadmap model was developed, please see Appendix A, page 65.

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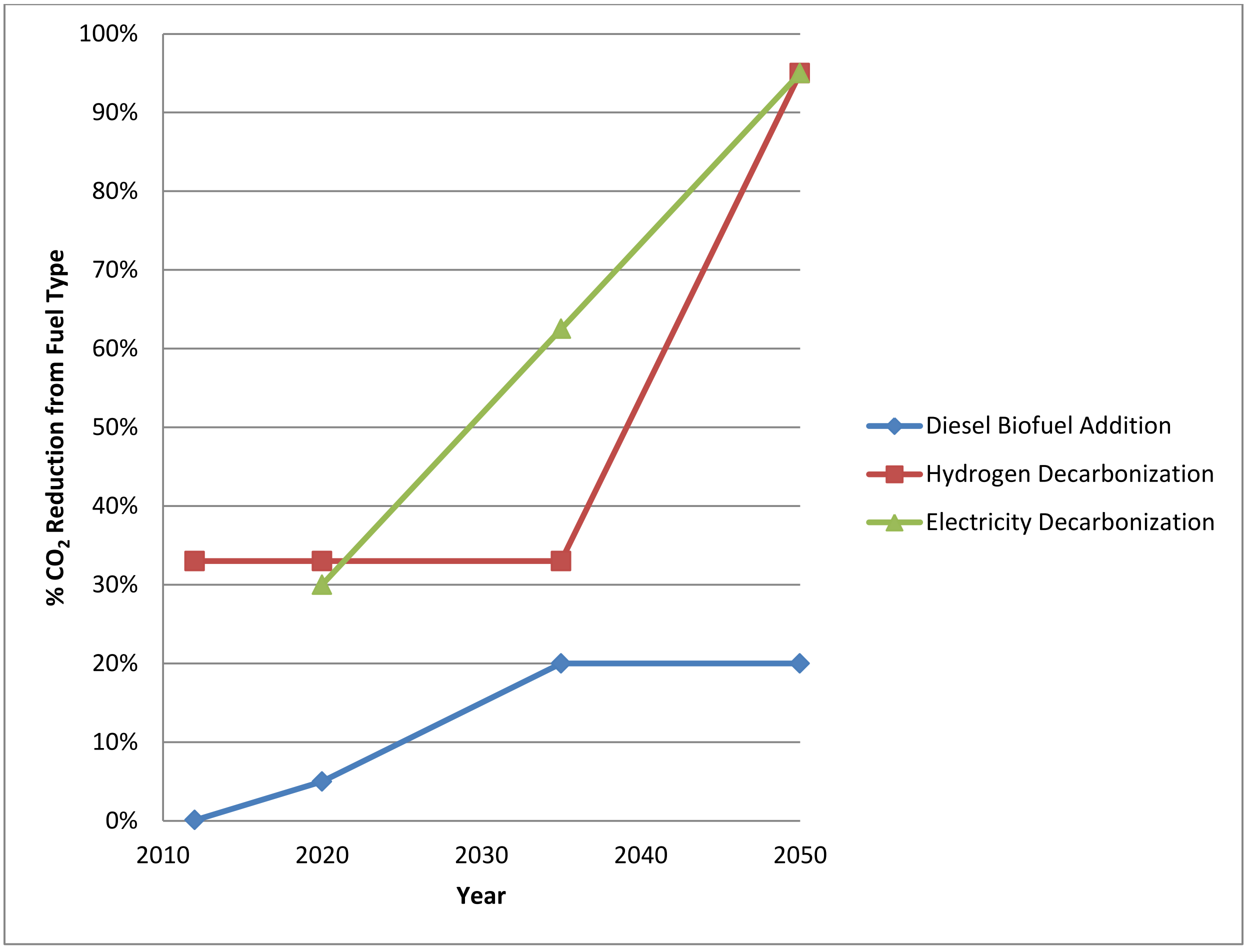
[20] California Air Resources Board, ***Advanced Biofuel Market Report 2011, Meeting the California LCFS.*** http://www.arb.ca.gov/fuels/lcfs/workgroups/advisorypanel/20110825_e2_report.pdf

[21] Williams, James H.; DeBenedictis, Andrew; Ghanadan, Rebecca; Mahone, Amber; Moore, Jack, Morrow, William R., III; Price, Snuller; and Torn, Margaret S. 2011. ***The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity.*** *Science*, April 20, 2012.

Figure 9: Fuel-related CO_2 Reduction Assumptions



Increased use of biofuels and decarbonization achieved by using renewable energy sources will contribute to the CO_2e reductions projected by the CalHEAT Roadmap. Significant reductions can be achieved through electricity decarbonization, by using clean or renewable energy sources for electric power, and hydrogen decarbonization, a process that removes carbon while creating hydrogen for use in fuel cells.

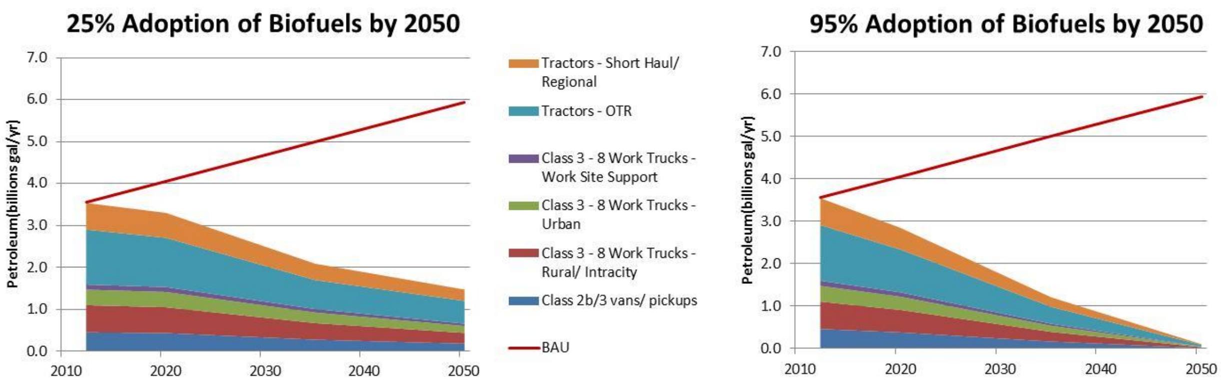
California Hybrid, Efficient and Advanced Truck Research calculations

The Roadmap projections for CO_2e and petroleum use are based in part on biofuel adoption, assuming a moderate adoption rate of 25% by 2050. At this level of biofuel adoption, petroleum use decreases from 3.5 billion gallons per year across all truck categories to 1.5 billion gallons per year in 2050, as shown in the chart on the left in Figure 10, below. Compared to 2012 levels, this would result in a 6.9% reduction in petroleum used by trucks in California by 2020, a 41% reduction by 2035, and a 58% reduction by 2050. The rate of adoption of biofuels will be dependent on how fast they ramp to a competitively priced commercial scale, but if the adoption rate is higher, much greater reductions in petroleum use and CO_2e can be achieved.

Figure 10: Impact of Biofuel Adoption on Petroleum Reduction shows reduction curves for petroleum of 25% adoption by 2050 on the left and 95% biofuel adoption on the right. In the

high adoption rate scenario, petroleum use decreases from a total of 3.5 billion gallons per year across all truck categories in 2012 to 0.098 billion (98 million) gallons per year in 2050. This scenario results in a 20% reduction in petroleum use by 2020, a 66% reduction by 2035, and a 97% reduction by 2050, compared to 2012 levels.

Figure 10: Impact of Biofuel Adoption on Petroleum Reduction



The CalHEAT Roadmap assumes a 25% adoption rate for biofuels by 2050, which is projected to result in a reduction of petroleum-based fuels from 3.6 billion gallons/year in 2012 to 1.5 billion gallons/year in 2050, as shown in the chart on the left. A higher rate of adoption of biofuel can further reduce petroleum requirements, as illustrated in the chart on the right.

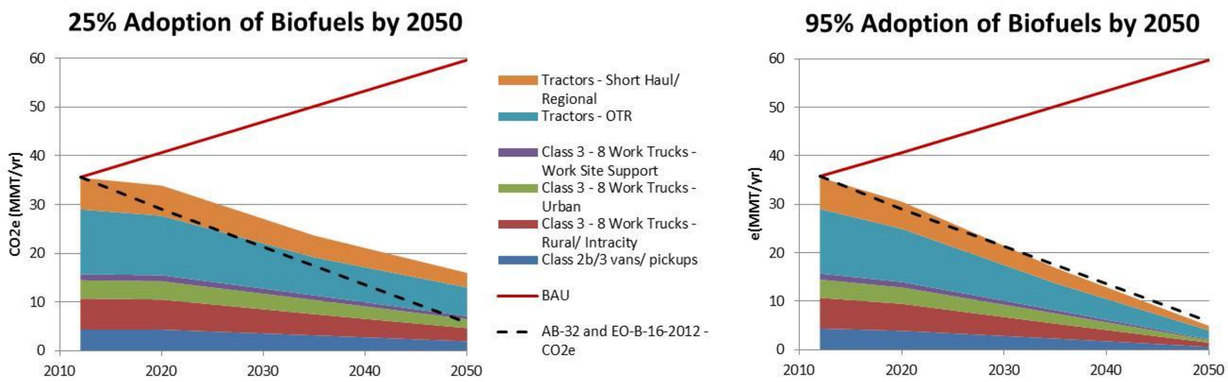
California Hybrid, Efficient and Advanced Truck Center calculations

Impact of Biofuel Adoption on CO_2e Reduction

The impact on CO_2e emissions from a transition to biofuels is shown in Figure 11, below. The chart on the left shows the curves used for the projections in this Roadmap, using a 25% biofuel adoption rate, which results in a decrease of CO_2e from 36MMT in 2012 to approximately 16MMT/year in 2050. Compared to 2012 levels, the reductions are 4.9% by 2020, 33% by 2035, and 55% by 2050.

As with petroleum use, CO_2e emissions under a higher adoption rate of biofuels could be much lower. In the comparative curve on the right side of Figure 11, which is based on a 95% biofuel adoption rate, CO_2e could be reduced to 4.9MMT in 2050, with the largest reductions coming from tractors, in both the short-haul /regional and OTR categories. Compared to 2012 levels, this could result in an 86% reduction of CO_2e in 2050.

Figure 11: Biofuel Related Impact on CO_2e Reduction



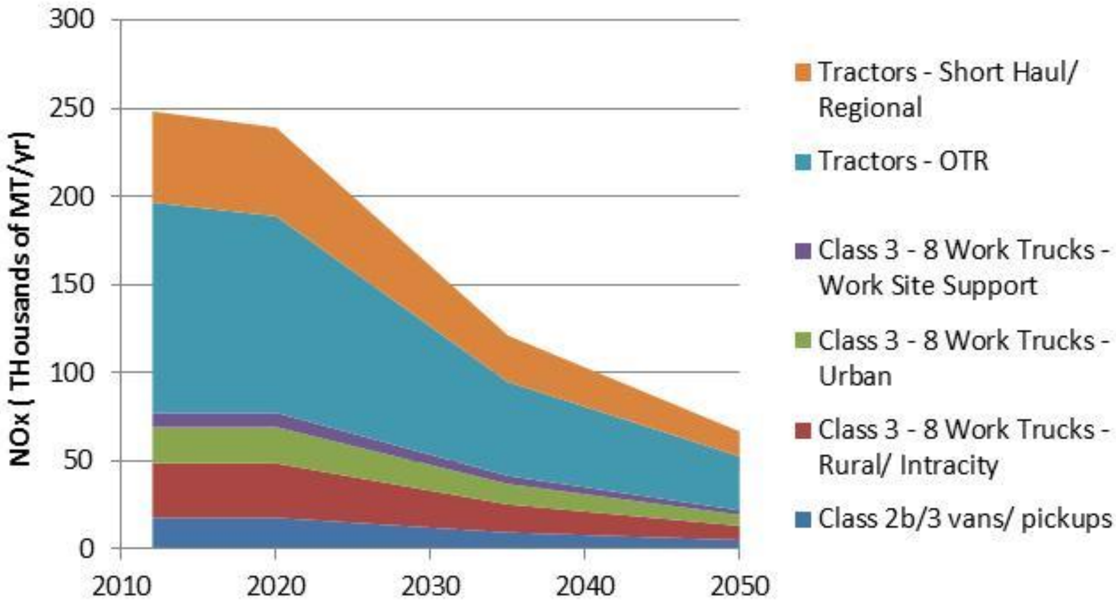
The CalHEAT Roadmap assumes a 25% adoption rate for biofuels by 2050, which would result in a reduction of CO_2e from 36MMT/year in 2012 to 16MMT/year in 2050, as shown in the chart on the left. A higher rate of adoption of biofuel can further reduce CO_2e, as shown in the example on the right, which assumes a 95% adoption rate by 2050. At a 95% adoption rate, a reduction to 4.9MMT/year of CO_2e could be achieved across all truck categories, which would reach the California target levels defined for 2050.

California Hybrid, Efficient and Advanced Truck Center calculations

NOx Reduction

The Roadmap projects a reduction in NOx from 249,000 MT/year in 2012 to 67,000 MT/year by 2050, as shown in Figure 12, below. On a percentage basis, the reductions are 4% by 2020, 51% by 2035 and 73% by 2050, and are expected to be achieved through increases in miles per gallon, beginning in 2012, and from adoption of NOx reduction technologies beginning in 2020. Under the assumptions used, NOx reduction does not vary with the biofuel content.

Figure 12: Projected NOx Reductions



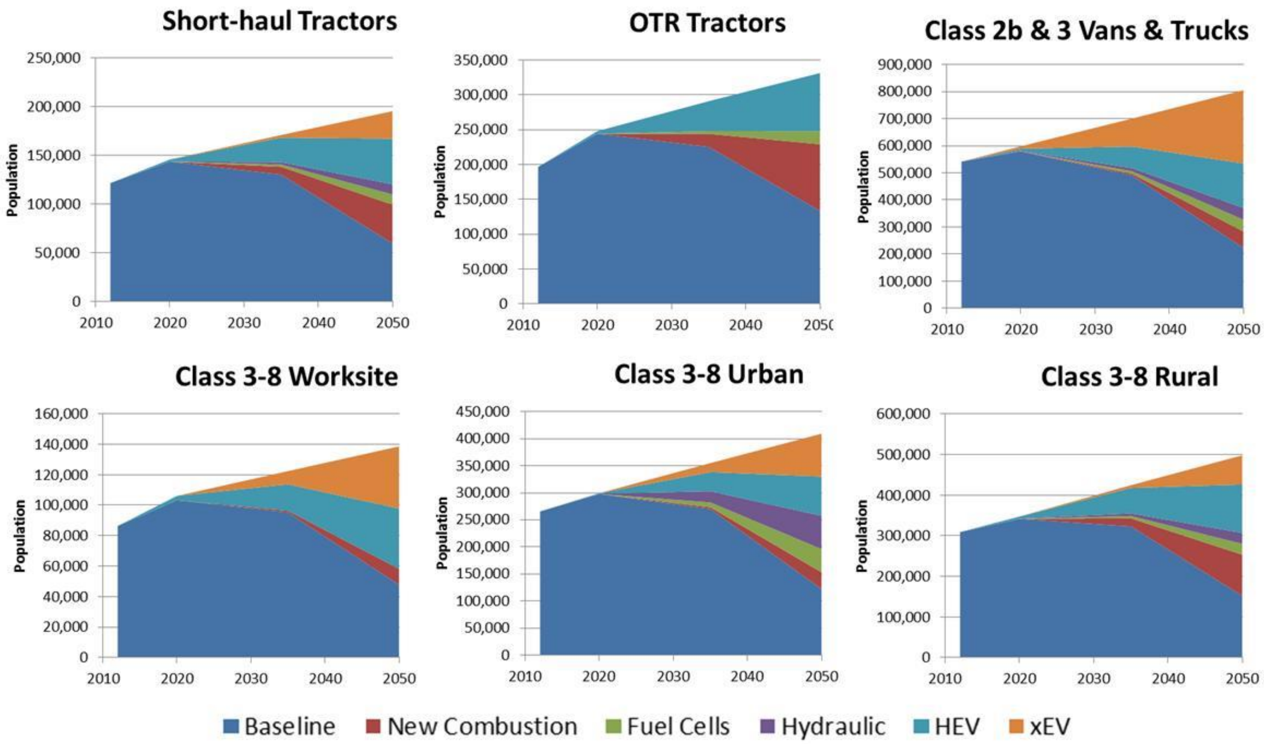
CalHEAT Roadmap projections result in a reduction of NOx, a greenhouse gas that is a precursor to ozone, from 249,000 metric tons per year in 2012 to 67,000 metric tons per year in 2050. The highest reductions will result from short-haul/regional and over-the-road tractors.

California Hybrid, Efficient and Advanced Truck Center calculations

Technology Adoption

Projected timelines for technology adoption and the impact by number of vehicles is shown in Category , page 27, by CalHEAT truck category and in Figure 14, page 28, for all six truck categories combined. Baseline technologies include waste heat recovery; engine optimization; transmission and driveline improvements; light-weighting; aerodynamics; lower rolling resistance; intelligent vehicle technologies such as forecasting and adapting; corridors and platooning; and longer, heavier single trucks. The other evaluation groups are New Combustion; Fuel Cells; Hydraulic Hybrids; Hybrid Electric Vehicles (HEV), which includes hybrid-electric trucks, electrified auxiliaries and power take-off; and xEV which includes E-Trucks with full electric powertrains, and plug-in hybrid electric vehicles; and Electrified Corridors, which provide external power to electric powertrains for ZEV Corridors. By 2020, more than 1.7 million trucks are expected to have adopted some of the recommended technologies, and by 2050, projected adoption of some of the Roadmap technologies will affect approximately 2.4 million trucks, as shown in Figure 14.

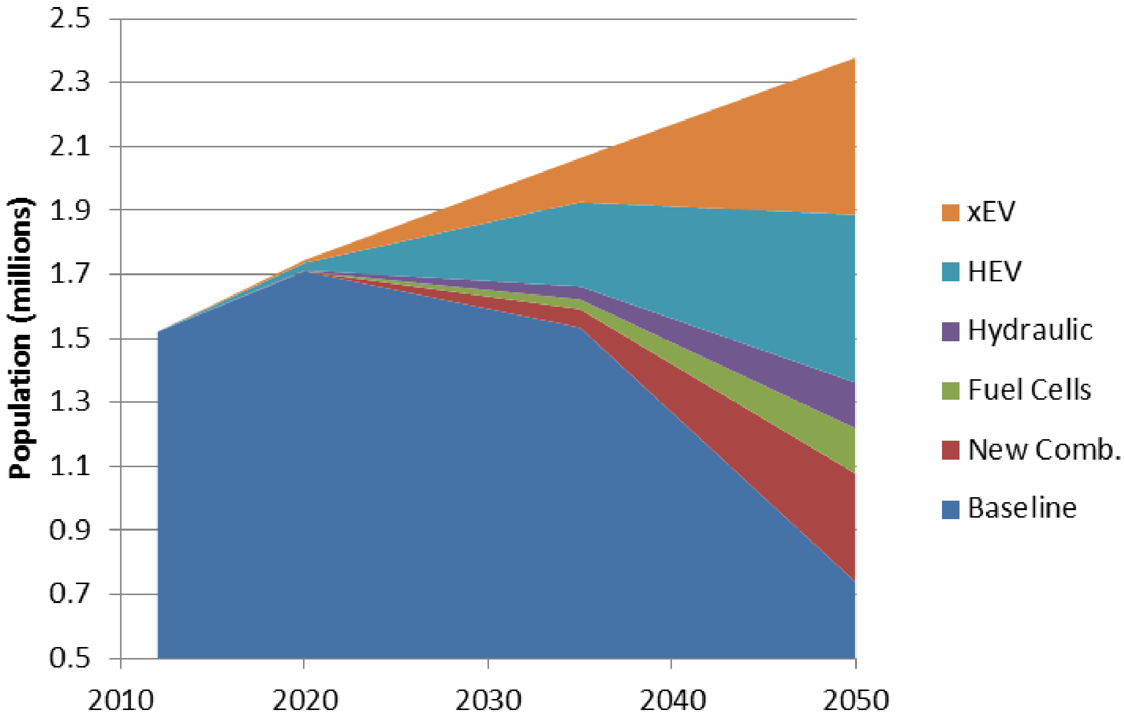
Figure 13: Technology Adoption by Truck Category



Projected adoption of CalHEAT Roadmap Action Items by Technology Group and Truck Category, shown by number of vehicles affected from 2010 through 2050.

California Hybrid, Efficient and Advanced Truck Research

Figure 14: Technology Adoption all Truck Categories



Projected adoption of CalHEAT Roadmap Action Items by Technology Group for all CalHEAT Truck Categories combined, shown by number of vehicles affected, 2010 through 2050. By 2020, the Roadmap action items could result in efficiency and emission improvements in approximately 1.7 million trucks, and by 2050, this impact could increase to 2.4 million trucks.

California Hybrid, Efficient and Advanced Truck Research Center

CHAPTER 2: Technology Solutions and Action Roadmaps

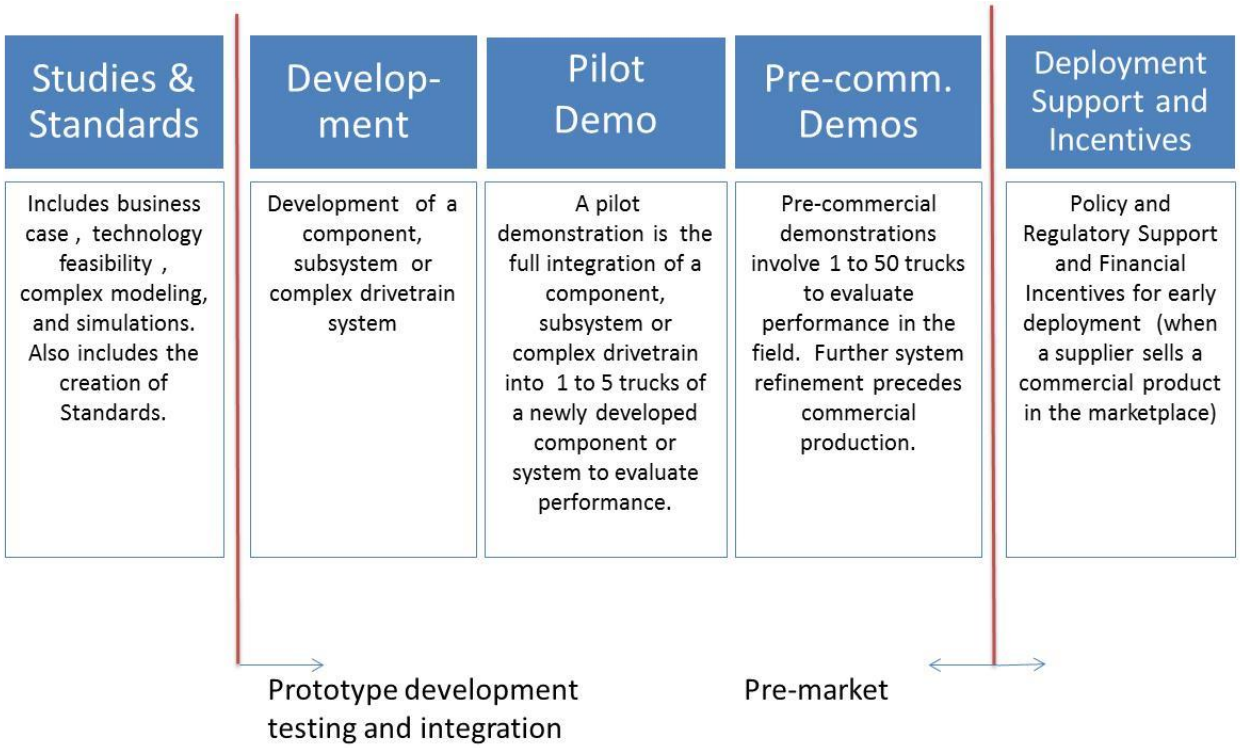
From the information gathered in its initial Inventory of the California Truck Fleet, and the Forums held with CalHEAT Advisory Council and Technical Advisory Group members, various technology pathways were identified as a starting point for discussion and analysis as the *Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks*, as described in the Technology Evaluation Grouping, page 20.

From these pathways, 13 technology strategies were selected as those most likely to provide achievable opportunities to reduce petroleum use and carbon emissions, and increase efficiency. They are shown in shown in Figure 17, Summary Roadmap Timelines, page 31. Actionable steps with milestones and timelines for technology research, development, demonstration and market introduction were identified for each of the strategies. The overall Roadmap covering the 13 technology strategies includes 66 action items. Each of these technology strategies is addressed in a separate section of this chapter, beginning with Hybrid Electric on page 33.

Introduction to the Roadmap

The CalHEAT Roadmap uses five types of actions to accelerate the development and commercialization of technology solutions, detailed in Figure 15, below. "Studies and Standards" cover business case or feasibility research prior to development of initial prototypes. "R&D", "Pilot Demonstrations" and "Pre-Commercial Demonstrations" are actions that cover the development and pre-market stages of bringing new technology to market. "Deployment Support and Incentives" for market-ready technologies provide regulatory or financial support to encourage adoption.

Figure 15: CalHEAT Technology Actions

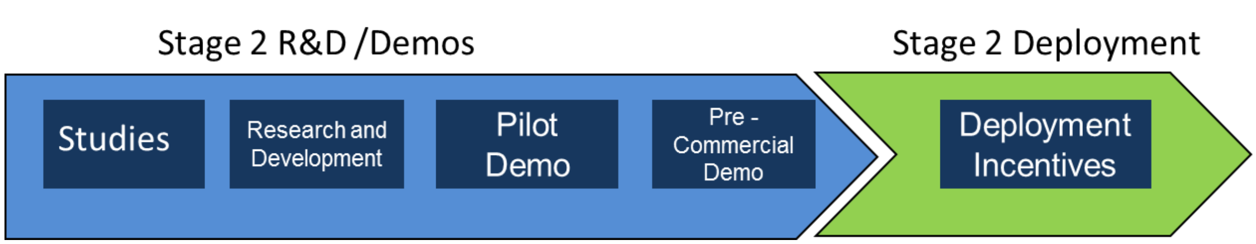


CalHEAT uses five types of actions to accelerate technology solutions in the market.

California Hybrid, Efficient and Advanced Truck Research Center

To convey the timelines associated with each action, summary timelines are used throughout the Roadmap. As shown in Figure 16, below, blue arrows are used for the four actions covering pre-market activity, and green arrows are used for deployment support and financial incentives to support market-ready technologies. The development actions or development stage are embedded in the arrow.

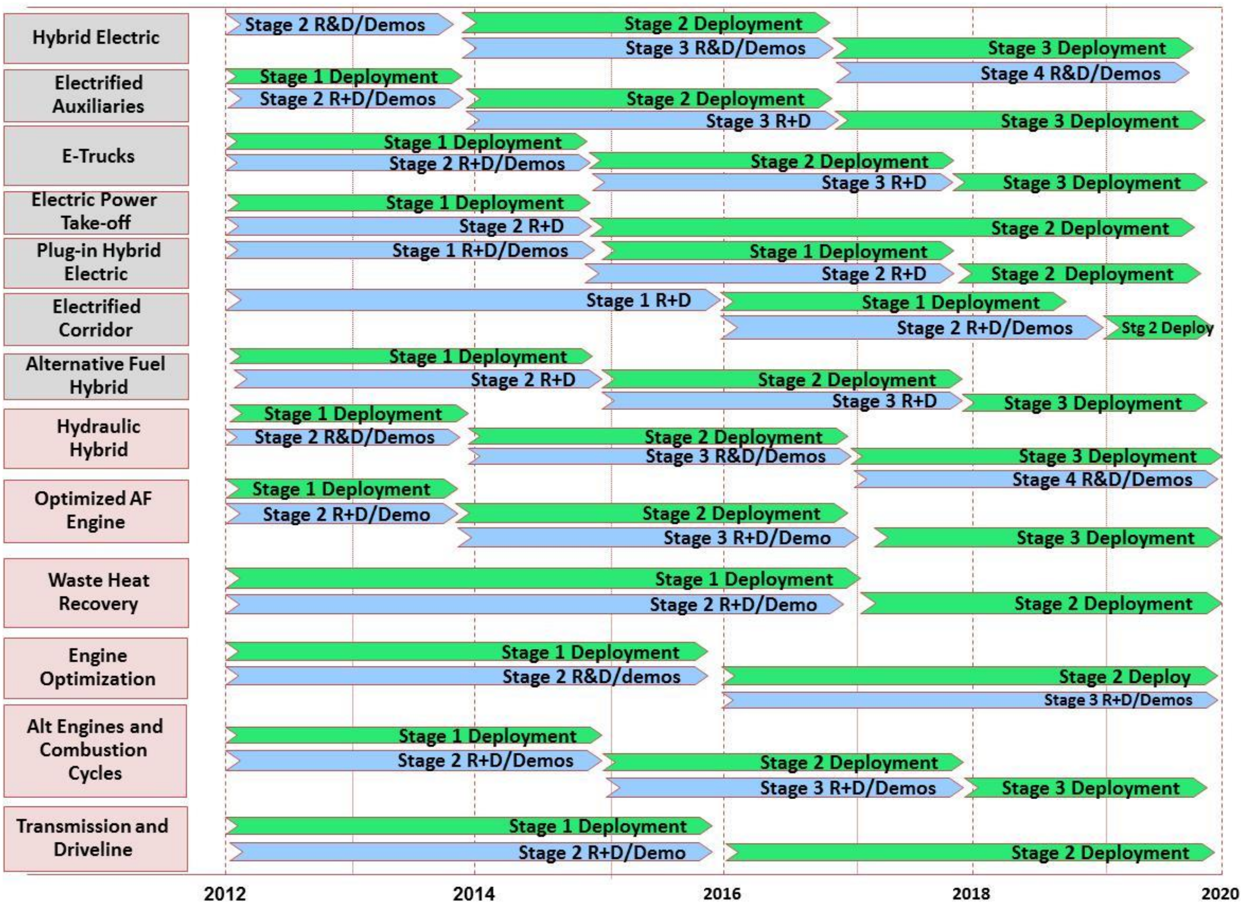
Figure 16: Summary Timeline



Summary timelines are used in the summary Roadmap timelines and in the 13 technology and action roadmaps that group goals and actions by technology strategy to show the development stages, actions and the period of time projected for each.

An overall summary timeline for the development stages of the Roadmap, by technology strategy, is shown in Figure 17, below. The 66 actions, identified by number and the type of action, from study or standard through deployment, are grouped by technology strategy in Figure 18, page 32.

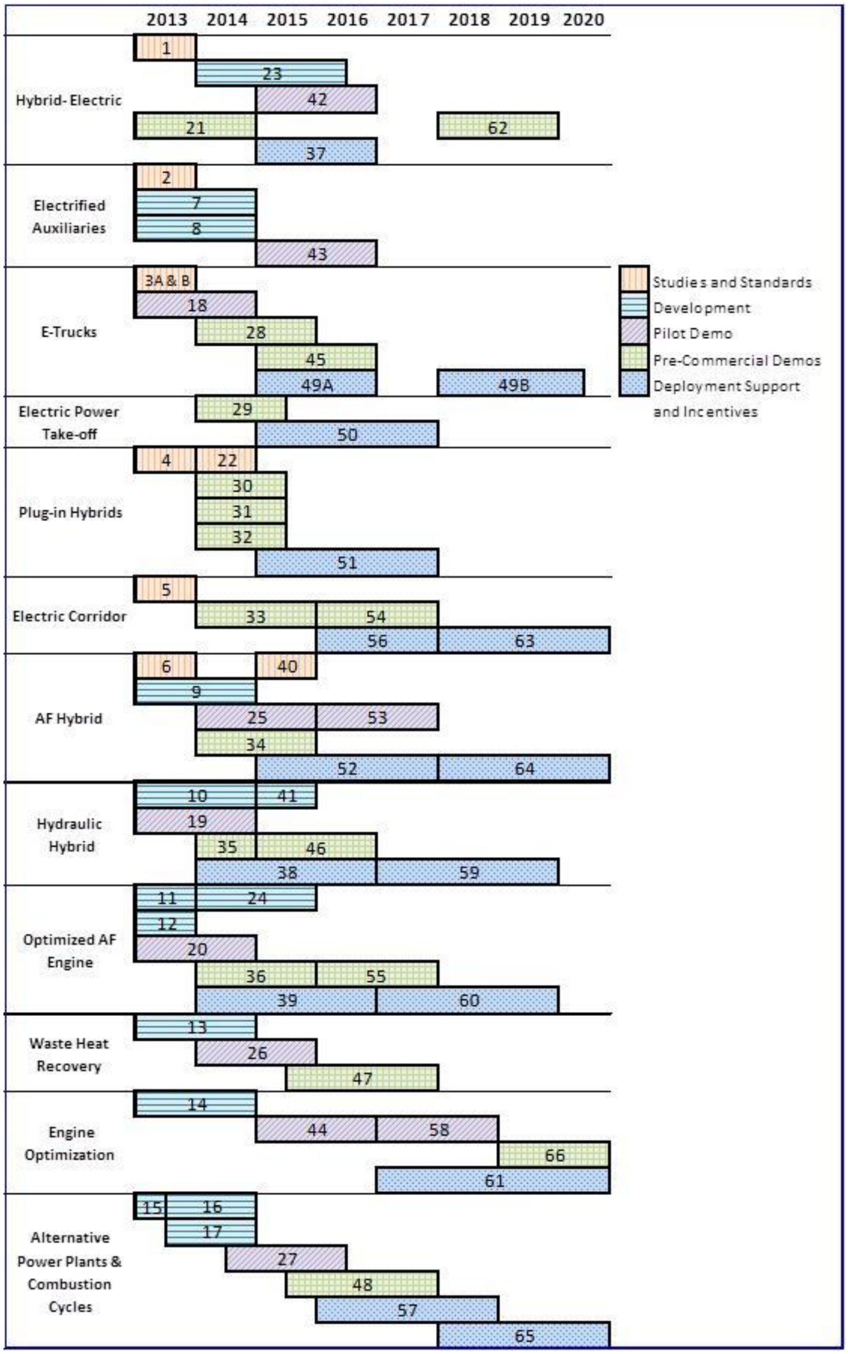
Figure 17: Summary Timeline for CalHEAT Roadmap Technology Strategies



Summary roadmap timeline for 13 technologies identified in the CalHEAT Research and Market Transformation Roadmap as promising strategies to contribute to both reduction of carbon and decreased use of petroleum by more than 70% by 2050 from 2012 compared to "Business as Usual."

California Hybrid, Efficient and Advanced Truck Research Center

Figure 18: Sixty-six Actions by Technology Strategy



The 66 actions to reduce petroleum, emissions or improve truck efficiency are grouped by technology strategy and identified by action category, from studies and standards through deployment. Refer to Table 6, Appendix B, page 70, for a numerical list, timeline and description.

California Hybrid, Efficient and Advanced Truck Research Center

Hybrid Electric

Hybridization allows significant increases in vehicle efficiency by reducing fuel consumption. Hybrid vehicles use two distinct power sources to move the vehicle. In a typical medium- or heavy-duty hybrid electric truck, an internal combustion engine (ICE) fueled by gasoline or diesel powers the vehicle when sufficient electrical power is not available. During braking, descending a hill, or other times when excess kinetic energy is available, the hybrid system captures and stores it. This stored energy can then be used to help power the vehicle with electricity, thus reducing the amount of fuel required.

Further electric hybrid truck improvements to achieve higher fuel economy; optimize, downsize and integrate the engine; increase energy storage; and improve ROI are summarized in four technology/action stages in Figure 19, below. The technology improvements for each stage, described in the upper series of boxes, can be achieved through the corresponding actions shown below them.

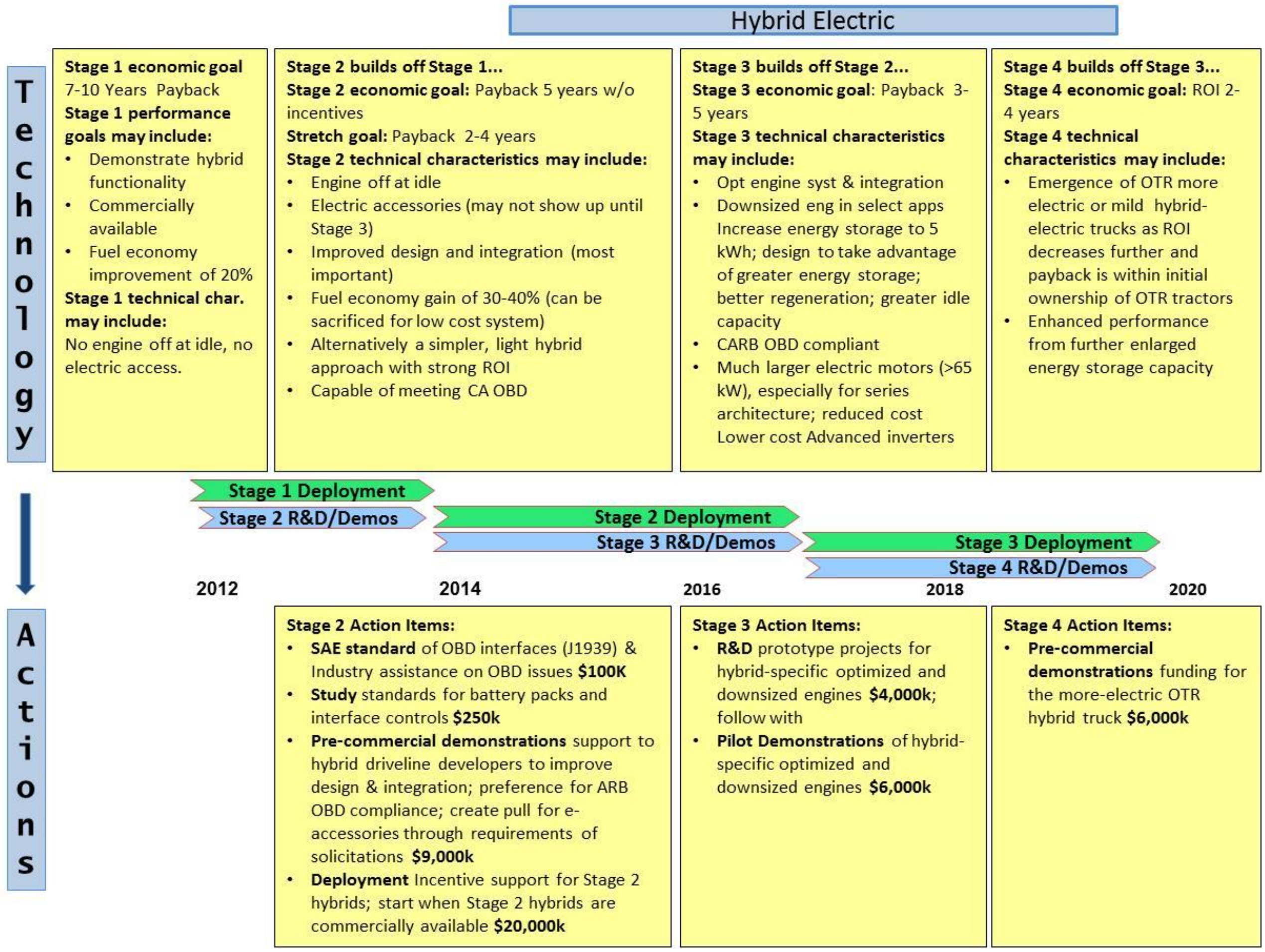
Over the four stages shown in the roadmap the ultimate goal will be to achieve a two-to-four year ROI. The key strategy to accomplish this will be an evolution of improved levels of system and chassis integration complemented by improvements in energy storage costs and performance.

Characteristics of hybrid trucks that were commercially available in 2012 are shown as Stage 1 technology. They provide a 20% improvement in fuel economy over conventional trucks, but may not have engine off at idle or electrified auxiliaries.

Stage 2 includes an economic goal of payback in 5 years without incentives. Technical characteristics include engine off at idle, electrified auxiliaries, improved integration, fuel economy gain of 30-40%, and CA on-board diagnostic (OBD) compliance. Related actions include efforts to overcome California OBD issues and support development of an SAE standard for OBD interfaces (J1939), a study on battery packs and interface controls (shared with E-Trucks), pre-commercial demonstration of Stage 2 technology, and deployment incentives for 1,000 Stage 2 hybrids drivelines when they become commercially available. Stage 3 hybrid electric advances, targeted for 2014-2016, call for larger, lower-cost electric motors, greater integration, and optimized engine systems. To achieve these objectives, greater cooperation among the engine, drivetrain and platform manufacturers is needed. Stage 3 actions include R&D prototype projects and pilot demonstrations of hybrid-specific optimized and downsized engines.

Stage 4 advances call for a two-to-four-year ROI and the emergence of more electric or mild hybrid electric over-the-road (OTR) trucks as enhanced performance from larger energy storage capacity and decreased ROI makes payback feasible for OTR tractors. A Stage 4 Roadmap action includes pre-commercial demonstration funding for a more-electric OTR truck.

Figure 19: Hybrid Electric Technology and Action Roadmap



Four stages of technology development have been defined to advance hybrid electric trucks through 2020, achieving increased fuel economy through features such as engine off at idle, electrified auxiliaries, hybrid-optimized and downsized engines for greater efficiency, and increased energy storage. The actions needed to achieve them are shown below the arrows of the summary timeline.

California Hybrid, Efficient and Advanced Truck Research Center

Electrified Auxiliaries

Auxiliary loads or accessories, such as air conditioning, alternators, power steering, power brakes, the engine water pump, air compressor, power-steering pump, and cooling fans can represent up to 9% of the energy used in a truck. In many cases, the energy they require can be reduced by converting them to electric power. Electrically-powered accessories such as the air compressor or power steering operate only when needed, but these accessories impose a parasitic demand all the time when they are engine driven. In other cases, such as the cooling fans or the engine water pump, electric power allows the auxiliary load to run at speeds independent of the engine speed, which can reduce power consumption.[22] The use of a hybrid system, thermo-electrics, or an electric turbocompound provides a source of electrical energy that can be used to drive auxiliaries that are engine-driven on today's vehicles. Electrified accessories are a critical enabling technology for E-trucks, Plug-In Hybrid Trucks, idle off for Hybrids and the further electrification of Class 8 Over-the-Road Tractors.

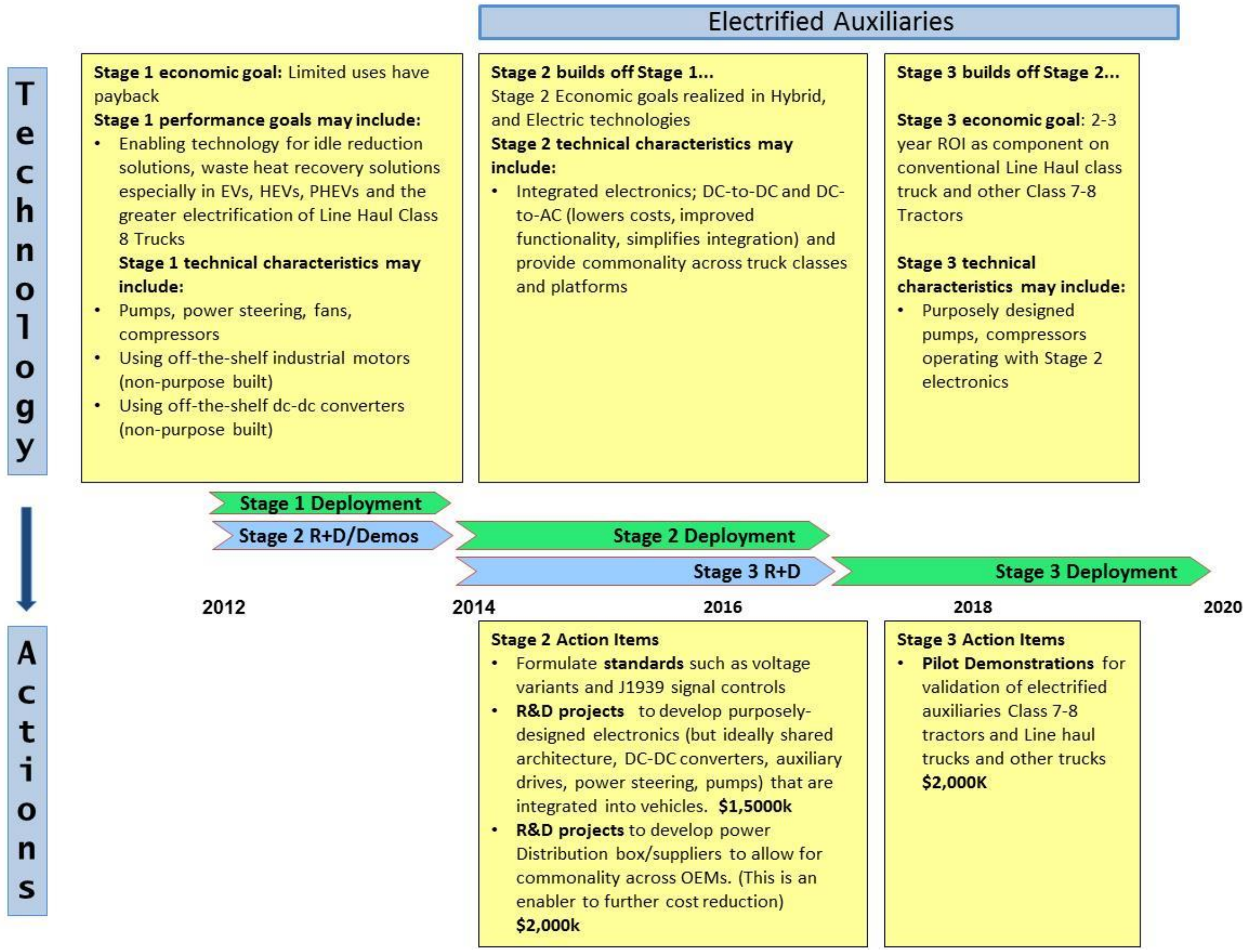
Electrifying components is essential in many emerging truck systems because of the efficiency benefit that can be gained. This is true even on otherwise conventional powertrains, but becomes especially important with hybrid powertrains, and critical when considering the ability for a hybrid to operate in electric-only or engine-off modes. Without electrified power steering and brakes, the vehicles cannot operate in these modes.

The CalHEAT Technology and Actions Roadmap for Electrified Auxiliaries is shown in Figure 20, page 36. Stage 1 development was already underway in 2012. The objective of converting auxiliary loads to electric power is to reduce fuel used by HEV or PHEV trucks operating in idle mode just to power accessories. Technical characteristics of the Stage 1 electrified auxiliaries commercially available in 2012 are that they are based on off-the-shelf industrial motors and DC-to-DC converters, and typically include pumps, power steering, fans and compressors.

Stage 2, from 2014 to 2017, targets are economical implementation of integrated DC-to-DC and DC-to-AC electronics to lower costs, improve functionality, simplify integration, and provide commonality across truck classes and platforms. One of the barriers to adoption of such accessories is non-standard voltages across vehicle platforms, so one Roadmap action includes development of standards for voltage variants and J1939 signal controls. Other actions include R&D to develop purpose-designed electronics that can operate in a shared architecture for DC-to-DC converters, such as auxiliary drives, power steering, and pumps integrated into vehicles. Stage 3 goals are to achieve purpose-designed pumps and compressors operating with Stage 2 electronics to improve efficiency and achieve a two-to-three-year ROI for components on conventional Line Haul and other Class 7-8 tractors. Pilot demonstrations for validation of electrified auxiliaries in Class 7-8 tractors and Line-Haul trucks are projected for 2017 to 2019.

[22] National Academy of Sciences site visit to Daimler/Detroit Diesel, April 7, 2009.

Figure 20: Electrified Auxiliaries Technology and Action Roadmap



Three stages of technology development for electric-powered accessories are shown above. The actions for Stage 1 were already underway by truck manufacturers in 2012 and are being deployed. The actions for Stage 2 and Stage 3 development focus on voltage standards and purpose-designed electronics, with validation of electrified auxiliary loads in line-haul trucks planned for Stage 3, 2018-2019.

E-Trucks

There is a distinct category of zero-emission trucks with electric motors and powertrains, referred to as E-Trucks, which do not include a combustion engine. Their environmental footprint is primarily defined by the source of the electricity. Clean sources have a large environmental benefit, and even “dirty” sources of electricity tend to show a net “well-to-wheels” benefit for electric vehicles. Electric motors are also efficient and able to produce maximum torque, giving EVs strong driving characteristics, particularly in stop-and-go or urban driving situations. The torque characteristics of electric motors are well-suited for moving heavy loads, as evidenced by their long use in freight trains, and suggest that the upper limits of their power capabilities will not be tested in trucks. Electric motors also offer the ability to operate with very low noise, an advantage in certain applications.

Currently, EVs have some disadvantages over conventional vehicles, primarily in cost, weight and range. EV components are relatively expensive, and storing electricity using currently available technology is expensive, bulky, and heavy. The California Energy Commission estimates the current incremental cost for a fully-electric medium- or heavy- duty vehicle to be between $50,000 and $100,000.[23] . Reduction of petroleum dependence is a major objective of the U.S. Department of Defense and it has been a significant supporter of advancing alternative powertrain trucks. As of 2011, initial E-Trucks capable of silent operation were available in Classes 3-8, primarily for worksite and urban delivery applications.

The CalHEAT Roadmap for E-Trucks, shown in Figure 21, below, identifies three technology stages. Currently available commercial trucks are shown as Stage 1, without accompanying actions. Stage 2, targeted for 2013-2017, builds off Stage 1 to improve ROI. This will be accomplished through improved integration of the electric driveline, optimization of system design to reduce use of expensive components such as copper connectors and wiring, development of standards for battery packs in multiple sizes, and fast charging. Stage 2 assumes a $450/kW-hr battery pack cost. An additional objective for Stage 2 is expansion of applications into drayage trucks. Related actions in Stage 2 include deployment incentives to help reduce projected ROI to five years; pre-commercial demonstrations of Stage 2 E-Trucks; development of energy storage standards for pack-level interfaces through SAE, IEEE, or regulations; a study on best applications for fast charging; and a pilot demonstration of a Smart Charging System.

Stage 3 technology goals, targeted for 2018-2020, increase performance to a range of 150 miles and reduce cost for the battery pack to $350/kW-hr. Technical characteristics for Stage 3 include larger rapid charging energy storage systems capable of storing greater than 20kW, and electric driveline cost reduction, which is expected to allow an option for cost-effective use of smaller batteries. Another technical objective is development of a secondary market for batteries.

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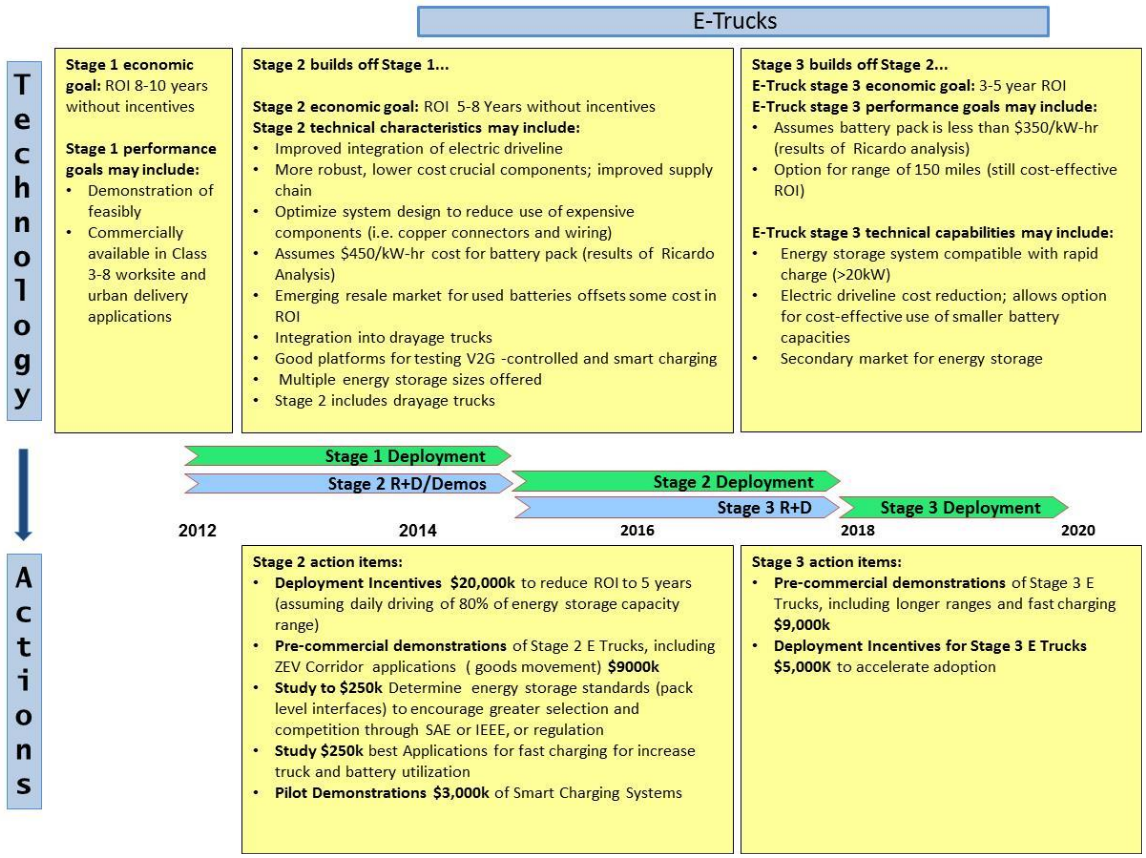
[23] California Energy Commission, ***2009 Integrated Energy Policy Report***, December 2009, http://www.energy.ca.gov/2009_energypolicy/index.html

Related Stage 3 actions include pre-commercial demonstrations of Stage 3 E-Trucks, with longer ranges and fast charging, and deployment incentives for Stage 3 E-Trucks.

Figure 21: E-Truck Technology and Action Roadmap



Three stages of development have been defined for E-Trucks. Stage 1 defines technology available in 2012. Stage 2, with development from 2013 to 2015 and deployment continuing through 2017, targets improved ROI through cost reduction and greater integration, along with standardization of energy storage, and smart charging systems. Stage 3 developments begin in 2015, working toward greater energy storage capacity, longer ranges, and fast charging for E-Trucks late in the decade.

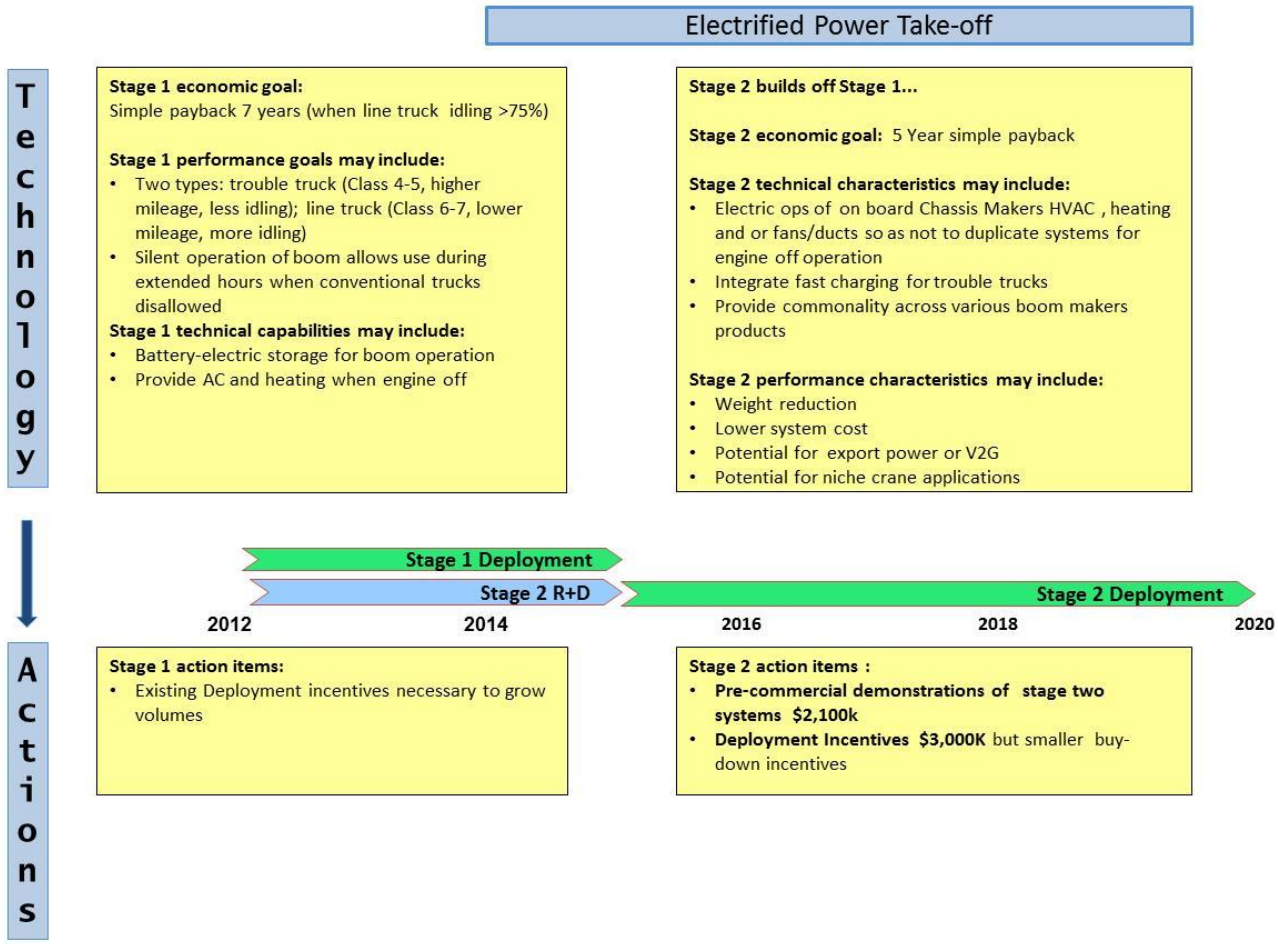
Electrified Power Take-off

A portion of work truck emissions come from the engine powering worksite equipment, such as a boom, tools, or other accessories not linked to the truck's propulsion system. Use of power take-off systems to power these tools with electricity instead of liquid fuel when the engine is not running can significantly reduce emissions and fuel consumption.

The Roadmap defines two stages of development for Electrified Power Take-off, shown in Figure 22, page 40. Stage 1 defines existing technology, which include Class 4-5 trouble trucks and Class 6-7 line trucks with battery-electric storage for boom operation and the ability to provide AC and heating when the engine is off. The Roadmap action for Stage 1 is continuation of deployment incentives currently in place.

Stage 2 calls for weight reduction and lower system cost to support a 5-year ROI, integration of fast charging for trouble trucks, commonality across boom manufacturers' products, and electric operation of on-board AC and heating systems, including fans and ducts, to eliminate the need for duplicate systems for engine-off operation. Additional performance improvements may include potential for export power and niche crane applications. Stage 2 actions include pre-commercial demonstrations and deployment incentives.

Figure 22: Electrified Power Take-off Technology and Action Roadmap



Electrified Power Take-off provides a battery system to power trouble trucks, and the booms of line trucks when the engine is off, to reduce the need for the engine to run only to power worksite activities. Stage 1 covers existing technology, for which deployment incentives are already in place. Stage 2 will work toward a faster ROI, integration of fast charging in trouble trucks, operation of the chassis maker's HVAC to eliminate duplicate systems, the potential for export power, and additional niche crane applications.

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Plug-in Hybrids

Plug-in hybrids are similar to regular hybrid electric trucks, but have the ability to recharge using external electric power, and typically feature a larger battery pack and powertrain system that potentially allow some amount of operation in electric-only mode. This can vary from the ability to “creep” while waiting in a line, to driving considerable distances in electric mode. Outside of these situations, the larger battery pack can allow the hybrid powertrain to maximize driving efficiency through capture of more braking energy and greater use of electricity to offset combustion fuels.

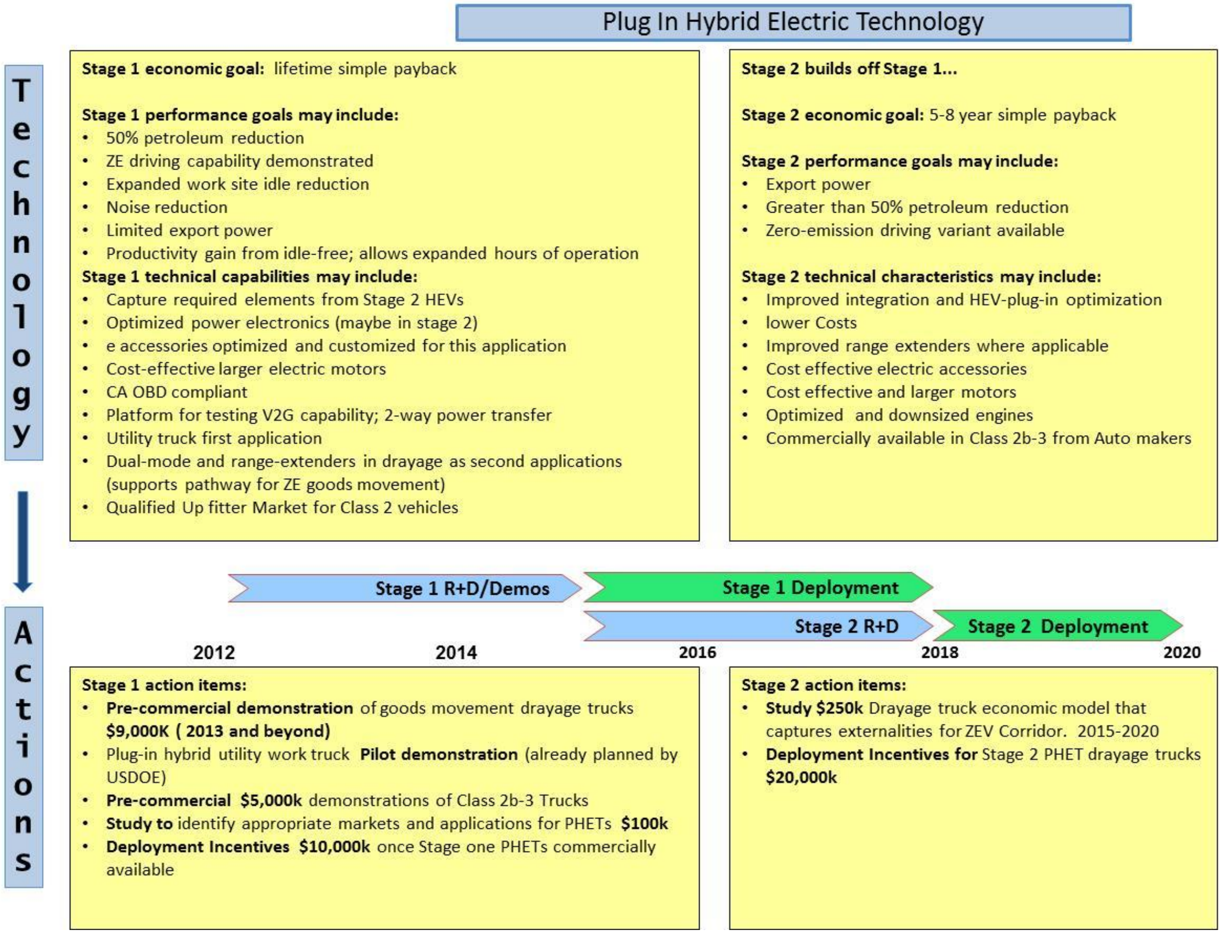
The CalHEAT Roadmap identifies two stages for Plug-in Hybrid Electric Technology, as shown in Figure 23, page 42. The economic goal for Stage 1, from 2010 through 2015, is lifetime payback of the incremental cost of the vehicle, compared to a conventional truck, through reduced fuel costs. Stage 1 performance goals include a 50% decrease in petroleum consumption, demonstration of zero-emission driving capability, noise reduction, and reduced use of conventional powertrain idle at work sites, increasing productivity, reducing emissions and fuel consumption, and allowing expanded hours of operation.

Stage 1 technical characteristics include incorporation of the required elements from Stage 2 HEVs, with features such as engine off at idle, electric accessories, improved integration, and lighter weight, as shown in Figure 19: Hybrid Electric Technology and Action Roadmap, page 33. Additionally, larger, cost-effective motors, and CA-compliant on-board diagnostics are specified. The first targeted application is utility trucks; a second application in drayage has been identified for dual-mode use with range-extenders, which may also support a pathway for zero-emissions goods movement. Stage 1 actions include pre-commercial demonstration of goods movement drayage trucks, a plug-in hybrid utility work truck (already planned by the U.S. DOE), pre-commercial demonstrations of Class 2B and 3 trucks, a study to identify appropriate markets and applications for PHETs, and deployment incentives for the first 500 trucks when Stage 1 PHETs are commercially available.

Stage 2 PHET, 2016 to 2020, has an economic goal of a five-to-eight-year ROI, with performance goals including the ability to export power, greater than 50% petroleum reduction compared to conventional combustion engine vehicles, and a zero-emission driving variant available. Technical characteristics may include improved integration and HEV plug-in optimization, lower costs, improved range, cost-effective electric accessories, and larger, more cost-effective electric motors. Stage 2 PHETs are expected to be commercially available in Class 2B and 3 from auto makers during the last half of the decade.

Stage 2 actions include a study to develop an economic model that captures externalities for a ZEV Corridor and deployment incentives for Stage 2 PHET drayage trucks.

Figure 23: Plug-in Hybrid Technology and Action Roadmap



Plug-in electric hybrids have the potential to reduce petroleum use by 50% or more, and have application in short-range utility trucks and in drayage. Two stages of development have been defined for PHET, with Stage 1, 2010 through 2015, including pre-commercial and pilot demonstrations of goods movement drayage trucks, utility work trucks and Class 2b-3 trucks. A study is recommended to identify appropriate markets and applications for PHETs, with cumulative deployment incentives of $3,000,000 for the first 500 Stage 1 PHETs when they become commercially available. Stage 2, 2015 to 2020, targets improved ROI through cost reduction and greater integration, and improved performance with longer ranges.

Electrified Corridor

Various strategies have been investigated to reduce traffic congestion and related fuel consumption[24]. Intelligent vehicle technologies can take a vehicle's position into account, along with data about the roads, traffic, and more, to alter routes, speeds, and in the case of hybrids, adjust the amount of battery power being used versus the engine. Among the more advanced and complicated strategies to implement are dedicated truck corridors or lanes, where trucks can save fuel and reduce emissions by being kept separate from passenger car traffic. These corridors have the potential to provide power for electrification, further increasing their benefits. Bus lanes have demonstrated higher average travel speeds which, particularly in urban areas, have the potential to significantly increase fuel efficiency for trucks.

The Roadmap for Electrified Corridors, shown in Figure 24, below, identifies areas of development related to external electric power for power pickup devices in on-road yard hostlers and electrified corridors in Stage 1, and integration of a power pickup device into dual-mode hybrids and range-extended drayage trucks in Stage 2.

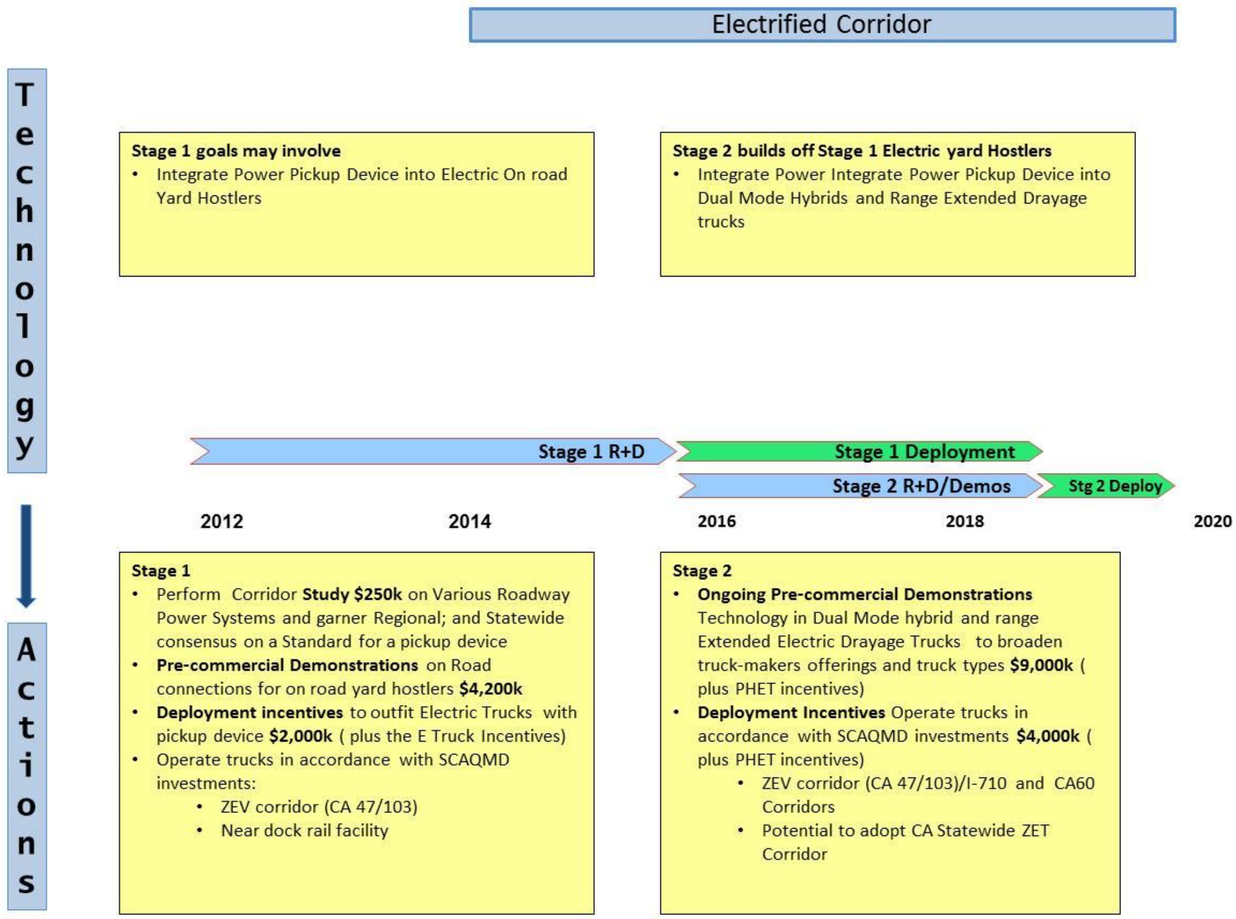
In Stage 1, the technology goal is to integrate a power pickup device into electric on-road yard hostlers. The addition of the electric power pickup device on an electric truck is intended to allow the truck to operate using electricity with zero emissions along the corridor.

Related Stage 1 actions involve a corridor study on various roadway power systems and efforts to garner regional and statewide consensus on a standard for a power pickup device. Additionally, a pre-commercial demonstration of road connections for on-road yard hostlers is identified in the Roadmap, along with deployment incentives to outfit electric trucks with the pickup device. The trucks will be required to operate in accordance with guidelines established under SCAQMD investments for ZEV Corridors near dock rail facilities.

In Stage 2, efforts to integrate power pickup devices into electric vehicles will expand into dual-mode hybrids and range-extended drayage trucks. Actions identified include pre-commercial demonstrations and deployment incentives to operate trucks in accordance with SCAQMD in ZEV Corridors on the CA47/103/I-710 and CA 60.

[24] National Academy of Sciences report, ***Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles***, August 2010, Figure 4-1

Figure 24: Electrified Corridor Technology and Action Roadmap



The Roadmap for Electrified Corridors involves technology developments and related actions to support integration of electric power pickup devices into on-road electric yard hostlers, and a research study on roadway power systems to support development of a standard power system for a power pickup device.

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Alternative Fuel Hybrids

Low-carbon alternative fuels including biodiesel and natural gas (NG) can offer significant carbon savings, even when used in an otherwise fairly conventional vehicle. There is further potential for carbon reduction through use of renewable natural gas generated from agricultural feedstocks, wastewater treatment plants, and biowaste.

The combination of a hybrid powertrain that reduces fuel consumption with an alternative fuel that cuts carbon per unit of fuel creates a multiplier effect and generates much less carbon overall.

Hybrid drive trains in certain applications are estimated to have as much as a 50% improvement compared to a standard diesel unit. Currently, there are hybrid-alternative fuel vehicles available for demonstration and commercial operation (primarily bio-diesel hybrids and NG hybrid buses and refuse vehicles), but the weight, cost, and complexity of these systems has prevented their greater adoption. Further information will be available in a companion CalHEAT report, *Barriers and Opportunities in Alternatively Fueled Hybrids*[25].

Three stages in the Roadmap have been defined for Alternative Fuel Hybrids, as shown in Figure 25, page 46. Stage 1, 2012-2013, focuses on advances in B5 to B20 biodiesel hybrid trucks and buses (which use fuel containing 5% and 20% biodiesel, respectively) to achieve 22 -38% CO_2e reduction, along with a significant petroleum reduction. The Stage 1 action is to encourage a broader selection of B20-certified engines through an outreach effort to the industry.

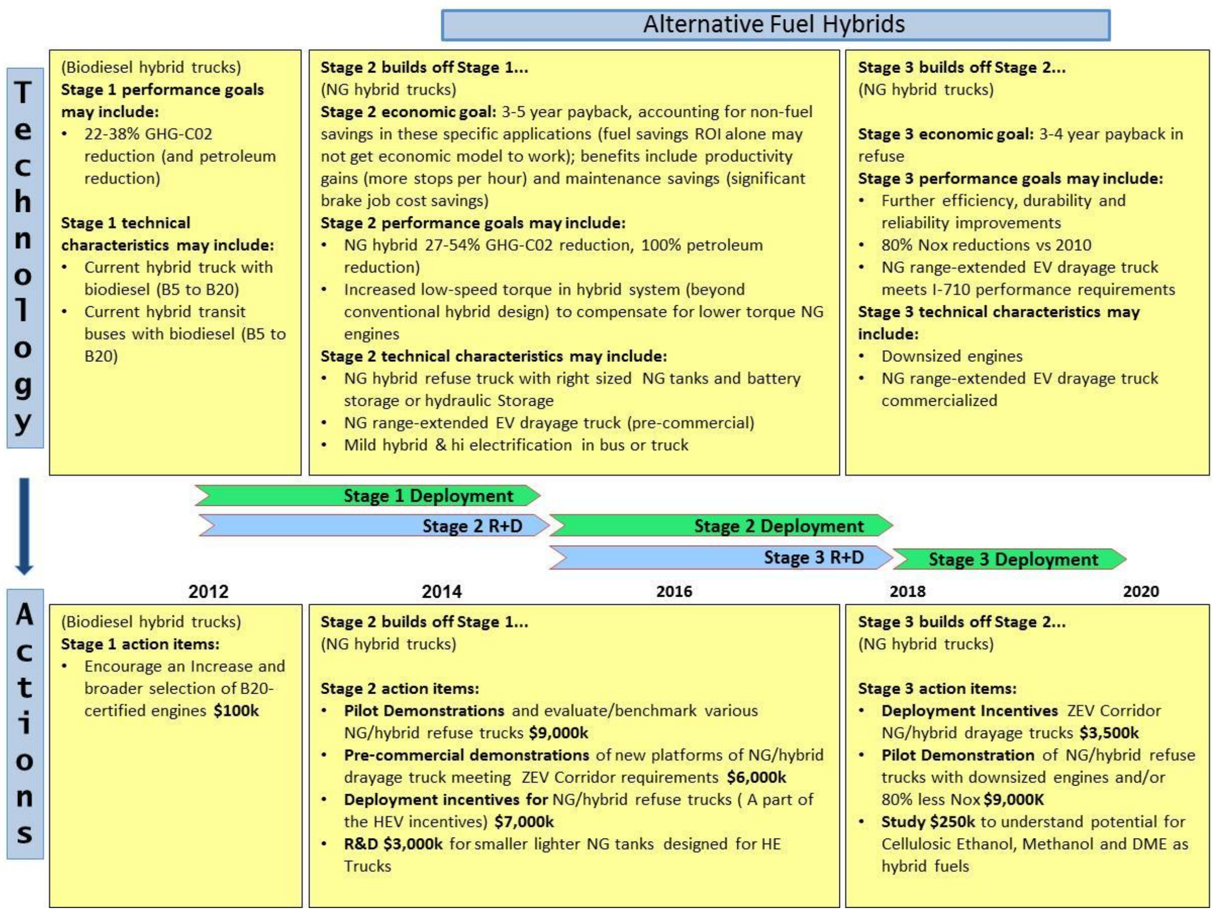
In Stage 2, the focus is on NG hybrid trucks from 2013 through 2017, with an economic goal of a three-to-five-year payback. This ROI is based on a combination of fuel savings and productivity gains of more stops per hour for refuse trucks enabled by hybrid technology with faster acceleration. These trucks also realize maintenance savings from a reduction in brake replacement. Performance goals include a 27-54% reduction in CO_2, 100% petroleum reduction, and increased low-speed torque in hybrid systems to compensate for lower-torque NG engines. Technical characteristics may include right-sized NG tanks and battery or hydraulic storage for a NG hybrid refuse truck, and achieving a pre-commercial range-extended HEV drayage truck with high electrification of accessories. Actions specified in conjunction with these technology goals include pilot demonstration and evaluation of NG hybrid refuse trucks, a pre-commercial demonstration of new platforms for NG hybrid drayage trucks meeting ZEV Corridor requirements, deployment incentives for 200 NG hybrid refuse trucks, and R&D for smaller, lighter NG tanks designed for hybrid electric trucks.

In Stage 3, the focus remains on NG hybrid trucks from 2017 to 2020. An economic goal of a three-to-four-year payback for a refuse truck has been defined, combined with performance

[25] Dr. Lawrence Wnuk, CalHEAT, ***Barriers and Opportunities in Alternatively Fueled Hybrids***, Publication number: CEC-XXX-2013-XXX.

goals of further efficiency, durability and reliability improvements, an 80% reduction in NOx compared to 2010, and development of an NG range-extended drayage truck capable of meeting zero-emission operations for ZEV corridors. Actions corresponding to these technology goals include deployment incentives for 100 ZEV Corridor NG hybrid trucks, and a pilot demonstration of NG hybrid refuse trucks with reduced NOx emission. In addition, the Roadmap calls for a study to identify the potential of other alternative fuels in hybrids including cellulosic ethanol, methanol and dimethyl ether (DME).

Figure 25: Alternative Fuel Hybrid Technology and Action Roadmap



The Roadmap for Alternative Fuel Hybrids, which combines the advantages of electric hybrid capability with low carbon fuels, focuses on biodiesel hybrids in Stage 1, 2012 to 2013. In Stages 2 and 3, emphasis is on natural gas hybrids with improved performance and extended range during the remainder of the period to 2020. A study of other alternative fuels in Stage 3 is included in the Roadmap to increase understanding of the potential for cellulosic ethanol, methanol and dimethyl ether as hybrid fuels.

Hydraulic Hybrids

Hybrids come in many forms, and have already made inroads in certain segments of the truck industry. The fundamental theory behind hybridization, regardless of type, is that the storage of energy reduces fuel consumption. Hybrids typically combine some form of internal combustion engine with an energy storage device and are able to recapture energy and power the vehicle or some of its systems with it. The energy storage system in an electric hybrid involves a battery pack and electric motors, while, in the case of hydraulic hybrids, it uses a hydraulic tank (accumulator) and hydraulic motors. The accumulator stores hydraulic pressure, typically by using fluids to compress a gas-filled balloon inside a pressure tank. When hydraulic power is needed, the pressure is released, driving a hydraulic motor.

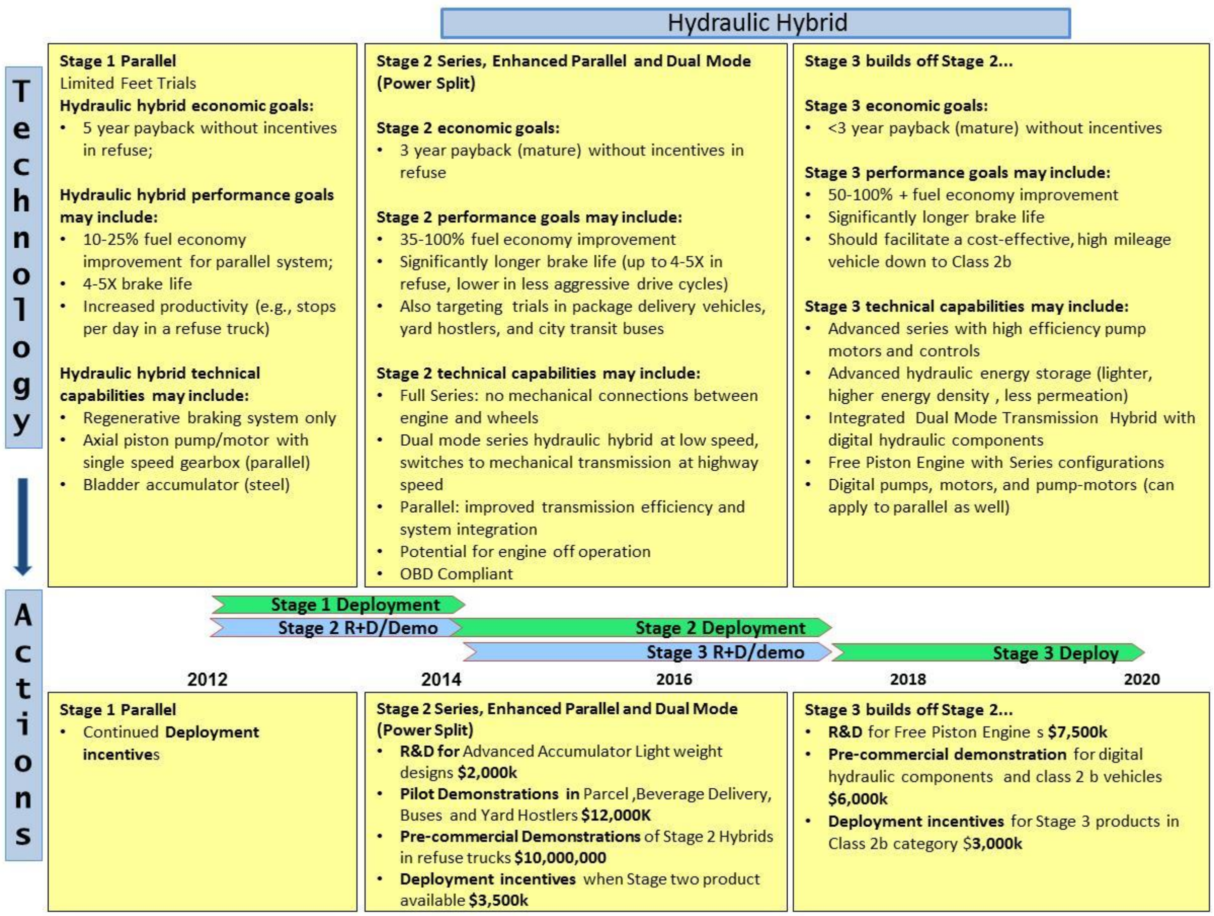
The second primary distinction among hybrids is the architecture. Series hybrids have drive wheels that are driven exclusively by the electric or hydraulic motor, and the internal combustion engine serves to keep the system charged, but has no direct mechanical link to the drive wheels. In a parallel hybrid, both the electric (hydraulic) motor and the internal combustion engine are linked mechanically to the drive wheel, typically through a shared transmission. Power split, or series-parallel hybrids use a system, like a planetary gear, to allow the system to adjust the power ratio coming from the ICE or the electric/hydraulic power source. This gives the vehicle the ability to operate from 100% electric/hydraulic power to 100% ICE, depending on the power needs of the vehicle.

Parallel or dual-mode hybrid architectures are used in the three stages defined in this Roadmap for Hydraulic Hybrids, shown in Figure 26, page 48. Stage 1 covers hydraulic hybrid refuse trucks with parallel hybrid architectures, commercially available in 2012. They feature an economic payback of five years without incentives in refuse applications. Performance improvements of 10-25% fuel reduction from parallel hybrid architectures have been demonstrated, along with a 4x to 5x improvement in brake life resulting from use of a regenerative brake system. The hydraulic accumulator also captures kinetic energy to increase torque and enable the vehicle to accelerate much faster, leading to improved productivity in terms of number of stops possible per day.

Stage 2 development, which begins in 2014, includes additional technological development of series, enhanced parallel and dual-mode, or power-split, hybrid architectures and increased fuel economy improvement in the 35% to 100% range, compared to conventional trucks. Performance characteristics in the full series architecture include no mechanical connection between the engine and wheels. The dual-mode series hydraulic hybrid will operate in dual-mode powered by both the hydraulic system and the ICE at low speeds and switch to mechanical transmission at highway speeds, powered by the ICE. The parallel architecture is expected to improve transmission efficiency and system integration. Related actions in Stage 2 include R&D for advanced, lightweight accumulator designs; pilot demonstrations in parcel, beverage delivery, buses and yard hostlers; pre-commercial demonstrations of Stage 2 hydraulic hybrids in refuse trucks; and deployment incentives when Stage 2 trucks are commercially available.

Stage 3 technology developments call for a three-year payback without incentives, performance goals of 50-100% fuel economy improvement compared to conventional vehicles, significantly longer brake life, and the potential to build a cost-effective, high-mileage vehicle in smaller sizes down to Class 2b. Technical capabilities include advanced series architecture with high-efficiency pump, motors and controls; advanced higher density energy storage; an integrated dual-mode transmission hybrid with digital hydraulic components; a free piston engine with series configurations; and digital pumps, motors and pump-motors that can be used for parallel or series architectures. Actions for Stage 3 include R&D for the free piston engine, pre-commercial demonstrations of digital hydraulic components and Class 2b vehicles, and deployment incentives for Stage 3 products in Class 2b vehicles.

Figure 26: Hydraulic Hybrid Technology and Action Roadmap



The Hydraulic Hybrid Technology and Action Roadmap defines a series of achievable stepping stones to improve efficiency. Improvements in hybrid architectures are expected to increase fuel economy improvements from 10-25% in Stage 1 to 50-100% in Stage 3, and expand applications from primarily refuse trucks to multiple truck categories down to Class 2b by the end of the decade.

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Optimized Alternative Fuel Engines

To improve performance, reduce emissions, and optimize the efficiency of engines using alternative fuels, various technologies have been investigated. While engines that burn natural gas and other alternative fuels can be cleaner than conventional diesel engines, reduce emissions of GHGs, and contribute to mandated goals to reduce petroleum use, the initial spark-ignited engines developed to burn NG have been less efficient and provide lower torque than diesel engines. To offset this deficiency, high pressure direct injection (HPDI) is one approach that has been developed to enable NG-burning engines to approach diesel efficiency and torque.

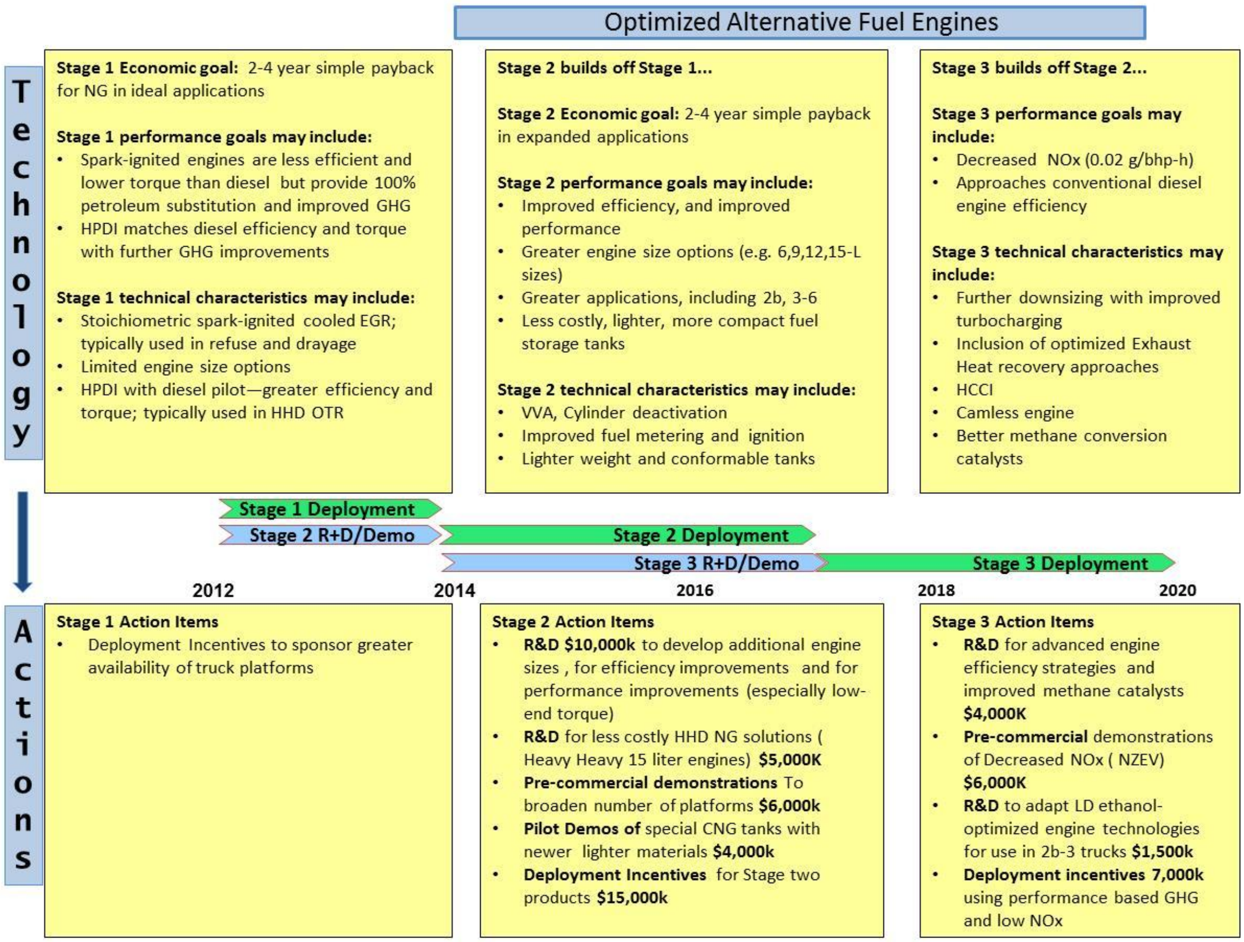
Other beneficial technologies to achieve significantly lower emissions and greater power using natural gas include alternative combustion modes such as homogenous charge compression ignition (HCCI). HCCI has desirable characteristics, such as low engine-out emissions combined with good fuel consumption, but can be difficult to control across all engine loads and in transient operation. HCCI helps reduce both NOx and particulate matter (PM) emissions, although like other alternative combustion modes, it typically achieves lower thermal efficiency than conventional diesel combustion. However, conventional diesel combustion suffers thermal efficiency degradation at low engine-out NOx levels, so the alternative combustion modes become more attractive as allowable NOx levels decrease during the forecast period.

To help achieve the mandated reductions in NOx, PM and petroleum use, the CalHEAT Roadmap for Optimized Alternative Fuel Engines, shown in Figure 27, page 50, focuses on both performance improvements to approach conventional diesel engine efficiency and techniques to reduce emissions. Three Stages have been defined for NG engine optimization in the Roadmap. Research to adapt ethanol-optimized engine technologies for use in Class 2b-3 trucks, to enable them to burn fuel with a higher percentage of biofuel, is also included as one of the Roadmap actions.

Stage 1 involves deployment support for recently developed NG-burning engines featuring HPDI with a diesel pilot for greater efficiency and improved torque, and stoichiometric spark-ignited cooled Exhaust Gas Recirculation (EGR). Stage 2 involves performance and efficiency improvements; less costly, lighter, and more compact storage tanks; and use of variable valve actuation with cylinder deactivation. Targeted for development in 2012-2014, with deployment following from 2014-2017, Stage 2 will also involve expansion of optimized NG engines into a wider range of applications, including Classes 2b and 3-8, with a greater range of engine size options. Actions in the Roadmap to support these advances include R&D projects to develop additional engine sizes and less costly heavy-heavy duty 1.5 liter engines, plus pre-commercial and pilot demos.

Stage 3 performance goals call for decreased NOx emissions to 0.02g/bhp-h, a reduction of 90% from 2008 levels, with efficiency approaching that of conventional diesel engines. Technological improvements may include further downsizing with improved turbocharging, optimized exhaust heat recovery, homogenous charge compression ignition, a camless engine and better methane catalysts. Related actions include R&D for advanced engine efficiencies and improved methane catalysts, and pre-commercial demonstration of decreased NOx emissions.

Figure 27: Optimized Alternative Fuel Engine Technology and Action Roadmap



The three stages defined in the CalHEAT Roadmap for Alternative Fuel Engine Optimization focus primarily on natural gas-burning engines to achieve performance improvements that increase torque and engine efficiency to levels approaching that of conventional diesel engines, while incorporating advanced emission reduction techniques such as HCCI, improved methane catalysts and optimized exhaust heat recovery to achieve very low NOx emissions. Stage 3 also calls for R&D into ethanol-optimized engines for use in Class 2b-3 trucks.

Waste Heat Recovery

Recovering waste heat, through the use of thermoelectric devices, low-grade energy recovery devices such as those using the Rankine cycle, small turbines or other techniques, allows a portion of the energy normally wasted by the engine to be converted back into useful energy. If the thermal energy is recaptured and used to charge batteries, run accessories, or perform similar tasks, overall vehicle efficiency can be dramatically improved. Captured and stored heat can also be used in conjunction with catalytic converters to ensure complete combustion and fewer emissions, and possibly reduce the size and cost of after-treatment systems.

An energy audit of a typical diesel engine in a Class 8 line haul truck[26] revealed that just 42% of the fuel energy consumed actually goes to perform useful work such as vehicle propulsion. This 42% is consumed by drivetrain losses, rolling resistance, aerodynamic drag, and auxiliary loads such as the alternator, air compressor, and power steering pump. Energy lost as engine heat accounts for 26% of the fuel consumed and exhaust heat accounts for another 24%. Finding ways to recapture the waste heat is an important part of reducing vehicle fuel consumption.

Turbocompound systems add a second exhaust turbine downstream of the engine's primary turbocharger to extract additional energy from the exhaust flow. Rather than compressing the intake air like the primary turbo, the turbocompound exhaust turbine converts a portion of the energy in the exhaust flow to useful energy. This conversion can provide either mechanical (rotational) or electrical energy back to the vehicle's powertrain. This regenerated energy lowers the fuel-derived energy demand on the engine, thus reducing the fuel consumption. In a mechanical turbocompound system, the exhaust turbine is connected to the engine's crankshaft through gearing and a fluid coupling to regenerate a portion of the exhaust flow energy back into the powertrain. In addition, the brake power output of the engine is also increased with mechanical turbocompounding, thus creating the potential for engine downsizing that can further reduce fuel consumption in the vehicle. An increase in power output of roughly 10% is not unusual. This would correspond to a roughly 5% decrease in fuel consumption. The fuel consumption is smaller than the power increase due to higher pumping losses from the higher exhaust backpressure[27].

A turbocompound system provides the greatest benefit at full load. The improvement is much less – or even zero – at light loads. Thus, these systems are best suited for vehicles that consume most of their fuel at fairly high loads. Examples include line-haul trucks and vocation vehicles such as refuse trucks.

Some of the advantages of mechanical turbocompound systems include high power density (more power for a given displacement) and reduced fuel consumption in highly-loaded vehicle applications. A potential reduction in fuel consumption of 3% can be achieved in long-haul

[26] National Academy of Sciences, p. 5-60.

[27] Anthony Grezler, Volvo Powertrain Corporation, ***Diesel Turbo-compound Technology,*** ICCT/NESCCAF Workshop presentation, February 20, 2008, slide 5.

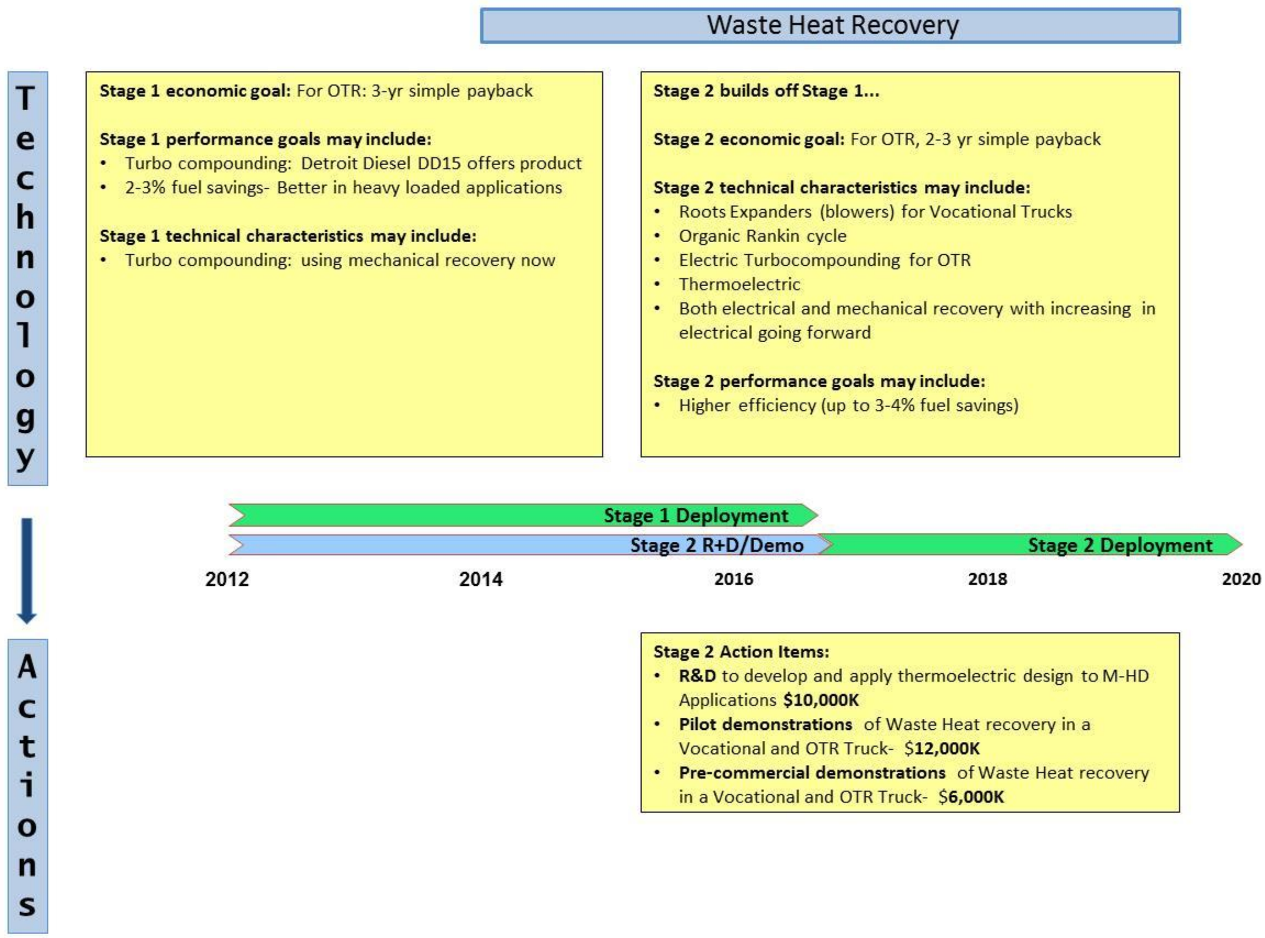
applications, although there can be a minimal or negative impact with light loads. Since exhaust manifold pressure is increased above intake manifold pressure, higher EGR flow can be achieved more easily to facilitate low NOx emissions.

Some of the challenges facing broad acceptance of turbocompounding are that the gear train, fluid coupling, and power turbine add weight, complexity (reliability concern), and cost.[28] Exhaust energy decreases with cooled EGR due to energy extracted into the cooling system, resulting in less energy available to the power turbine. Space requirements further constrain packaging of EGR and turbochargers and add complexity in design, control, and service. Additional cooling of exhaust reduces the effectiveness of exhaust after treatment systems. These systems may require more active regeneration for the particulate filter, and may reduce the time when NOx systems are effective, including those based on Low NOx Ammonia (LNA) applications, selective catalytic reduction (SCR), or Lean NOx Catalysts (LNC).

In the CalHEAT Roadmap for Waste Heat Recovery, shown in Figure 28, page 53, Stage 1 performance goals were identified for turbocompounding using mechanical recovery systems. At least two engine manufacturers have mechanical turbocompound systems in production today, so no actions were included for Stage 1. Stage 2 identifies technology improvements projected for 2015-2019, which will include blowers for vocational trucks, organic Rankine cycles, electric turbocompounding for OTR trucks, thermoelectric systems, and both electrical and mechanical recovery. An increase in electrical waste heat recovery is projected going forward. Two accompanying actions for Stage 2 include R&D to apply thermoelectric designs in medium- and heavy-duty trucks, and pilot and pre-commercial demonstrations of waste heat recovery in vocational and OTR trucks.

[28] Anthony Grezler, Volvo Powertrain Corporation, ***Diesel Turbo-compound Technology***, ICCT/NESCCAF Workshop presentation, February 20, 2008, slide 6.

Figure 28: Waste Heat Recovery Technology and Action Roadmap



Waste Heat Recovery offers the potential to recapture engine and exhaust heat to help power the vehicle. Mechanical turbocompounding systems are currently in production. CalHEAT Roadmap actions for this technology strategy begin in Stage 2, projected for 2015-2019, and are related to R&D and pilot and pre-commercial demonstrations of thermoelectric waste heat recovery.

Engine Optimization

Increasing efficiency and decreasing energy losses in truck engines are critical elements in the effort to reduce truck fleet fuel consumption. Optimized engines are one of the technology strategies to achieve this. Roughly 60% of the chemical energy of the fuel used in a truck diesel engine is lost in the engine, through heat losses or low combustion efficiency[29]. Gasoline engines are even less efficient at converting the fuel they consume into usable power to operate the vehicle.

In 2006, the 21st Century Truck Partnership[30] (21CTP) outlined goals to increase the energy efficiency of the engine system for class 7-8 trucks from 42% to 50% by 2010 and 55% by 2013. To build upon the energy efficiency improvements from the 21CTP, in January 2010, the DOE awarded $115 million for three projects under the Supertruck program. The Supertruck projects are intended to improve fuel efficiency of heavy-duty Class 8 long-haul trucks and will incorporate a wide range of technologies resulting from the 21CTP program over the past decade[31].

The CalHEAT Roadmap defines three technology stages for Engine Optimization, as shown in Figure 29, page 53. In Stage 1, 2012 to 2013, the technology-related goals from existing industry projects have been incorporated into the Roadmap, without accompanying actions. Performance goals, driven by National Highway Traffic Safety Administration (NHTSA) legislation, are to achieve a 47% brake thermal efficiency (BTE) improvement, on a level road at 65 miles per hour, compared to the baseline conventional diesel vehicles and engines. Technologies used to achieve this include engine boosting, downspeeding to 1000-1200 RPM (which requires faster transmission gear shifting), and other technologies required to meet Federal EPA/NHTSA Phase 1 rules for commercial vehicles.

The Stage 2 Engine Optimization Roadmap, 2014 to 2017, identifies a performance goal of 50% BTE corresponding to the DOE Supertruck project developments. Actions for Stage 2 include a pilot demonstration of a 50% BTE Class 8 truck, incorporating all needed technologies to achieve up to a 1.5 truck efficiency improvement over the baseline vehicle and engine performance.

Stage 3 builds upon Stage 2, and targets a 55% BTE DOE Supertruck, incorporating advanced technologies that may lead to a 200% more fuel efficient Class 8 OTR truck, with significant NOx reduction and advanced exhaust heat recovery advances described in the Waste Heat Recovery section, above. Actions for Stage 3 include R&D to promote NOx reduction technologies, pilot demonstration of a 55% BTE Class 8 truck with 200% fuel efficiency improvement, and pilot demonstration of an OTR truck with three to ten times lower NOx.

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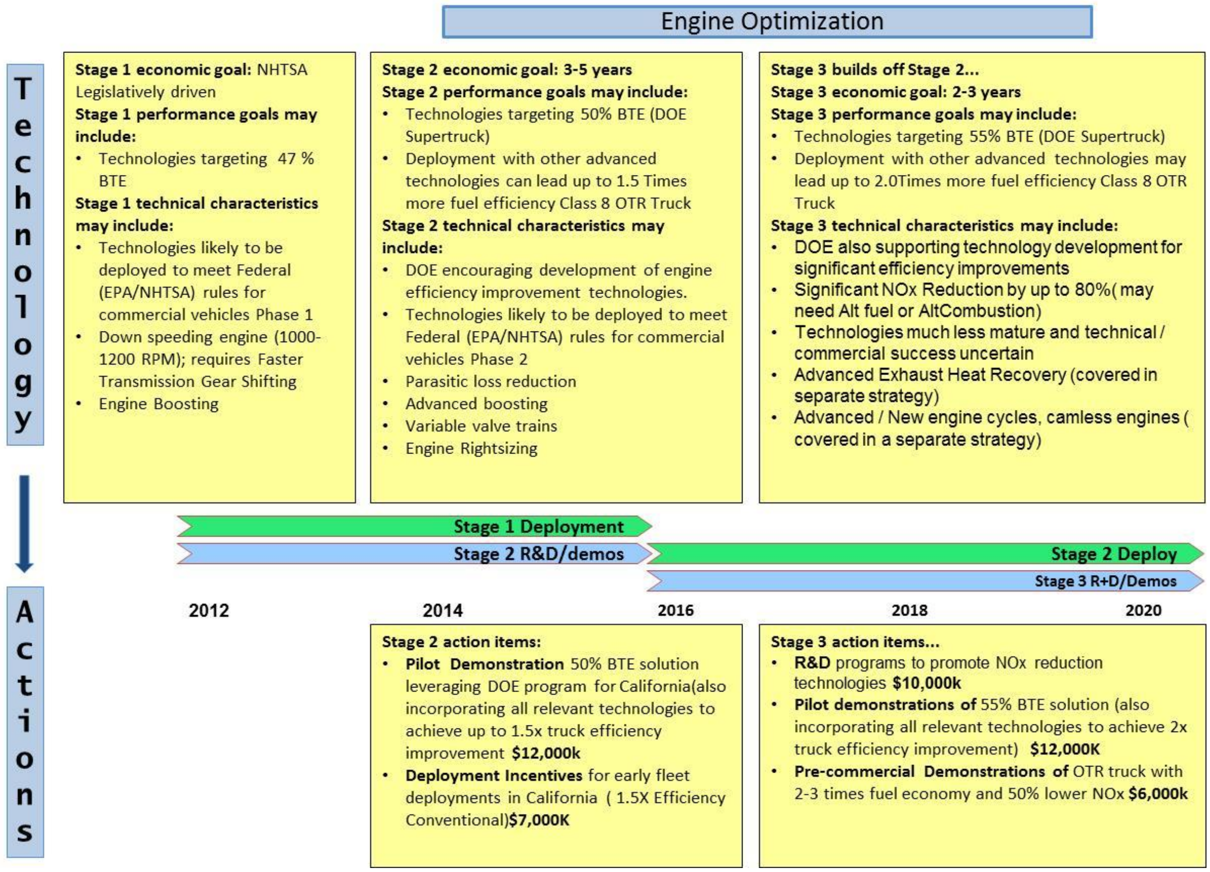
[29] National Academy of Sciences, Figure 4-1.

[30] National Academy of Sciences, p. 55-56.

[31] Committee to Review the 21st Century Truck Partnership, Phase 2, National Research Council. ***SuperTruck Program. Review of the 21st Century Truck Partnership, Second Report***. Washington, DC: The National Academies Press, 2012.

Figure 29: Engine Optimization Technology and Action Roadmap



The CalHEAT Roadmap defines three stages for Engine Optimization, starting with technologies already defined in the DOE Supertruck program to achieve 47% Baseline Efficiency in 2012 to 2013. Stages 2 and 3 leverage the Supertruck program for California, and include performance goals of 50% BTE in Stage 2 and 55% in Stage 3. Stage 2 actions in this Roadmap for California include a pilot demonstration of the 50% BTE Class 8 Truck and deployment incentives likely to begin in 2016 for early fleet deployments for the first 200 OTR trucks. Stage 3 actions include R&D programs for NOx reduction and pilot demonstrations of both a 55% BTE Class 8 OTR truck and an OTR truck with 3x to 10x lower NOx.

Alternative Power Plants and Combustion Cycles

Other CalHEAT research into opportunities to reduce petroleum consumption and GHG emission included fuel cells, alternative engine architectures and combustion technologies, along with turbines used as generators for electric drivelines. These technologies enable development of zero-emission and near-zero-emission vehicles. Near-zero-emission developments reduce NOx emissions approximately 90% from 2010 emissions for trucks.

The Alternative Power Plant and Combustion Cycle Technology and Action Roadmap, shown in Figure 30, below, covers technology developments in various areas including fuel cells in trucks, turbines, camless engines, opposed piston and free piston engines, and homogenous charge compression ignition (HCCI), which is an alternative combustion mode.

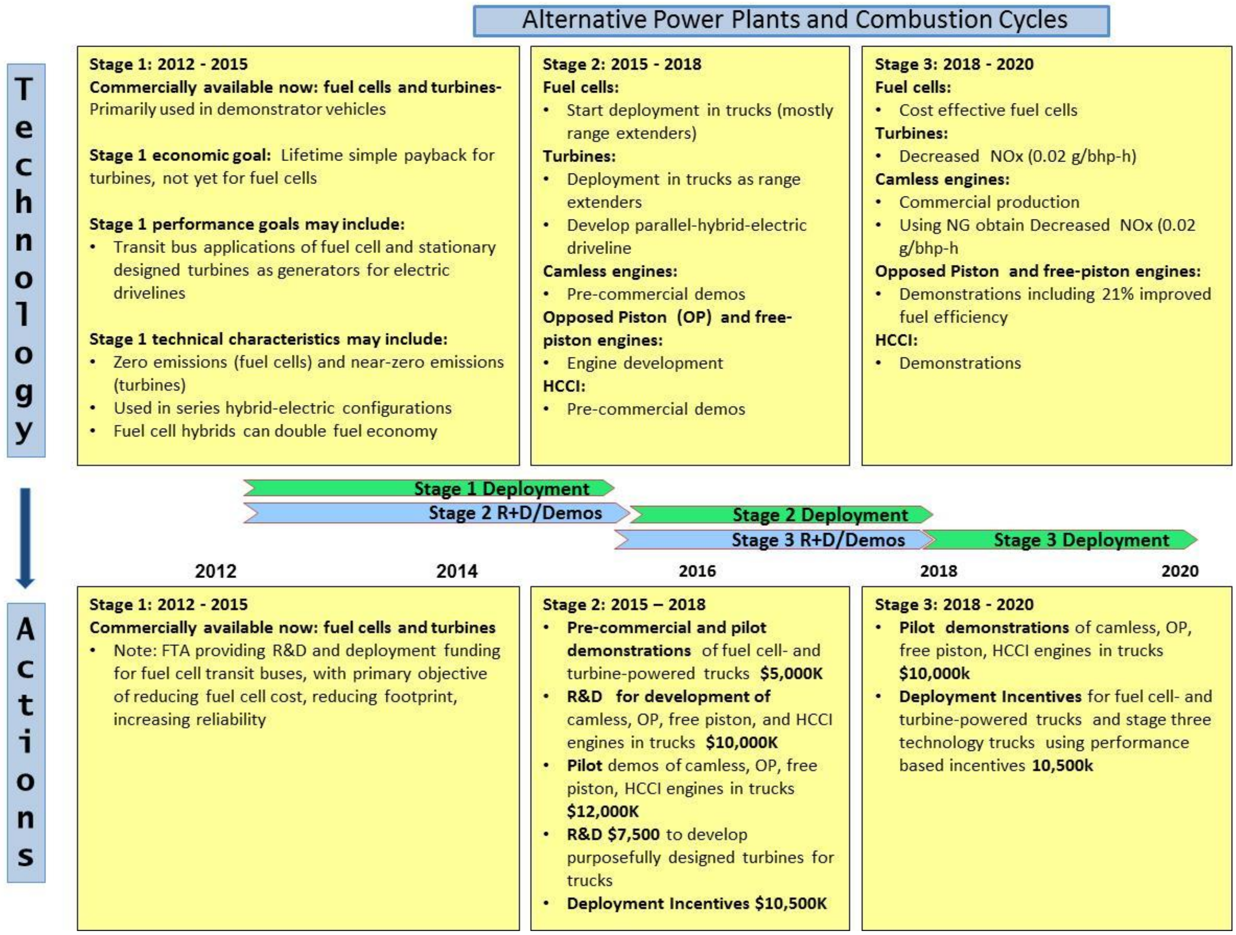
Fuel cells are a zero-emission power source that have shown promise as premium power generators in the 5-10 kW range but have not yet reached the packaging size, weight, and cost range needed for widespread acceptance for on-board power in trucks.

As the starting point for further development, Stage 1 describes fuel cell and stationary turbine technology available commercially in 2012 for use in transit buses. The Federal Transit Authority has been supporting R&D and deployment funding for fuel cell transit buses, with the primary objective of reducing fuel cell cost and footprint and increasing reliability.

Stage 2 developments, targeted for 2015-2018, show initial deployments of fuel cells and turbines in trucks as range extenders, with a parallel hybrid electric driveline used in conjunction with the turbine. These developments are supported by Roadmap actions for pre-commercial and pilot demonstrations. Alternative engine technology developments targeted for this stage include camless, opposed piston, free piston, and HCCI engines. Roadmap actions define R&D and pilot demonstrations, and deployment incentives for low NOx engines.

Stage 3 developments define further stepping stones for each of the Stage 2 technologies, with goals for 2018-2020 including cost-effective fuel cells, reduced NOx levels of 0.02g/bhp-h in turbines, commercial production of camless engines capable of burning NG to achieve NOx levels of 0.02g/bhp-h, and demonstrations of HCCI, opposed piston and free piston engines.

Figure 30: Alternative Power Plant and Combustion Cycle Technology and Action Roadmap



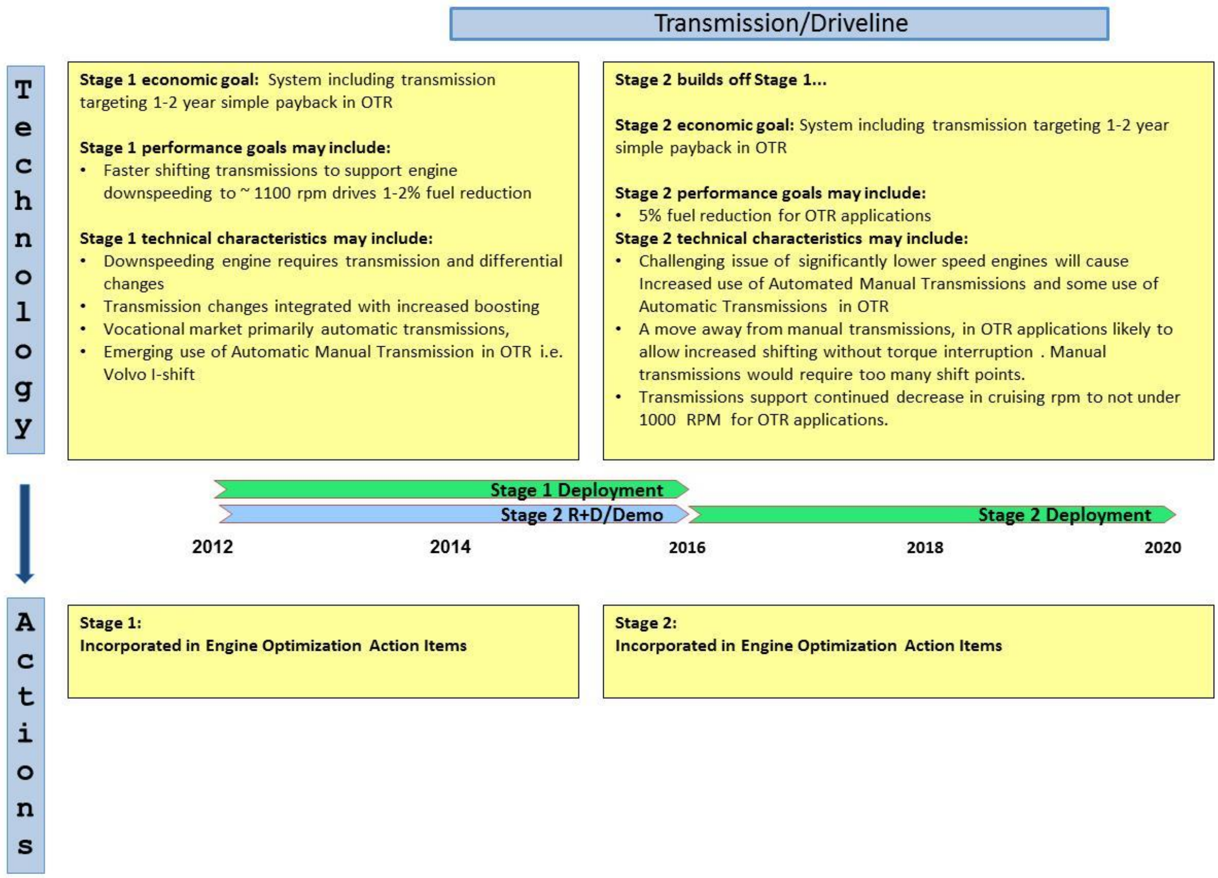
The CalHEAT Roadmap for Alternative Power Plants and Combustion Cycles defines existing fuel cell and stationary turbine technology for electric drivelines used in transit business in Stage 1, and defines a path for incorporating these technologies into trucks in Stage 2. Other technologies covered in this Roadmap include alternative engine architectures including camless, opposed piston, free piston and HCCI engines as avenues to achieve low NOx emissions before 2020.

Transmission/Driveline Improvements

The 21st Century Truck Partnership improvements in engine efficiency, discussed above in the Engine Optimization section, page 54, did not look at total powertrain system efficiency but instead focused on changes to the engine itself. A rich area identified in this Roadmap for additional improvement is fully-optimized powertrains, in which the entire powertrain is sized, calibrated and operated as a unit to achieve highest system efficiency. Potential improvements in powertrain system efficiency are likely to be achieved through advances in engine hardware and calibration, emissions control systems, accessories, and transmissions.

Two Stages have been defined for transmission and driveline improvement in this Roadmap as shown in Figure 31, page 59. Stage 1 covers deployment of improvements that are part of the DOE Supertruck program, 2012 through 2016, which have an economic goal of a one-to-two-year payback in OTR trucks. This will be achieved through performance improvements resulting in a 1-2% reduction in fuel use. The technology to do so uses faster shifting transmissions needed to support downspeeding to 1100 RPM, and may involve use of Automated Manual Transmissions. The related actions are included in the Engine Optimization Technology and Action Roadmap, Figure 29, page 55. Stage 2 calls for a 5% reduction in fuel for OTR trucks, and is likely to be achieved through further downspeeding to 1000 RPM and a shift to Automated Manual Transmissions. Research and demonstrations for Stage 2 are scheduled for 2012 to 2016, with deployment from 2016 through 2020.

Figure 31: Transmission/Driveline Technology and Action Roadmap



The Transmission/Driveline Roadmap focuses on improvements in powertrain system efficiency to be achieved through faster shifting transmissions needed to support lower RPM engines, greater powertrain integration and calibration, and shift to Automated Manual or Automatic Transmissions throughout the period to 2020.

CHAPTER 3: Conclusions

With the development of this *CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks*, CalHEAT has now nearly completed the goals established for its initial three years of operation. Analysis of the CalHEAT Action Plan shows that implementation of the 66 action items would result in a 73% reduction in CO_2e by 2050, and 75% reduction in petroleum use, compared to projected "Business as Usual" levels without these changes.

For CO_2e, the projected reduction would be 44MMT/year in 2050, from a BAU level of 60MMT to 16MMT with implementation of the Roadmap action items. For comparison, the 2012 level is 36MMT/year.

For petroleum, the projected reduction would be 4.5 billion gallons per year in 2050 compared to a projected BAU use of 5.9 billion gallons, to 1.5 gallons/year. For comparison, truck-related 2012 petroleum consumption is 3.6 billion gallons/year. These projections are based on the assumption of a moderate 25% adoption rate for biofuels. The "Business as Usual" projections used for comparison assume use of existing technology and practices, adjusted for anticipated growth in number of vehicles and vehicle miles travelled. There is potential for significantly greater reductions of CO_2e and petroleum with a higher adoption rate of biofuels.

Over the same period, NOx emissions are projected to decrease 73%, or 180 MT/year, from 249,000 MT/year in 2012 to 67,000MT/year in 2050.

This transformation Roadmap for California outlines specific actions to drive down climate and criteria emissions and fuel use in the medium- and heavy-duty truck and goods movement sectors. Nineteen strategies in three pathways, as shown in Figure 32 below, were identified as having the potential to achieve significant energy and environmental benefits to meet State policy goals.

Figure 32: Technology Pathways

Electrification
- **Hybrid Electric**
- **Electrified Auxiliaries**
- **E-Trucks**
- **Electrified Power Take-off (EPTO)**
- **Plug-in Hybrid Electric**
- **Electrified Corridors**
- **Alternative Fuel Hybrids**

Engine and Driveline Efficiency
- **Hydraulic Hybrid**
- **Optimized Engines for Alternative Fuel**
- **Waste Heat Recovery**
- **Engine Optimization**
- **Alternative Power Plants and Combustion Cycles**
- **Transmission and Driveline Improvements**

Chassis, Body, and Roadway Systems
- **Light-weighting**
- **Aerodynamics**
- **Lower Rolling Resistance**
- **Intelligent Vehicle Technologies, e.g. Forecasting, Adapting**
- **Corridors and Platooning**
- **Longer, heavier single trucks**

Nineteen technology strategies were identified by CalHEAT as pathways to enable reductions in carbon and criteria emissions and fuel use in trucks. The Electrification and Engine & Driveline Efficiency pathways are the focus of the 66 actions in the Roadmap. The technology strategies shown under Chassis, Body and Roadway Systems are already planned by manufacturers or transportation authorities.

California Hybrid, Efficient and Advanced Truck Research Center

The 13 technology strategies shown above, under Electrification and Engine & Driveline Efficiencies, were selected as the focus of the CalHEAT Roadmap. Those listed under Chassis, Body and Roadway Systems are receiving reasonable attention by the industry and industry stakeholders and as such are not a focus of the present CalHEAT Action plan. Within these 13 strategies, 66 actions have been identified, with target dates and milestones for the period from 2012 through 2020. Appendix B, page 65, includes a summary of the actions by technology strategy, followed by a numerical list with descriptions, and Appendix C, beginning on page 74, summarizes them by action category: Studies and Standards, Development, Pilot Demonstrations, Pre-Commercial Demonstrations and Deployment Support and Incentives.

As a first step toward developing the Roadmap during this three-year project, CalHEAT established the CalHEAT Truck Research Center in Pasadena and recruited its Advisory Council , Steering Committee , and Technical Advisory Group , which consist of qualified professionals from the truck and utility industries and a diverse range of regional, State, and Federal government agencies. CalHEAT also conducted Phase I research to characterize the California truck population by size, use, and emissions, and prepared a baseline report of available technology and pathways for improvement. Phase II research identified gaps along the pathways and barriers to progress, and developed a decision-making tool to identify the most efficient choices to meet the State’s goals. Phase III was the development of the Roadmap that comprises this report. Additional research and demonstration projects were also conducted for advanced Class 8 trucks, plug-in parcel delivery trucks and alternative fuel hybrid technologies.

As a result of this process, CalHEAT has also become a key consensus point for industry and the public sector to meet and reach agreement on the key action steps and investments needed to transform medium- and heavy-duty trucks in the state.

Priority Actions

Critical to the implementation of these sixty-six Roadmap actions is funding. Next steps would be to prioritize and act on the sixty-six step action plan, initiate critical action items that relate to more efficient drive lines in Class 8 Over-the-Road Tractors which represent a projected 40% of CO_2e emissions from trucks in 2050, and provide technical assistance to fleets and policy makers in order to accelerate the adoption of clean and efficient technologies.

The process would involve development of criteria for priority ratings, along with implementation of the action items by catalyzing, facilitating, or administering related projects.

Recommendations for Next Steps

The CalHEAT Advisory Council has recommended additional research to support implementation and update of the roadmap. This would include updating the Roadmap and related model with adoption rates and an improved inventory analysis on natural gas trucks. There is also an ongoing need to track and search for new breakthrough technologies and incorporate these breakthroughs into the Roadmap.

Further research on clean and efficient driveline technologies would include more focused investigation of the Class 8 Truck population in the state, and within regions of the state, on their points of origin as well as the corridors they use, both in and out of California. Development of a plan is recommended to leverage federal funding on advanced and clean-fuel buses in order to expedite the entry of these technologies in to California's truck market.

Additional recommendations include projects and partnerships to continue development of advanced and efficient Class 8 Over-the-Road Trucks, as Class 8 tractors are the largest contributor of CO_2e in the medium- and heavy-duty truck market. This activity could build off CALSTART's High-Efficiency Truck Users Forum's (HTUF) Class 8 Working Group findings to develop and demonstrate the following suggested projects or programs:

a. A more electrified Over-the-Road Truck
b. Advanced and highly-efficient combustion technologies and fuel cell solutions
c. Three hundred percent greater vehicle efficiencies leveraging driveline improvements, engine efficiencies, and improved vehicle aerodynamics and rolling resistance
d. Technical assistance to fleets, dealers, and maintenance shops to assure a better understanding of early market adoption issues and provide help understanding the business case. Technical assistance would also be provided to state and regional agencies to support development of future investments and policies, and to industry suppliers in order to help them prioritize and understand the technologies and need for development and innovation.

Strategies related to clean and efficient drivelines in Class 8 OTR trucks could address as much as 8 million annual metric tons of CO_2e by 2050. Recommendations include more specific research to identify the major state and regional corridors, the key destinations of the out-of-state registered vehicles, and the in-state registered usage of Class 8 OTR trucks. Additional research could focus on the market barriers and benefits from zero-emission truck corridors extending from the Ports of Los Angeles and Long Beach through the Central Valley to the Ports of Stockton and Oakland.

Additional work with industry stakeholders could identify ongoing near-zero-emissions technologies and help establish near-term voluntary standards. These standards are critical to achieving an 85% reduction of NOx in the South Coast region.

The Advisory Council also recommends formulation of a plan to leverage large investments by the Federal Transit Administration in clean and efficient bus technology and expeditiously transition these developments to ZEV and NZEV trucks. This plan could potentially accelerate the early adoption of Heavy Trucks that are ZEV and NZEV by 2 to 3 years, resulting in a more significant adoption rate by 2050.

Finally, next steps could also include additional research on new focus areas that could lead to significant reductions in carbon, criteria emissions, or fuel use that were not necessarily a focus of the initial CalHEAT work. These include biofuel availability and efforts to reduce the growth of vehicle miles travelled by California trucks.

Research and action recommendations to increase use of renewable diesel, bio-diesel, renewable natural gas, and/or ethanol in heavy long distance trucks is considered critical, as use of renewable fuels could have a significant impact on the CO_2e emissions projected by the roadmap for 2050, as shown in Figure 11: Biofuel Related Impact on CO2e Reduction, page 25. Finding additional ways to reduce the projected growth of VMT in California could also have a significant impact, as increases in VMT contribute to 40% growth in the business as usual projections for CO_2e. The objective related to VMT research is to identify roadway systems and policy approaches that could reduce VMT with little or no impact on commerce. Suggested research projects in these areas include:

a. Biofuel Availability and Projections for Medium- and Heavy-Duty Vehicles: Update forecasts for potential production of renewable natural gas, renewable diesel and bio-diesel. Increased availability of these biofuels could have an impact as great as 12MMTCO_2e reduction by 2050.

b. Best Policies, Technologies and Practices in Reducing Vehicle Miles Traveled (VMT): State predictions for VMT growth are significant and can easily contribute up to 25 million metric tons of CO_2e per year by 2050. The projections are based on conventional technologies and regulations. There are opportunities to increase the payload per truck through use of double trailers, and consider use of regulations to maximize the payload in each truck to avoid less than full loads. Additional opportunities include platooning of trucks, expansion of truck corridors, and driverless vehicles.

APPENDIX A:
Methodology and Sources

Resources

The CalHEAT Advisory Council and Steering Committee listed on page ii of the *Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks* (CEC-XXX-XXXX-2013) assisted and reviewed materials developed in the Roadmap and action plan. The CalHEAT Technical Advisory Group listed on page iii of the Roadmap reviewed technical strategies and results.

Two outside consulting firms were utilized as additional resources. Ricardo plc (www.ricardo.com), a global engineering and innovation consultancy with expertise in the automotive market, analyzed CO_2 benefits and adoption rates for technologies. ZMassociates Environmental Consultants (www.zmassociates.com) calculated petroleum, CO_2e, and NOx reductions, and assembled the report.

California Truck Inventory and Impact Study

As the first step in the development of this Roadmap, CalHEAT performed a California Truck Inventory and Impact Study[32] to better understand the various types of trucks used in California, their relative populations, and how they are used. The baseline inventory, acquired through Polk, consisted of commercial Class 2b through Class 8 vehicles registered through the California Department of Motor Vehicles. Data was taken from 2009 registrations consisting of about 1.5 million commercial medium- and heavy-duty trucks, grouped by weight and application, to establish a baseline inventory, fuel use, and emissions, to be used to evaluate the potential for efficiency and emissions improvements.

A CalHEAT-specific system of reclassifying the vehicles into six categories by a combination of weight and duty cycles was devised. In order to do this correctly, a Technical Advisory Group was created consisting of nationally-recognized medium- and heavy-duty truck associations, manufacturers, and experts. After the six Cal HEAT truck categories were defined, a logic table was developed to automatically reclassify the 1.5 million trucks into breakout populations for each of the categories.

[32] Jennings, Geoff, and Brotherton, Tom. (CalHEAT). June, 2012.

The next step was to create a baseline emissions inventory, broken out by the six truck categories. This was done by performing secondary research on the average VMT, fuel consumption, and emissions per mile for each of the truck categories to define the average fuel used and NOx and CO_2e emission levels. These averages were then multiplied by the vehicle populations derived in the truck population inventory to develop baseline fuel consumption, CO_2e and NOx levels as shown in Figure 3: Truck CO_2e, Average Vehicle Miles Traveled and Population by Truck Category, page 12, and Figure 4: Relative NOx by Truck Category, page 13.

Vehicle Technologies

Vehicle Technology Pathways

Technology strategies were initially proposed for the action plan based on CALSTART's experience on its High-Efficiency Truck Users Forum (HTUF) Program. The initial advisory council meetings focused on developing consensus on which technology strategies to pursue in the Roadmap and action plan.

Gap Analysis

This phase of the Roadmap focused on research to identify gaps along technology pathways, the status of market penetration and barriers that may be holding back progress. Initial interviews were established with a variety of technology advisory committee members and with Ricardo automotive consultants. Ricardo was selected as a consultant to CalHEAT for the purpose of vetting the industry feedback received.

Initially CalHEAT was able to determine near term gaps and in what timeframe a given technology strategy may be able to have some significant impact on the CO_2 profile for California, classified by each of the six truck categories. These are illustrated under Table 5: Promising Technology Pathways by Truck Category, page 19, using Harvey balls to identify technologies that are expected to make a significant reduction in CO_2 before 2020, vs. those not expected to be implemented until after 2020, or not make a significant contribution in CO_2 reduction at all.

Petroleum, CO_2e, and NOx Reduction Analysis

To project likely CO_2e, NOx, and petroleum reductions, a look-up table and model was developed for a near term generation and a future long term generation of each truck category, and correlated to the 13 technology strategies.

A straw man action plan and Roadmap for the generations of each technology was developed, culminating in a long-term commercial product that could ultimately provide a 2-to-4 year return on investment. The initial Roadmap was developed based on industry interviews and CALSTART knowledge of electrification technologies from the HTUF Program. A corresponding action plan for each technology strategy was developed providing actions along with their cost to culminate in a mature, cost-effective technology offering.

The set of straw man Roadmap and action plans were submitted to the full Technology Advisory Group for review. Nearly 90% of the Technical Advisory Group members provided detailed responses in their areas of expertise. Additional interviews were performed in areas that the CalHEAT staff considered to be incomplete, and then the Roadmap and action plan was generated.

The results of the Roadmap technologies combined with the model resulted in the projected reductions of petroleum, CO_2e, and NOx, discussed in the Results section of Chapter 1, under Truck Fuel Use, page 13, through the Fuel-Related Reductions section, which begins on page 22.

The EMissions FACtor (EMFAC) model was used for projecting increases in vehicle populations and VMT. EMFAC categories were mapped to the CalHEAT categories in order to project the increase in each CalHEAT category. As EMFAC only provided data to 2035, the data were extrapolated to 2050 using the period 2020 to 2035, where it was expected effects from the recession would be minimal.

Assumptions for NOx calculations discussed in the Results section and shown in Figure 12: Projected NOx Reductions, page 26, are that NOx emissions decrease with a decrease in fuel consumption due to higher efficiencies, but are not affected by use of biofuels or decarbonization. NOx reduction technologies will be adopted beginning in 2020.

Adoption Analysis

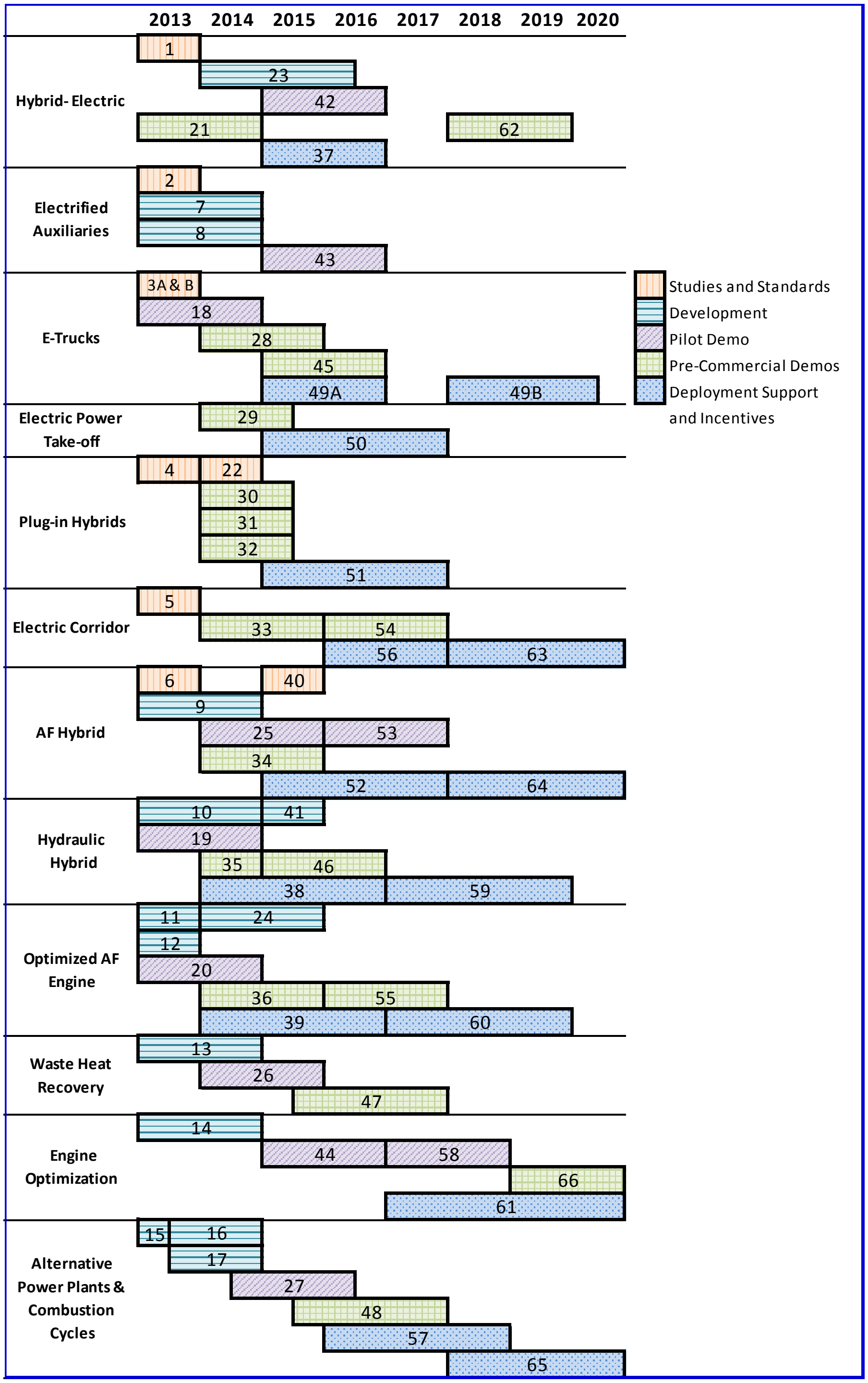
The CalHEAT staff, with the assistance of Ricardo, developed a model which used the CalHEAT categories developed for the emissions reduction model, added unique vehicle technology adoption rates for each truck technology and category, and then rolled up the result of the CO_2 reduction over time to obtain projections for 2020, 2035 and 2050. The adoption rates were generated by reviewing recent Class 8 Truck Adoption rates provided by the North American Council for Freight Efficiency (NACFE) and some general automotive adoption rate curves.

The model was ultimately used to generate the adoption curves shown in Category Figure 13: Technology Adoption by Truck Category , page 27, and Figure 14: Technology Adoption all Truck Categories, page 28.

APPENDIX B:
Sixty-six Actions by Technology Strategy

In this Appendix, the 66 Roadmap actions to reduce petroleum, CO_2e, and NOx, or improve truck efficiency are grouped by technology strategy and identified by action category, such as studies and standards through deployment, in Figure 33, page 69. A numerical list with descriptions of each action follows in Table 6, page 70.

Figure 33: Sixty-Six Actions by Technology Strategy



The 66 actions to reduce petroleum, CO_2e, and NOx, or improve truck efficiency are grouped by technology strategy and identified by action category, from studies and standards through deployment. Refer to Table 6, below, for a numerical list, timeline and description.

Table 6: Sixty-six Actions in CalHEAT Roadmap

#	Technology Strategy	Action Category	Year(s)	Description
1	Hybrid Electric	Studies and Standards	2013	Industry assistance to overcome California OBD issues.
2	Electrified Auxiliaries	Studies and Standards	2013	Formulate and expedite adoption of standards such as voltage variants and J1939 signal controls.
3a	E-Trucks	Studies and Standards	2013	Develop energy storage standards (pack level interfaces) to encourage greater selection and competition through SAE or IEEE or regulation.
3b			2013	Study best Applications for fast charging for increase truck and battery utilization
4	Plug-in Hybrids	Studies and Standards	2013	Identify appropriate markets and truck platforms that have a potential business case.
5	Electric Corridor	Studies and Standards	2013	Assess various roadway power systems and garner regional and statewide consensus on a standard for a pickup device.
6	AF Hybrid	Studies and Standards	2013	Perform outreach to encourage an increase and broader selection of B20-certified engines.
7	Electrified Auxiliaries	Development	2013-14	Develop more purposely-designed electronics (but ideally shared architecture, DC-DC converters, auxiliary drives, power steering, pumps) that can be integrated into vehicles.
8	Electrified Auxiliaries	Development	2013-14	Develop a power distribution box/suppliers to allow for commonality across OEMs an enabler for cost reduction.
9	AF Hybrid	Development	2013-14	Develop smaller & lighter CNG tanks designed for HE trucks.
10	Hydraulic Hybrid	Development	2013-14	Develop a light-weight advanced accumulators.
11	Optimized AF Engine	Development	2013	Develop additional smaller engine sizes for efficiency and performance improvements (especially low-end torque).
12	Optimized AF Engine	Development	2013	Develop lower cost HHD NG solutions (Heavy - Heavy 1.5 liter engine).
13	Waste Heat Recovery	Development	2013-14	Develop/apply thermoelectric designs to M-HD applications.
14	Engine Optimization	Development	2013-14	Develop engines and systems to provide 50% reduced NOx.
15	Alt Power Plants and Combustion Cycles	Development	2013	FTA providing development funding for fuel cell transit buses, with the primary objective of reducing fuel cell cost, reducing footprint, increasing reliability.
16	Alt Power Plants and Combustion Cycles	Development	2013-14	Develop one or two new advanced engine designs such as camless, opposed piston or HCCI.
17	Alt Power Plants and Combustion Cycles	Development	2013-14	Develop a purposely-designed turbine for vehicles.
18	E-Trucks	Pilot Demonstrations	2013-14	Pilot demos of smart charging systems.
19	Hydraulic Hybrid	Pilot Demonstrations	2013-14	Pilot demos of stage 2 in Parcel, Beverage Delivery, Buses and Yard Hostlers.
20	Optimized AF Engine	Pilot Demonstrations	2013-14	Pilot demos of special CNG tanks with newer lighter materials.
21	Hybrid Electric	Pre-Commercial Demonstrations	2013-14	Demos of next stage 2 hybrid drivelines incorporating improved design and integration and a preference for ARB OBD compliance, as well as electrified auxiliaries
22	Plug-in Hybrids	Studies and Standards	2014	Formulate a drayage truck economic model that captures externalities for ZEV Corridor.

Sixty-six actions identified in the CalHEAT Research & Market Transformation Roadmap for Medium- and Heavy-Duty Trucks are listed above by action number, technology strategy, action category, and years in which action is planned, with a description. The table continues on the next two pages.

Table 6: Sixty-six Actions in CalHEAT Roadmap (Continued, page 2 of 3)

#	Technology Strategy	Action Category	Year(s)	Description
23	Hybrid Electric	Development	2014 -15	Develop prototypes for optimized and downsized engines to be used in hybrid systems.
24	Optimized AF Engine	Development	2014-15	Develop advanced engine efficiency strategies and improved methane catalysts.
25	AF Hybrid	Pilot Demonstrations	2014-15	Pilot demos to evaluate/benchmark various NG/hybrid refuse trucks.
26	Waste Heat Recovery	Pilot Demonstrations	2014-15	Pilot demos of waste heat recovery in a vocational and line-haul truck.
27	Alt Power Plants and Combustion Cycles	Pilot Demonstrations	2014-2016	Pilot demos of camless, opposed piston , free piston or HCCI engines in trucks.
28	E-Trucks	Pre-Commercial Demonstrations	2014-15	Demos of improved integration, lower-cost stage 2 E-Trucks for ZEV Corridor applications & goods movement.
29	Electric Power Take-off	Pre-Commercial Demonstrations	2014-15	Demos of next-gen lower-cost state 2 systems.
30	Plug-in Hybrids	Pre-Commercial Demonstrations	2014-15	Demos of good movement and drayage trucks.
31	Plug-in Hybrids	Pre-Commercial Demonstrations	2014-15	DOE SCAQMD utility trucks (ARRA Funded).
32	Plug-in Hybrids	Pre-Commercial Demonstrations	2014-15	Demos of stage 1 in Class 2b trucks.
33	Electric Corridor	Pre-Commercial Demonstrations	2014-15	Demos of preferred on-road connection device for electric or PHET yard hostlers.
34	AF Hybrid	Pre-Commercial Demonstrations	2014-15	Demos of new platforms of NG/hybrid drayage truck meeting ZEV Corridor requirements.
35	Hydraulic Hybrid	Pre-Commercial Demonstrations	2014	Demos of series, enhanced parallel and/or dual-mode (power split) stage 2 hybrids in refuse trucks.
36	Optimized AF Engine	Pre-Commercial Demonstrations	2014-15	Demos of lower engine sizes and new lower cost 15 liter engines to broaden number of platforms.
37	Hybrid Electric	Deployment Support and Incentives	2014	Support for 1000 stage 2 hybrids when they become commercially available.
38	Hydraulic Hybrid	Deployment Support and Incentives	2014-15	Support for the first 100 stage 2 vehicles when they become commercially available.
39	Optimized AF Engine	Deployment Incentives	2014-15	Support for 1000 stage 2 trucks.
40	AF Hybrid	Studies and Standards	2015	Understand potential for cellulosic ethanol, methanol and DME as hybrid and optimized engine fuels.
41	Hydraulic Hybrid	Development	2015	Free Piston engine development.
42	Hybrid Electric	Pilot Demonstrations	2015-16	Pilot demos of optimized and downsized engine/s to be used in hybrid systems.
43	Electrified Auxiliaries	Pilot Demonstrations	2015-16	Pilot demos for validation of electrified auxiliaries in Class 7-8 (non-hybrid) tractors, line-haul trucks and other trucks.
44	Engine Optimization	Pilot Demonstrations	2015-16	Pilot demos of 50% brake thermal efficiency engines leveraging DOE program and also incorporating all relevant technologies to achieve up to 1.5x truck efficiency improvement.

Actions 23 through 44 in the CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks are listed above by action number, technology strategy, action category, and years in which the action is planned, with a description. The table continues on the next page.

California Hybrid, Efficient and Advanced Truck Research Center

Table 6: Sixty-six Actions in CalHEAT Roadmap (Continued, page 3 of 3)

#	Technology Strategy	Action Category	Year(s)	Description
45	E-Trucks	Pre-Commercial Demonstrations	2015-16	Demos of significantly lower cost stage 3 E-Trucks, including longer ranges & fast charging.
46	Hydraulic Hybrid	Pre-Commercial Demonstrations	2015-16	Demos of ultra-high efficiency stage 3 technology using digital hydraulic components into a Class 2b and one other larger truck platform.
47	Waste Heat Recovery	Pre-Commercial Demonstrations	2015-2017	Demos of waste heat recovery in vocational and line-haul trucks.
48	Alt Power Plants and Combustion Cycles	Pre-Commercial Demonstrations	2015-2017	Demos of camless, opposed Piston, free piston or HCCI engines in trucks.
49a	E-Trucks	Deployment Support and Incentives	2015-16	Support for 1000 stage 2 trucks to reduce ROI to 5 years (assuming daily driving of 80% of energy storage capacity).
49b			2018-20	Support for Stage 3 Trucks to accelerate adoption
50	Electric Power Take-off	Deployment Support and Incentives	2015-17	Support for next-gen, stage 2 lower cost EPTO deployments
51	Plug-in Hybrids	Deployment Support and Incentives	2015-17	Support for 500 stage 1 PHETs when they become commercially available.
52	AF Hybrid	Deployment Support and Incentives	2015-17	Support for 200 NG hybrid refuse trucks.
53	AF Hybrid	Pilot Demonstrations	2016-17	Pilot demos of NG/hybrid refuse trucks with downsized engines and/or 80% less NOx.
54	Electric Corridor	Pre-Commercial Demonstrations	2016-17	Demos of dual-mode hybrid and range-extended electric drayage trucks to broaden manufacturers offerings and truck types.
55	Optimized AF Engine	Pre-Commercial Demonstrations	2016-17	Demos of 80% decreased NOx (NZEV).
56	Electric Corridor	Deployment Support and Incentives	2016-17	Support for stage 2 PHET Class 7 & 8 drayage trucks (focus on Electric Corridor).
57	Alt Power Plants and Combustion Cycles	Deployment Support and Incentives	2016-18	Stage 2 tech support for 100 drayage truck buy-downs and introduce performance-based incentives for 200 low NOx higher efficiency line-haul trucks.
58	Engine Optimization	Pilot Demonstrations	2017-18	Pilot demos of 55% brake thermal efficiency engines also incorporating all relevant technologies to achieve 2x truck efficiency improvement and 50% lower NOx
59	Hydraulic Hybrid	Deployment Support and Incentives	2017-19	Support for first 300 vehicles in Class 2b when they become commercially available.
60	Optimized AF Engine	Deployment Support and Incentives	2017-20	Introduce performance-based incentives for 200 NZEV/higher-efficiency trucks.
61	Engine Optimization	Deployment Support and Incentives	2017-20	Introduce performance-based incentives for early fleet deployments in California (1.5x efficiency conventional and 50% lower NOx) for first 200 OTR trucks.
62	Hybrid Electric	Pre-Commercial Demonstrations	2018-19	Demos of the more electric OTR hybrid truck.
63	Electric Corridor	Deployment Support and Incentives	2018-20	Support for dual-mode hybrid and range-extended electric drayage.
64	AF Hybrid	Deployment Support and Incentives	2018-20	Support for 100NG hybrid drayage trucks for ZEV Corridor.
65	Alt Power Plants and Combustion Cycles	Deployment Support and Incentives	2018-20	Support for fuel cell- and turbine-powered trucks and stage three technology trucks using performance based incentives
66	Engine Optimization	Pre-Commercial Demonstrations	2019-2020	Demo of 55% brake thermal efficiency engine incorporating all relevant technologies to achieve 2x truck efficiency improvement and 50% lower NOx.

Actions 45 through 66 in the CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks are listed above by action number, technology strategy, action category, and years in which the action is planned, with a description.

California Hybrid, Efficient and Advanced Truck Research Center

APPENDIX C:
Sixty-six Actions by Timeline and Action Category

The sixty-six actions in the *Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks* are summarized by action category and technology strategy in the five tables included in this Appendix, which cover Studies and Standards, Development, Pilot Demonstrations, Pre-Commercial Demonstrations, and Deployment Support and Incentives.

Table 7: Studies and Standards Action Summary

Studies and Standards			
Includes business case studies, technology feasibility studies, complex modeling, and simulations. Also includes the creation of standards.			
Technology	**2013**	**2014**	**2015**
Hybrid-Electric	1. Industry assistance to understand California OBD Requirements		
Electrified Accessories	2. Formulate and expedite adoption of standards such as voltage variants and J1939 signal controls		
E-Trucks	3a Develop energy storage standards (pack level interfaces) to encourage greater selection and competition through SAE or IEEE, or regulation 3b Study best Applications for fast charging for increase truck and battery utilization		
Plug-in Hybrids	4. Identify appropriate markets and truck platforms that have a potential business case	22. Formulate a drayage truck economic model that captures externalities for ZEV corridor	
Electric Corridor	5. Assess various roadway power systems and garner regional and statewide consensus on a standard for a pickup device		
AF/Hybrid	6. Perform outreach to encourage an increase and broader selection of B20-certified engines		40. Understand potential for Cellulosic Ethanol, Methanol and DME as Hybrid and Optimized Engine Fuels

Studies and Standards planned in the CalHEAT Roadmap, shown by technology strategy and year.

Table 8: Development Action Summary

Development				
Development of a component, subsystem or complex drivetrain system				
Technology	**2013**	**2014**	**2015**	**2016**
Hybrid-Electric		23. Develop prototypes for optimized and downsized engines to be used in hybrid systems		
Electrified Accessories	7. Develop more purposely-designed electronics (but ideally shared architecture, DC-DC converters, auxiliary drives, power steering, pumps) that can be integrated into vehicles.			
	8. Develop power distribution box/suppliers to allow for commonality across OEMs. (This is an enabler to further cost reduction.)			
AF Hybrid	9. Develop smaller & lighter CNG tanks designed for HE trucks			
Hydraulic Hybrid	10. Develop a light-weight advanced accumulators		41. Free Piston Engine Developments	
Optimized AF Engine	11. Develop additional smaller engine sizes for efficiency and performance improvements (especially low-end torque)	24. Develop advanced engine efficiency strategies and improved methane catalysts		
	12. Develop lower cost HHD NG solutions (Heavy – Heavy 15 liter engines)			
Waste Heat Recovery	13. Develop/apply thermoelectric designs to M-HD applications			
Engine Optimization	14. Develop engines and systems to provide 50% reduced NOx			
Alternative Power Plants and Combustion Cycles	15. FTA providing development funding for fuel cell transit buses, to reduce fuel cell cost, reducing footprint, increasing reliability			
	16. Develop new advanced engine designs such as camless, Opposed Piston, free piston and HCCI Engines			
	17. Develop purposely-devised turbinesfor vehicles			

Development projects outlined in the CalHEAT Roadmap, shown by technology strategy and year.

California Hybrid, Efficient and Advanced Truck Research Center

Table 9: Pilot Demonstration Action Summary

Pilot Demonstrations						
A pilot demonstration is the full integration of a component, subsystem or complex drivetrain into1 to 5 trucks to evaluate performance.						
Technology	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Hybrid Electric			42. Pilot demos of optimized and downsized engine/s to be used in hybrid systems			
Electrified Auxiliaries			43. Pilot demos for validation of electrified auxiliaries in Class 7-8 (non-hybrid) tractors, line haul trucks and other trucks			
E-Trucks	18. Pilot demos of smart charging systems					
AF Hybrid		25. Pilot demos to evaluate/benchmark various NG/hybrid refuse trucks		53. Pilot demos of NG/hybrid refuse trucks with downsized engines and/or 80% less NOx		
Hydraulic Hybrid	19. Pilot demos of stage 2 in Parcel ,Beverage Delivery, Buses and Yard Hostlers					
Optimized Alternative Fuel Engines	20. Pilot demos of special CNG tanks with newer lighter materials					
Waste Heat Recovery		26. Pilot demos of waste heat recovery in a vocational and line-haul trucks				
Engine Optimization			44. Pilot demos of 50% break thermal efficiency engines leveraging DOE program and also incorporating all relevant technologies to achieve up to 1.5x truck efficiency improvement		58. Pilot demos of 55% break thermal efficiency engines also incorporating all relevant technologies to achieve 2x truck efficiency improvement and 50% lower NOx	
Alt Power Plants and Combustion Cycles			27. Pilot demos of Camless, Opposed Piston , free piston or HCCI engines in trucks			

Pilot demonstrations planned in the CalHEAT Roadmap, shown by technology strategy and year.

California Hybrid, Efficient and Advanced Truck Research Center

Table 10: Pre-Commercial Demonstration Action Summary

Pre-Commercial Demonstrations								
Pre-commercial demonstrations involve 1 to 50 trucks to evaluate performance in the field. Further refinement precedes commercial production.								
Technology	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Hybrid Electric	21. Demos of next Stage 2 hybrid drivelines with improved design and integration, and ARB OBD compliance and electrified accessories					62. Demos of the more electric OTR hybrid truck		
E-Trucks		28. Demos of improved integration- lower cost Stage 2 E-Trucks, for ZEV Corridor applications & goods movement						
			45. Demos of lower cost Stage 3 E-Trucks, including longer ranges & fast charging					
Electric Power Take-off		29. Demos of next-gen lower-cost Stage 2 systems						
Plug-in Hybrid Electric		30. Demos of goods movement and drayage trucks						
		31. DOE SCAQMD utility trucks (ARRA Funded)						
		32. Demos of Stage 1 in Class 2b trucks						
Electric Corridor		33. Demo of preferred on-road connection device for electric or PHET yard hostlers		54. Demos of dual-mode hybrid and range-extended electric drayage trucks to broaden mfrs offerings and truck types				
AF Hybrid		34. Demos of new platforms of NG/hybrid drayage truck meeting ZEV Corridor requirements						
Hydraulic Hybrid		35. Demos of Series, Enhanced Parallel and/or Dual Mode (Power Split) Stage 2 Hybrids in refuse trucks	46. Demos of ultra-high efficiency Stage 3 technology using digital hydraulic components into a Class 2b and other larger truck platforms					
Optimized AF Engine		36.Demos of lower engine sizes and new lower cost 15 liter engines to broaden number of platforms		55. Demos of 80% decreased NOx (NZEV)				
Waste Heat Recovery			47. Demos of waste heat recovery in vocational and line-haul trucks					
Engine Optimization							66. Demo of 55% brake thermal efficiency engine with technologies to achieve 2x truck efficiency improvement and 50% lower NOx	
Alt Power Plant/ Combustion			48. Demos of camless, Opposed Piston, free pistons and HCCI engines in trucks					

Pre-commercial demonstrations in the CalHEAT Roadmap, shown by technology strategy and year.

California Hybrid, Efficient and Advanced Truck Research Center

Table 11: Deployment Support and Incentives Action Summary

Deployment Support and Incentives								
Policy and Regulatory Support and Financial Incentives for early deployment of commercial products in the marketplace								
Technology	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Hybrid Electric		37. Support for 1,000 Stage 2 hybrids starting when they become commercially available						
E-Trucks			49 A.Support for 1000 Stage 2 trucks to reduce ROI to 5 years (assuming daily driving of 80% of energy storage capacity			49 B Support for Stage 3 Trucks to accelerate adoption		
Electric Power Take-off			50. Support for next-gen Stage 2 lower cost EPTO deployments					
Plug-in Hybrid			51. Support for the first 500 Stage one PHETs when they become commercially available					
Electric Corridor				56. Support for Stage 2 PHET Class 7 & 8 drayage trucks (focus on Electric Corridor)		63. Support for dual-mode hybrid and range-extended electric drayage		
AF Hybrid			52. Support for 200 NG hybrid refuse trucks			64. Support for 100 NG hybrid drayage trucks for ZEV Corridor		
Hydraulic Hybrid		38. Support for the first 100 Stage 2 vehicles when they become commercially available			59. Support for first 300 vehicles in Class 2b when they become commercially available			
Optimized AF Engine		39. Support for 1000 Stage 2 trucks			60. Introduce performance-based incentives for 200 NZEV/higher-efficiency trucks			
Engine Optimization					61. Introduce performance-based incentives for early fleet deployments in California (1.5X efficiency conventional and 50% lower NOx) for first 200 OTR trucks			
Alternative Engines and Combustion Cycles				57. Stage 2 tech support for 100 drayage truck buy-downs and introduce performance-based incentives for 200 low NOx higher efficiency line-haul trucks				
						65. Support for fuel cell- and turbine-powered trucks and stage three technology trucks using performance based incentives		

Deployment incentives and support planned in the CalHEAT Roadmap, shown by technology strategy and year.

APPENDIX D: Glossary

AB	Assembly Bill
AQMD	Air Quality Management District
ARB	Air Resources Board
BTE	Brake Thermal Efficiency
CalEPA	California Environmental Protection Agency
CEC	California Energy Commission
CO_2e	Carbon dioxide equivalents
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EMFAC	EMissions FACtor, a computer model for quantification of pollutants from on-road sources
EPA	Environmental Protection Agency
EPTO	Electrified Power Take-off
HDV	Heavy-duty vehicle
HEV	Hybrid EA Electric Vehicle
g/bhp-h	Grams/brake horse power per hour
GHG	Greenhouse gas
LNA	Low NOx Ammonia application
LNC	Lean NOx Catalysts
MDV	Medium-duty vehicle
MMT	Million Metric Tons
$MMTCO_2e$	Million Metric Tons of CO_2 Equivalent Emissions
NACFE	North American Council for Freight Efficiency
NHTSA	National Highway Traffic Safety Administration
NOx	Oxides of Nitrogen

OBD	On-board Diagnostics
OEM	Original Equipment Manufacturer
PHET	Plug-in Hybrid Electric Truck
PIER	Public Interest Energy Research
PM	Particulate matter
PTO	Power Take-off
ROI	Return on Investment
RPM	Revolutions per Minute
SCR	Selective Catalytic Reduction
Supertruck	Under its Supertruck program, the DOE has funded demonstration projects of Class 8 long-haul trucks that incorporate a wide range of technologies developed under the 21st Century Truck Partnership, with the objective of creating highly efficient and clean-burning diesel-powered trucks with 50% or greater vehicle freight efficiency and brake thermal efficiency.
xEV	Fully Electric Vehicle
ZEV Corridor	Zero-emission Corridor