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PREFACE

The California Energy Commission Energy Research and Development Division 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 Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Transportation

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For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

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 to promote more fuel-efficient medium- and heavy-duty vehicles and reduction of emissions. The role of the research center is to coordinate the development of clear, actionable steps to help meet or exceed the 2020 goals for California in petroleum reduction, carbon reduction, and air quality standards, and identify long-term goals through 2050. Medium- and heavy-duty trucks account for 9 percent of greenhouse gases in California, and approximately 20 percent of fuel consumption. Improvements in efficiency or reduction of petroleum use by trucks provide a substantial opportunity to reduce emissions. CalHEAT's initial activities included developing a roadmap for research and market transformation activities through 2020 in the medium- and heavy-duty transportation and goods movement sector with a target of 40-50 percent fuel efficiency improvements. CalHEAT also conducted outreach events that informed more than 100 fleet operators, all major truck makers, and at least 30 system and technology developers on recent research and development in the medium-and heavy-duty truck and goods field. CalHEAT has collaborated with the State's Air Resources Board, Energy Commission, Air Quality Management Districts; the U.S. DOE and EPA; and nationally recognized medium- and heavy-duty truck associations, manufacturers, and experts. By 2050, implementation of advanced truck technologies through CalHEAT recommendations 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. With an assumed adoption rate of 25 percent of biofuels, 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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EXECUTIVE SUMMARY

Introduction

Medium- and heavy-duty vehicles are critical to the economy, yet remain a real and growing energy and carbon challenge that is insufficiently addressed. These vehicles are responsible for 9 percent of California greenhouse gas emissions and consume 20 percent of the fuel used in California trucking fleets. In the business-as-usual scenario projected by the California Energy Commission, diesel demand will increase by at least 42 percent by 2030. Greenhouse gas emissions in medium- and heavy-duty trucks are now increasing at a rate that is three times faster than for light-duty vehicles.

The challenge is particularly visible in Southern California, which is the State and nation's biggest transportation hub. Medium- and heavy-duty on-road truck traffic serving urban and goods movement needs combine with heavy-duty off-road vehicle use at distribution centers and ports, all of which contributes significantly to fuel use, poor regional air quality, and greenhouse gas emissions. Improving the emissions and fuel use of medium- and heavy-duty trucks is a promising avenue into helping the state meet its goals of reducing petroleum, carbon, and emissions from commercial medium- and heavy-duty trucks.

Regulatory Goals

The State of California passed regulations that establish emission reduction targets with the primary driver being 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 meeting more stringent ongoing environmental policies through 2050. In addition, Executive Order B-16-2012 establishes the goal of reducing CO_2 equivalent emissions in the transportation sector by 2050 to 80 percent less than 1990 levels, 85 percent less than 2010 levels, and 86 percent less than today's projected business-as-usual levels for 2050.

A number of overlapping state and federal regulations aim at decreasing emissions of greenhouse gases and particulate matter, improving air quality, increasing biofuel use, decreasing petroleum use and more.

Purpose

The purpose of this project was to address challenges and opportunities of implementing advanced truck technologies through creation and operation of a center devoted to research, planning, demonstration, and commercialization research for efficient medium- and heavy-duty vehicles called CalHEAT – the California Hybrid, Efficient and Advanced Truck Research Center.

The research center – CalHEAT – was to be the platform through which CALSTART would coordinate the development and delivery of clear, actionable steps for medium- and heavy-duty trucks to help meet or exceed the 2050 goals for California in petroleum reduction, carbon reduction, and air quality standards, and set a plan for longer term goals.

Objectives

The project aimed to tackle the long-term environmental challenge inherent in the trucking industry through the establishment of the CalHEAT center.

Specifically, this meant the center would establish partnerships with diverse stakeholder groups, including leading companies and organizations in the advanced, efficient truck arena, including testing, vehicle use/port, energy, regulatory and technology development partners. These partners provided guidance, feedback and "virtual" and core assets, including testing centers, staff expertise, project co-funding, demonstration venues and support. The main objective of this project was to create a state and national resource to develop technology and market transformation projects and investments for reducing petroleum use, greenhouse gas emissions and air pollution in medium- and heavy-duty trucks.

In addition, CALSTART, through the CalHEAT center operations, worked to advance changes in the California truck industry, especially in reducing emissions, improving fuel efficiency, and stimulating economic activity, through several immediate objectives:

- Develop a roadmap for research and market transformation activities through 2020 in the medium- and heavy-duty transportation and goods movement sector with a target of driving 40-50 percent fuel efficiency improvements.
- Conduct initial research and demonstration projects and activities following the strategic goals of center with fuel efficiency improvements of 20–40 percent for vocational trucks and 5-10 percent for long-haul trucks.
- Recommend next phase projects moving the advanced technology products into the medium- and heavy-duty market and developing a sustainable marketplace involving six major truck manufacturers and five system suppliers.
- Conduct outreach and provide industry support on research and development activities in medium-and heavy-duty truck and goods movement industry that reaches and informs more than 100 fleet operators, all major truck makers and at least 30 system and technology developers.

Results

In 2010, CalHEAT was launched. It established a strong precedent for collaboration by working with California's Air Resources Board, Energy Commission, Air Quality Management Districts, andMetropolitan Planning Organizations; the U.S. Department of Energy and Environmental Protection Agency; and nationally recognized medium- and heavy- duty truck associations and experts. These stakeholders worked alongside CalHEAT staff to participate in the development of a market transformation roadmap that charts a path to reduction in CO_2 of more than 40 million metric tons per year as compared to business as usual.

As part of that effort, the center inventoried California's medium- and heavy-duty truck population, with testing and demonstration of vehicles currently being used to establish a baseline and do gap analysis.

Other activities advanced technological knowledge, researched potential technological solutions, analyzed markets and barriers, and performed outreach that increased the truck industry participation, knowledge sharing, and involvement. These included:

- Testing and demonstration of plug-in parcel delivery vehicles.
- Testing and demonstration of an advanced Class 8 hybrid beverage delivery truck.
- Identification of high-efficiency, alternative fuel hybrid truck market barriers.
- Holding CalHEAT Outreach Technology Interchange Forums across the state.

Conclusions and Recommendations

The establishment of CalHEAT and its initial operations accomplished much in the effort to help California meet its environmental goals through transformation of the medium- and heavy-duty truck population. The center has become an arena that brings together industry, policy makers, scientists and other stakeholders. Many important steps have been taken, including research, testing, analysis, and identification of effective technologies, practices, market issues, and possible paths to implementation. The CalHEAT roadmap identified 66 action items and 13 technology strategies. If implemented, these items are estimated to result in a reduction of more than 40 million metric tons of carbon dioxide-equivalent emissions per year by 2050, compared to what would happen if no changes were made.

Continued support of CalHEAT and its Steering Committee will be critical going forward. The CalHEAT Advisory Council has recommended additional research to support prioritization of implementing and updating the roadmap. There is also an ongoing need to track and search for new breakthrough technologies and incorporate these into the roadmap. Lastly, there is a critical need for CalHEAT to facilitate implementation of the roadmap.

Further research needs to be performed on clean and efficient driveline technologies with a focus on the Class 8 truck population in the state, which represents nearly 55 percent of the state's CO_2 equivalent emissions. Additional recommendations include projects and partnerships to continue development of advanced and efficient Class 8 over-the-road trucks. Additional work with industry stakeholders could identify research and development in progress such as near-zero-emissions technologies, and help establish near-term regulatory standards. These standards are critical to achieving an 85 percent reduction of NOx in the South Coast and San Joaquin Valley regions.

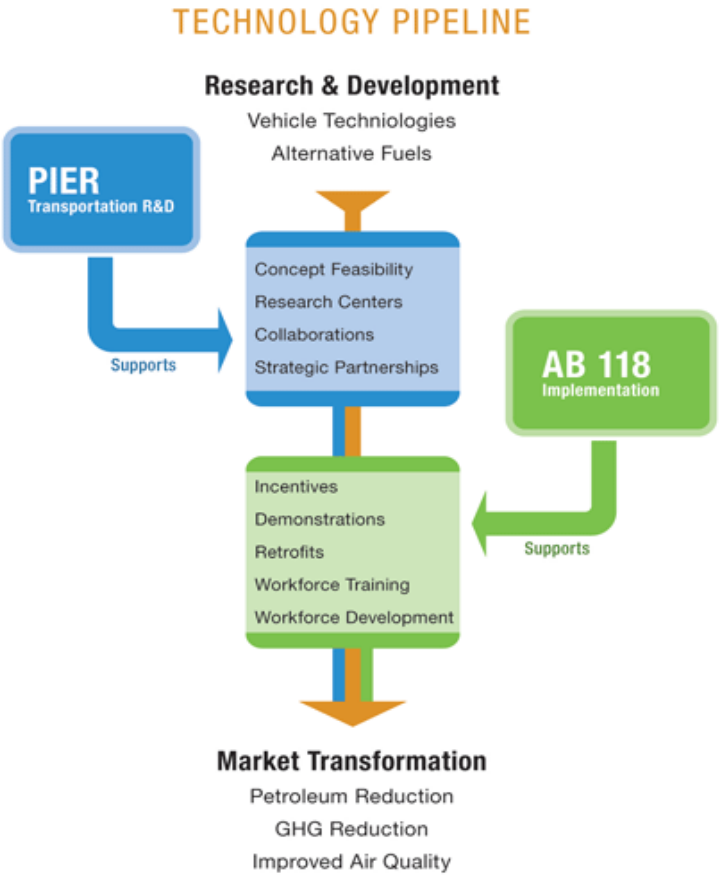
Finally, next steps to benefit Californians should include additional research and development that target significant reductions in carbon, criteria emissions, and/or fuel use. These include biofuel adoption by truck fleets and efforts to reduce the growth of vehicle miles travelled by California trucks.

CHAPTER 1:
Establishing an Operating Center

1.1 Initial Operations

In 2010, CALSTART established the organizational structure and key processes for operation of the California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT), as an innovative state and national research center to guide, design, coordinate, and perform accelerated research, development, and demonstration of cleaner, more-efficient trucks and buses in California. CalHEAT was designed to help feed high-efficiency, low-carbon technologies through the technology pipeline, as envisioned by the California Energy Commission, promoting projects and technologies that drive the Alternative and Renewable Fuel and Vehicle Technology Program (AB 118) goals, as illustrated in Figure 1-1.

Figure 1-1: Development and Integration of New Truck Technologies



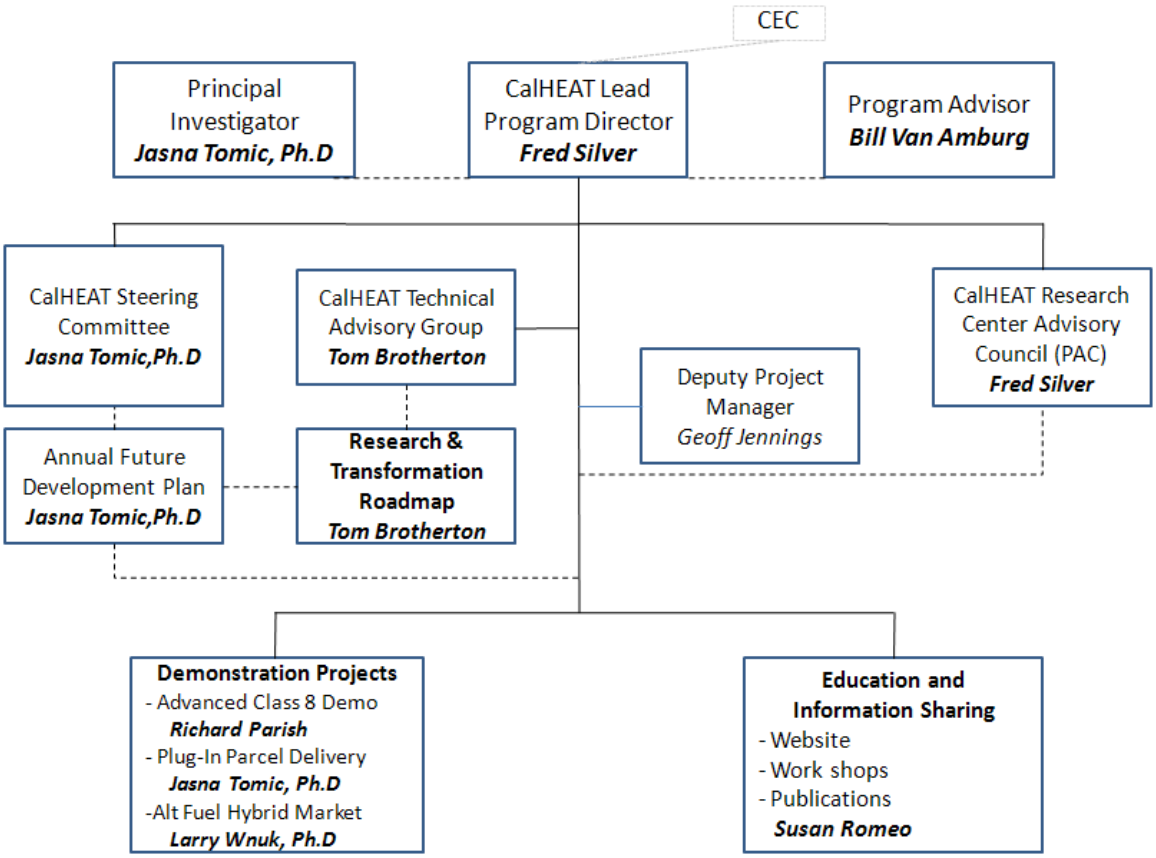
1.2 Structure

CALSTART assembled a leadership team for managing the CalHEAT project made up of individuals with many years of individual and combined industry experience and expertise. In

addition, CALSTART experts in specific sectors, technical areas, and markets contributed their expertise.

Figure 1-2 shows roles and responsibilities of the leadership team.

Figure 1-2: CalHEAT Leadership Chart



Source: California Hybrid, Efficient and Advanced Truck Research Center

A key component of CalHEAT's development was and is to create partnerships with organizations to ensure that the desired transformation and efficiency improvements will be achieved. Partnerships will also help leverage and supplement CalHEAT's research funds. This includes working with the High-Efficiency Truck Users Forum (HTUF) working groups as well as tapping the industry for the best thinkers in the trucking and goods movement industry for the purpose of developing the Transformation Roadmap and performing appropriate demonstration projects.

To help achieve its goals, CalHEAT set up an advisory committee, recruiting and selecting members from a cross-section of stakeholders representing the utility industry, key trucking fleets, appropriate industry trades/associations and environmental interest groups, government agencies associated with driving and regulating changes in the heavy duty market and visionaries with a strong knowledge of the medium- and heavy-duty vehicle research, development, demonstration, and commercialization community.

The CalHEAT Advisory Council was created to provide ongoing advice and guidance on the activities of the Center, including:

- Assisting CalHEAT to develop its strategic direction.
- Providing general feedback, guidance, and recommendations on the Transformation Roadmap.
- Enlisting others with who can facilitate research and co-funding for CalHEAT.
- Providing input on recommendations for an annual research plan.
- Reviewing and disseminating results of demonstration projects.

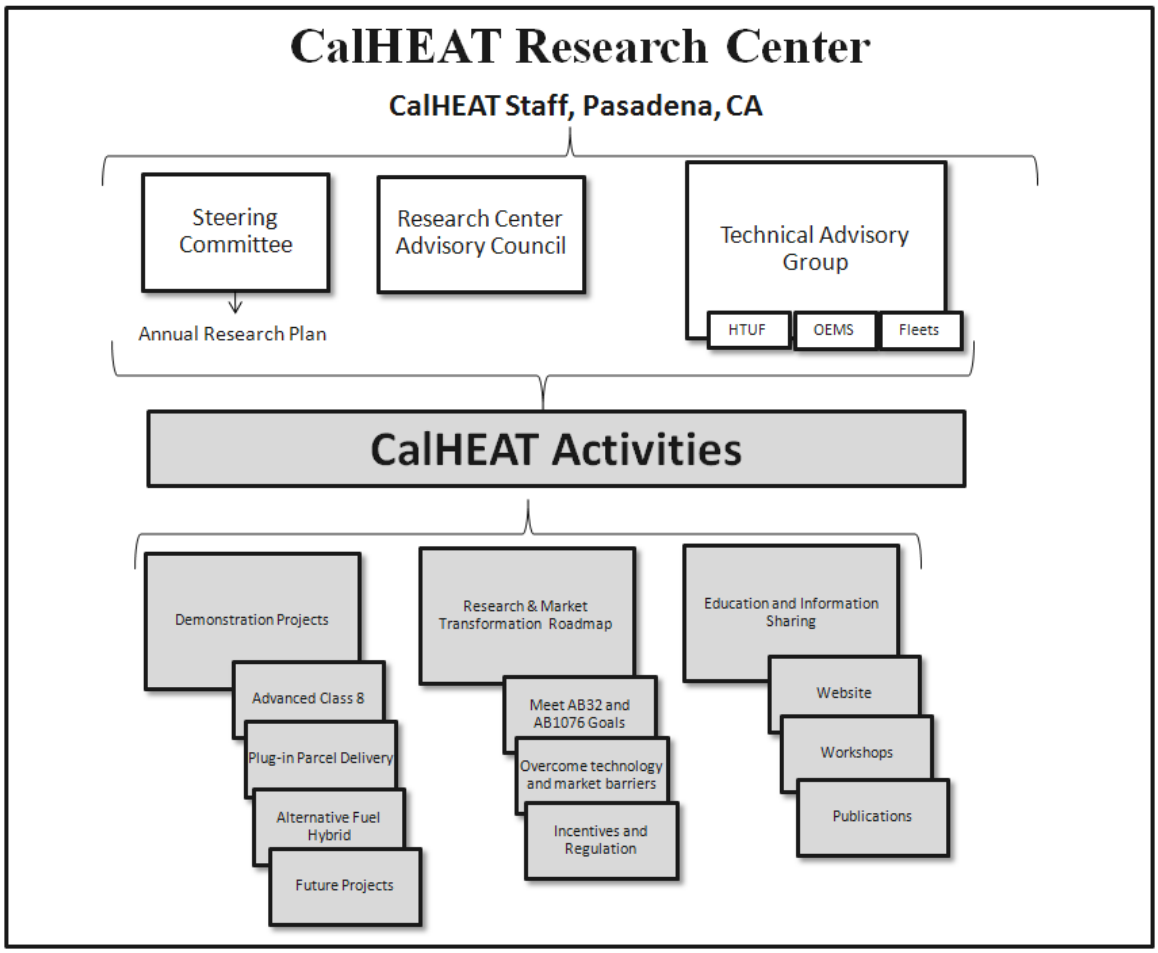
CalHEAT also set up a steering committee to review the needs for technology development and demonstration projects. Steering Committee members can also directly participate in demonstration projects, provide funding and pave the way for the market introduction of new products and the execution of the roadmap. Members were selected and recruited by CalHEAT staff to represent a cross-section of stakeholders and partners representing the utilities, ports, and government agencies associated with technology and project demonstration as it relates to the medium- and heavy-duty trucking sector.

Most importantly, the Steering Committee was developed to provide guidance and review of the CalHEAT Annual Research Plan (developed by CalHEAT Center staff).

In addition, CalHEAT formed technology advisory groups consisting of industry experts, technical advisors, equipment manufacturers, fleet operators, and the Hybrid Truck Users Forum (HTUF) working groups. These groups were created to provide advice and industry technical expertise on topic-specific areas.

Figure 1-3 shows how the committees and groups fit into the overall organizational structure developed for CalHEAT.

Figure 1-3: CalHEAT Organizational Structure



Source: California Hybrid, Efficient and Advanced Truck Research Center

1.3 Initial Objectives and Goals

CalHEAT drew up a list of initial goals to guide its activities:

- Outline and actuate an aggressive research and market transformation roadmap for medium- and heavy-duty vehicles that moves advanced technology products into the medium- and heavy-duty market by 2020. This effort will help meet or exceed the California AB 32, AB 1007 and AB 2076 goals for carbon and petroleum reduction as well as lead to increases in alternative fuel use.
- Help improve the efficiency and reduce the impact of goods movement with a focus on extreme conditions in Southern California, and by extension, California and the nation.
- Perform research and administer demonstration activities that will aid in speeding the implementation and commercialization of emerging technologies and fuels as they relate to medium- and heavy-duty trucks, with the first projects in Class 8 advanced hybrids, plug-in hybrids and alternative fuel-hybrids.

- Provide timely, valuable, and unbiased information for policymakers, industry professionals, fleets, and the environmental community on the ability of the medium- and heavy-duty truck industry to address California's transportation energy challenges.
- Help create economic activity in California through focused technology development and market initiatives.
- Identify potential research partners and funding opportunities.

1.4 Initial Activities

To realize these early objectives and goals, CalHEAT focused on:

- An action-oriented roadmap for research and market transformation.
- An annual research plan to guide the center in prioritizing research needs and strategies.
- Research and demonstration projects that test and validate technology solutions.
- Education to share results with industry, funding sources, and regulatory bodies.

During this initial period, CalHEAT's main focus was creating the transformation roadmap. The roadmap was designed to outline a plan of research and market transformation activities through 2020 in support of California's goals of reducing petroleum, emissions and carbon in the medium- and heavy-duty transportation and goods movement sector.

The development of the roadmap consisted of three distinct phases:

Phase I – Identification of baseline technology and key pathways for improvement.

Phase II – Performance of gap analysis, focusing on identifying technology and market gaps and barriers that impede progress.

Phase III – Assembly and production of the CalHEAT roadmap.

CalHEAT held three outreach forums during its first three years. These were focused on different aspects of the issues CalHEAT studies. For example, the first forum, held in 2011, was a discussion on the possible pathways for getting to zero/near-zero emissions statewide and in the Southern California region. This outreach is an important component of the CalHEAT project because it ensures that information will be spread to key players in the industry to spur action.

CHAPTER 2:
Research and Market Transformation Roadmap

2.1 Executive Summary

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, demonstrate truck technologies and support commercialization 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 percent of greenhouse gases in California, and approximately 20 percent of fuel used. Improvements in efficiency or reduction of petroleum use by trucks provide a substantial opportunity to reduce emissions.

2.1.1 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 greenhouse gas emissions to year 1990 levels by 2020 and meeting more stringent ongoing environmental policies through 2050. The regulations require a reduction of emissions of nearly 30 percent from the projected 2020 levels if no changes occurred, referred to as "Business as Usual" and a reduction of 15 percent 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, these regulations include AB 1007, which requires the preparation of a state-wide alternative fuel plan; AB 2076, which sets specific goals for state reduction of petroleum use; the 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 from 2000 levels by 2020.

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.

2.1.2 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.

2.1.3 CalHEAT Technology Roadmap Summary

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 or engine and driveline efficiency. CalHEAT collaborated in the development of this roadmap with the State's Air Resources Board, Energy Commission, and Air Quality Management Districts; the U.S. Department of Energy and 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 58 percent from 3.6 billion gallons per year in 2012 to 1.5 billion gallons per year in 2050, or more than 2 billion gallons per year, compared to Business as Usual. Nitrous oxide emissions are projected to decrease by 73 percent from 249,000 metric tons/year in 2012 to 66,000 metric tons/year by 2050.

2.2 Introduction and Summary

2.2.1 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 percent of California greenhouse gas (GHG) emissions and consume 20 percent of the total fuel used in California trucking fleets[1]. GHG from medium- and heavy-duty trucks increased by 77 percent from 1990-2006, a growth rate three times greater than that of light-duty vehicles during that period. The California Energy Commission predicts a 42 percent increase in the use of diesel fuel, a primary fuel for medium- and heavy-duty vehicles, by 2030[2]. 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 percent in 2007 to 20.7 percent in 2030.[3]

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

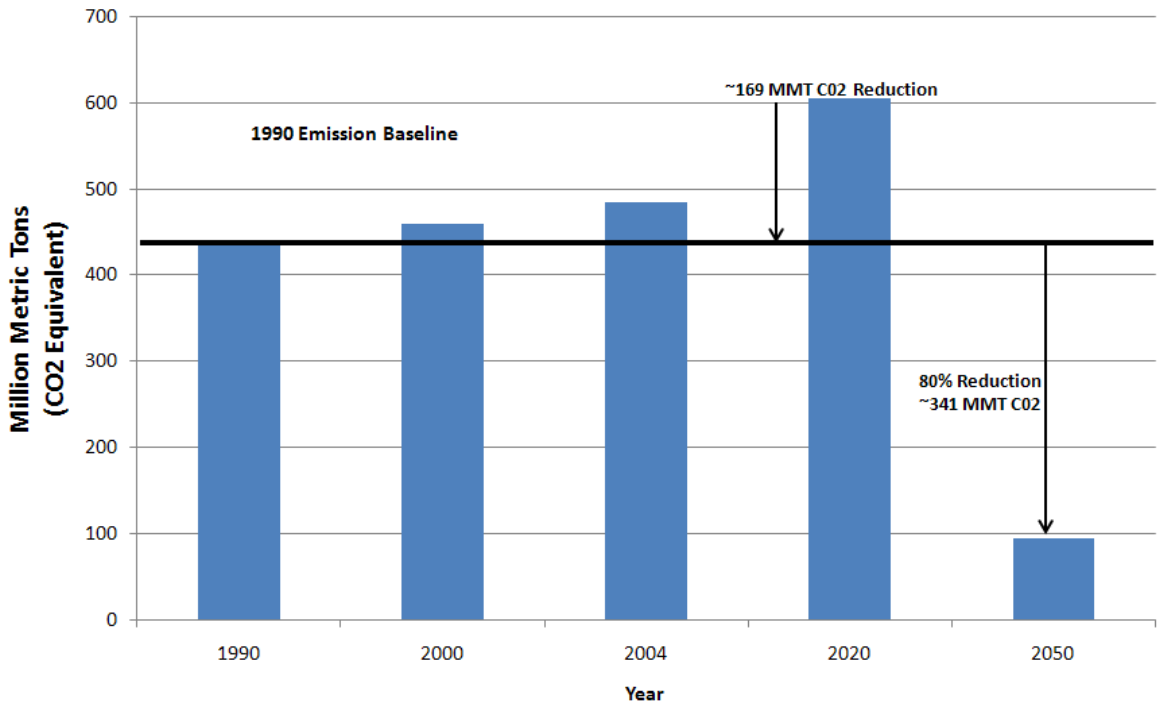
[2] http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf

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

2.2.1.1 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 2-1, page 2-4. The regulations require a nearly 30 percent reduction of emissions from the projected 2020 levels if no changes occurred, referred to as "Business as Usual," and a reduction of 15 percent from 2009 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 percent 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 2-1, page 2-4.

Figure 2-1: 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.

Source: California Air Resources Board Climate Change Scoping Plan

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

Table 2-1: 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.

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

2.2.1.2 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 percent by 2012, 11 percent by 2017, and 26 percent 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 percent of on-road transportation fuel use by 2020 and 30 percent by 2030[6].

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[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.

- Statewide truck and bus regulations, established to reduce emissions of diesel particulate matter, oxides of nitrogen 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 from 2000 levels[8] by 2020.

Executive Order (EO) B-16-2012 establishes the goal of reducing CO_2 equivalent emissions from the transportation sector in 2050 to 80 percent 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.

2.2.1.3 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 two NHTSA regulations are likely to be implemented as early as 2019, 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, 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 percent by 2030.[14] Much

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[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

[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

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 use 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 percent versus 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 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 linehaul 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 2-1, page **Error! Bookmark not defined.**. 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 Energy Commission 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 the three-year program was 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 and Environmental Protection Agency; and nationally-recognized medium- and heavy-duty truck associations, manufacturers, and experts.

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

2.2.2 California Energy Commission 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 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.

2.2.2.1 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_2 equivalent emission reductions from trucks are mandated by AB 32 and California EO B-16-2012, shown in Table 2-2, 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, approximately one-tenth of the projection under a business-as-usual scenario.

Table 2-2: 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]

[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

California's legislative target, under AB 2076, is to reduce petroleum use by 15 percent from 2003 levels by 2020. Additionally, AB 1007 establishes goals for alternative fuel penetration rates of 9 percent by 2012, 11 percent by 2017, and 26 percent by 2022. AB 2076 also includes recommendations to increase use of alternative fuels for on-road transportation fuel use by 20 percent by 2020 and 30 percent 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.

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.
- 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.

2.2.3 State of the Industry by CalHEAT Classification

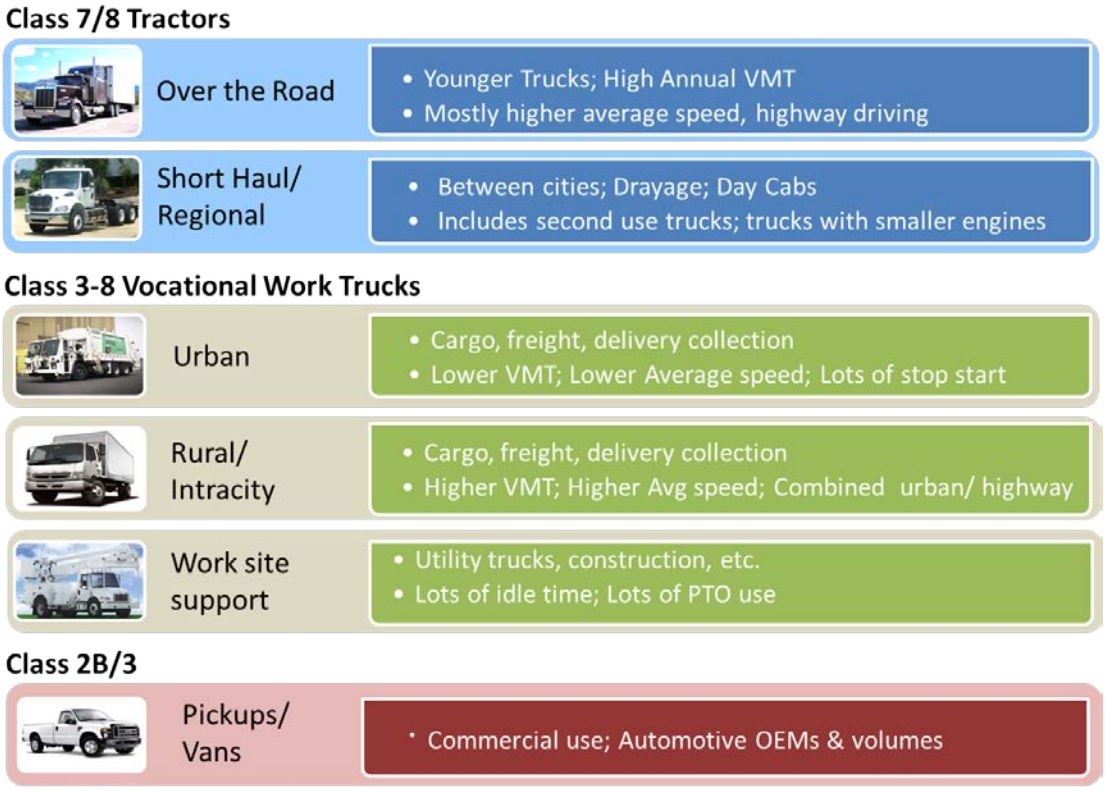
As the first step in the development of this roadmap, CalHEAT performed the California Truck Inventory Study[18] to better understand the various types of trucks used in California, their relative populations, and how they are used. As the State looks to technologies with the ability to reduce petroleum 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

[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

2B and above, via the Polk database.[19] The vehicle classes included in the inventory are shown in Figure 2-2 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.

Figure 2-2: Six Truck Categories Based on Technology Applicability



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

Source: 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.

[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.

Table 2-3, below, shows the 2010 California truck population by application and the contribution to CO_2 equivalent (CO_2e) emissions both in $MMTCO_2e$ per year and on a percentage basis. Figure 2-3, 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 2-4.

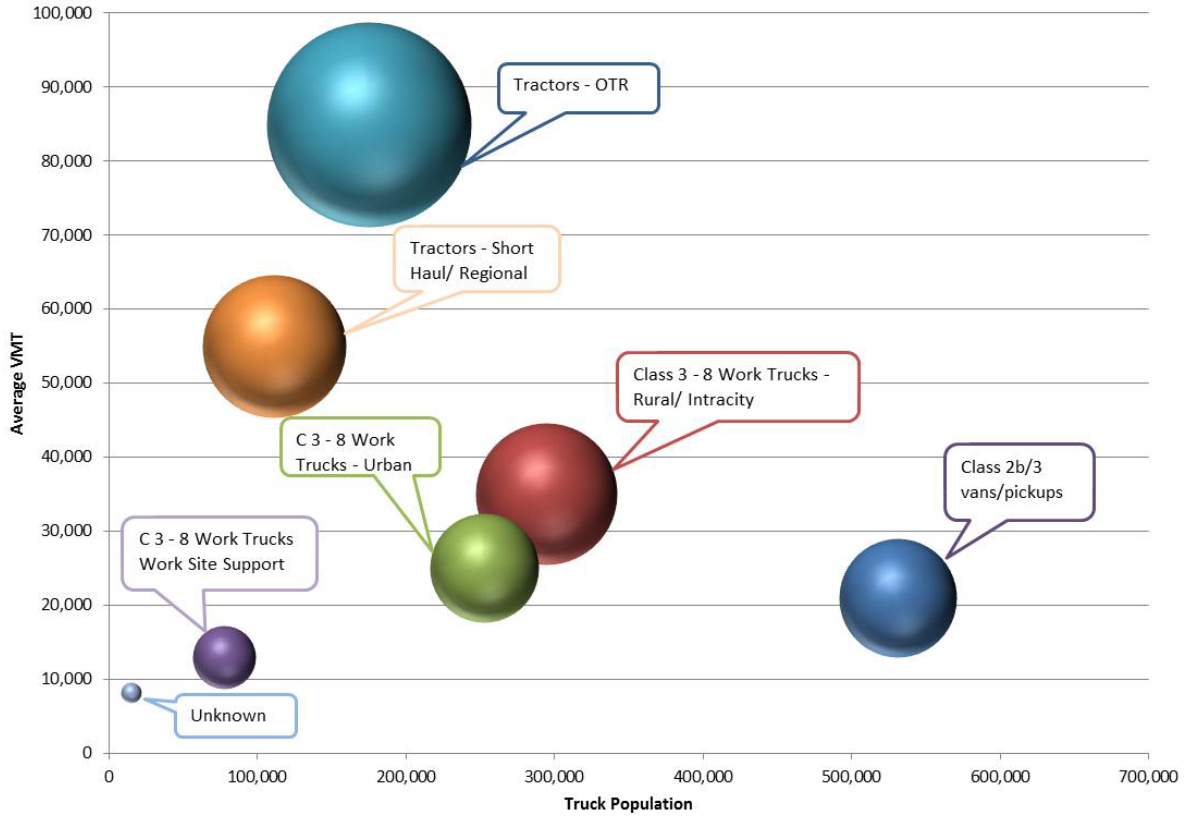
Table 2-3: Truck Categories, 2010 Populations and CO_2e Emissions

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.

Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

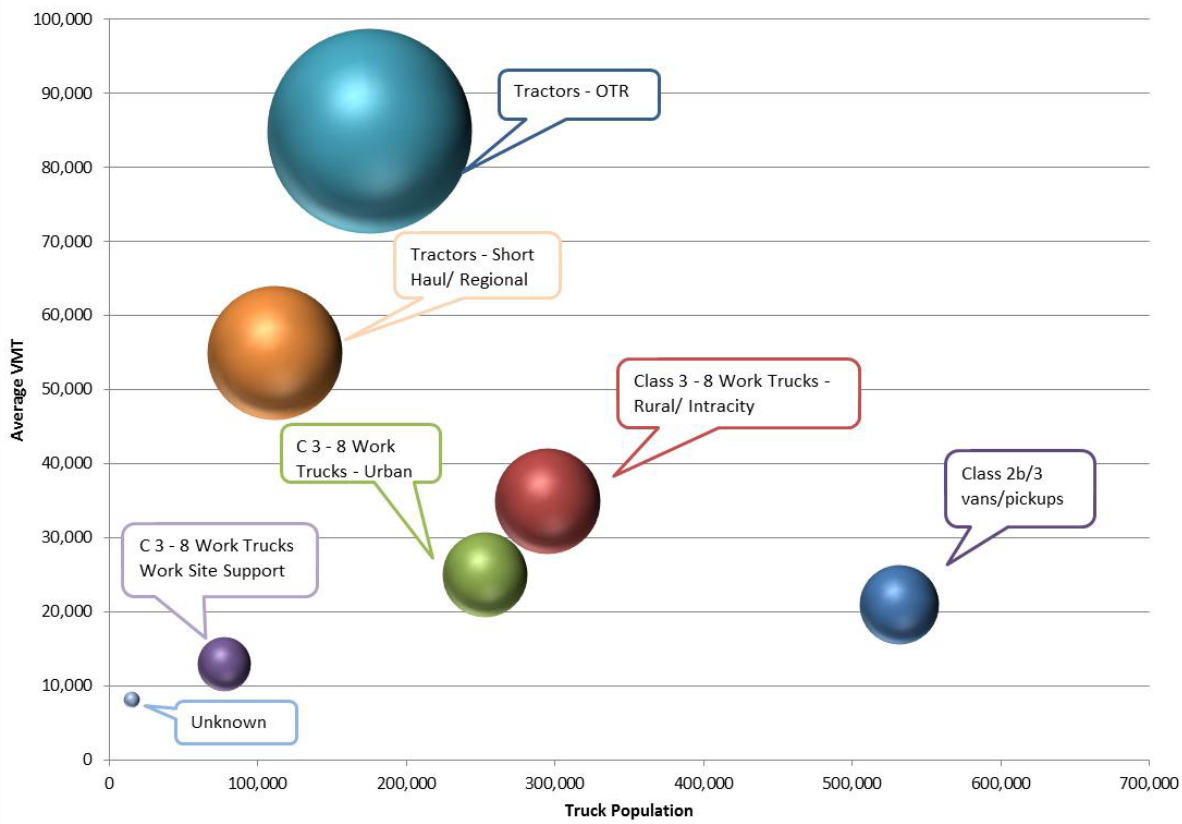
Figure 2-3: Truck CO_2e, Average Vehicle Miles Traveled and Population by Truck Category



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.

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

Figure 2-4: 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.

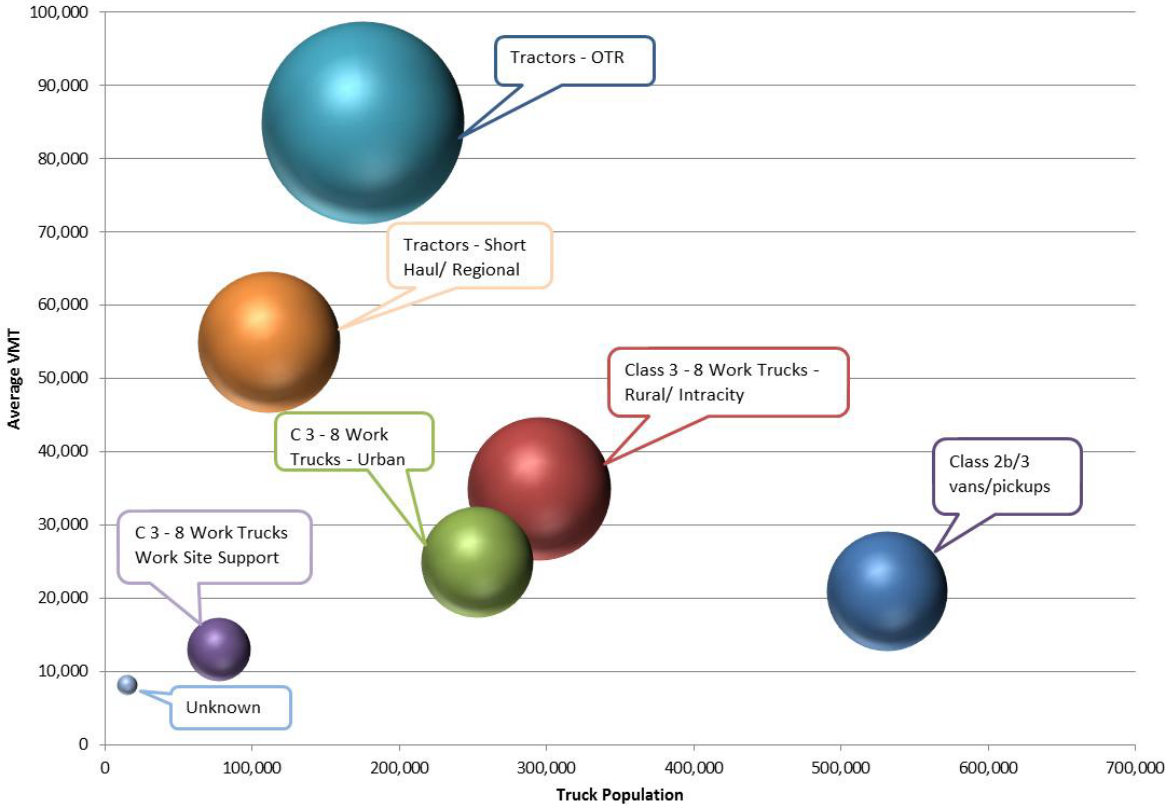
Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

2.2.3.1 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 -- there are more gasoline vehicles by total number. However, because the heaviest trucks use the most fuel, and are nearly 100 percent diesel, total diesel fuel use is higher for medium- and heavy-duty vehicles. As one moves up the weight classes, the percentage of vehicles goes from being primarily gas-powered on the light-duty end to nearly 100 percent diesel in the heaviest Class 8 segment.

The Energy Commission reports approximately 15 billion gallons of gasoline used in California 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 percent annually during the same period In 2010, trucks accounted for 20 percent of the petroleum fuels (gasoline and diesel combined) used in California, or a total of approximately 3.5 billion gallons, of which 60 percent was diesel.

Figure 2-5: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

2.2.4 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 medium- and heavy-duty vehicles. The seven 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 Section 2.3, with supporting information on the actions shown in Appendix 2B. 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.

2.2.4.1 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

2.2.4.2 Investment

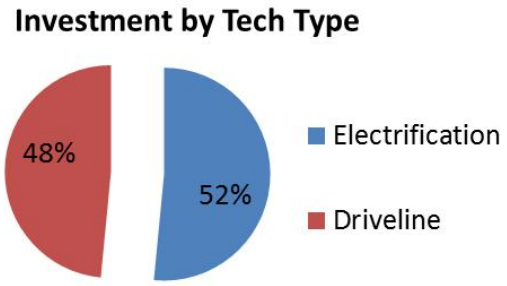
The projected investment required for the 66 action items included in this Roadmap between 2013 and 2020 totals $287,800,000. Investment for the major categories of "Engine and Driveline" and "Electrification", is shown in Figure 2-6, for two three-year periods from 2013-2016 and 2017-2020. Grouped by action, 47 percent of the projected investment needed to achieve the emission and efficiency targets would be in development and demonstrations, and 53 percent would be in deployments and incentives. By strategy, electrification-related actions comprise 52 percent of the projected investment, while 48 percent would be for engine and driveline improvements. "Chassis, Body, and Roadway Systems" improvements have not been

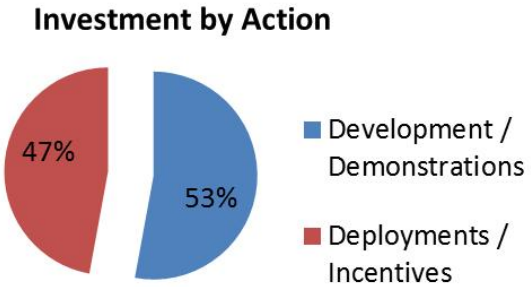
included in this roadmap, in the investments shown, or as part of the 66 action items because many advances in these areas are already underway by truck manufacturers.

Further detail showing projected investment required by specific strategy to achieve the 66 action items is shown in Figure 2-7 and Table 2-4.

Figure 2-6: Investment in Actions, 2013-2020

	2013 to 2016	2017-2020	Totals
Electrification	$74,800,000	$73,500,000	$148,300,000
Driveline	$73,000,000	$66,500,000	$139,500,000
Total	**$147,800,000**	**$140,000,000**	**$287,800,000**

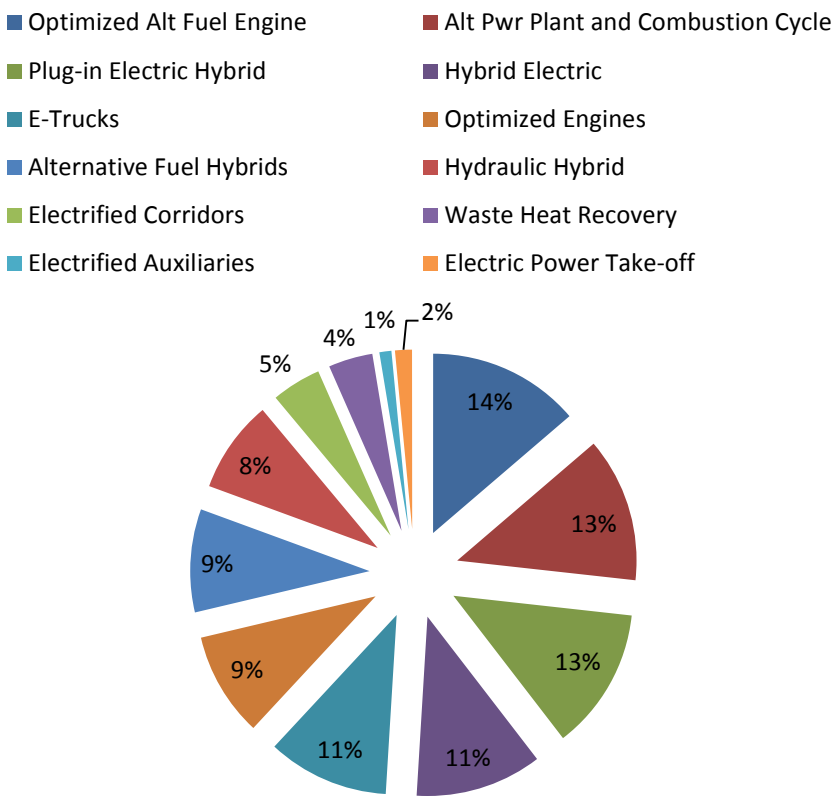




Projected investment by 2020 needed to address the 66 action items identified in the CalHEAT Roadmap.

Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

Figure 2-7: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

Table 2-4: Investment Portfolio by Strategy, in Millions

Technology	$ Million	Percentage
Optimized Alternative Fuel Engines	$39.5	14%
Alternative Power Plants and Combustion Cycles	$37.5	13%
Plug-in Electric Hybrid	$36.8	13%
Hybrid Electric	$32.8	11%
E-Trucks	$31.5	11%
Optimized Engines	$27.0	9%
Alternative Fuel Hybrids	$26.8	9%
Hydraulic Hybrid	$24.0	8%
Electrified Corridor	$12.8	4%
Waste Heat Recovery	$11.5	4%
Electrified Auxiliaries	$3.1	1%
Electric Power Take-off	$4.4	1%
Total	$287.8	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.

Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

2.2.4.3 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 2-5 summarizes feasibility of the 13 technology strategies by CalHEAT truck category. 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 2-5: 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

Source: 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 and Figure 2-14, Technology Adoption all Truck Categories.

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

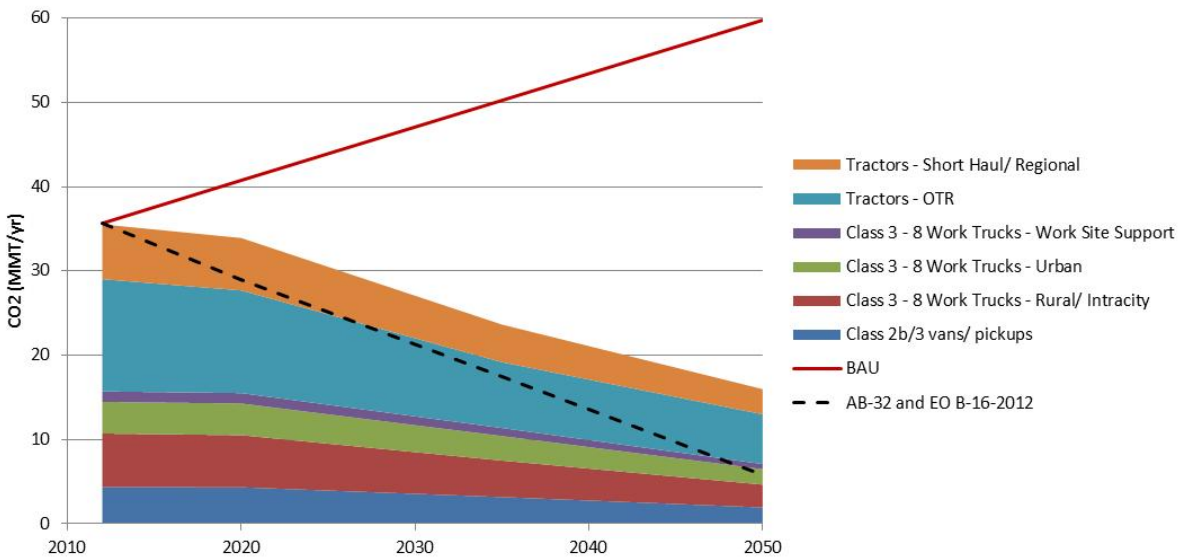
Corridors and Platooning

	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, and a reduction of over 40 $MMTCO_2e$ could be achieved by 2050. Figure 2-8 shows the impact of these implemented strategies by vehicle category compared to the "Business as Usual" projection. 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 percent 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 2-8: CO_2e Reduction from Roadmap



The combined impact of the 66 Actions included in the CalHEAT Roadmap as projected to reduce CO_2 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.

Source: 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 2-9. 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 percent 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 percent by 2020 that is expected to be achieved by blending biodiesel with petroleum-based diesel. The model assumes an increase to 20 percent biodiesel by 2035. These assumptions were developed in part in 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.

[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

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 targets established in 2006 by AB 32, with 30 percent renewable sources of energy for power generation by 2020. The fuel curves in the roadmap also assume an increase to 95 percent 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 continuing through 2050. The roadmap model assumes that 33 percent of hydrogen will be from solar-generated electrolysis or renewable natural gas through 2035. After 2035, the curve of hydrogen follows that used for electricity. For additional information on assumptions used and how the roadmap model was developed, please see Appendix 2A.

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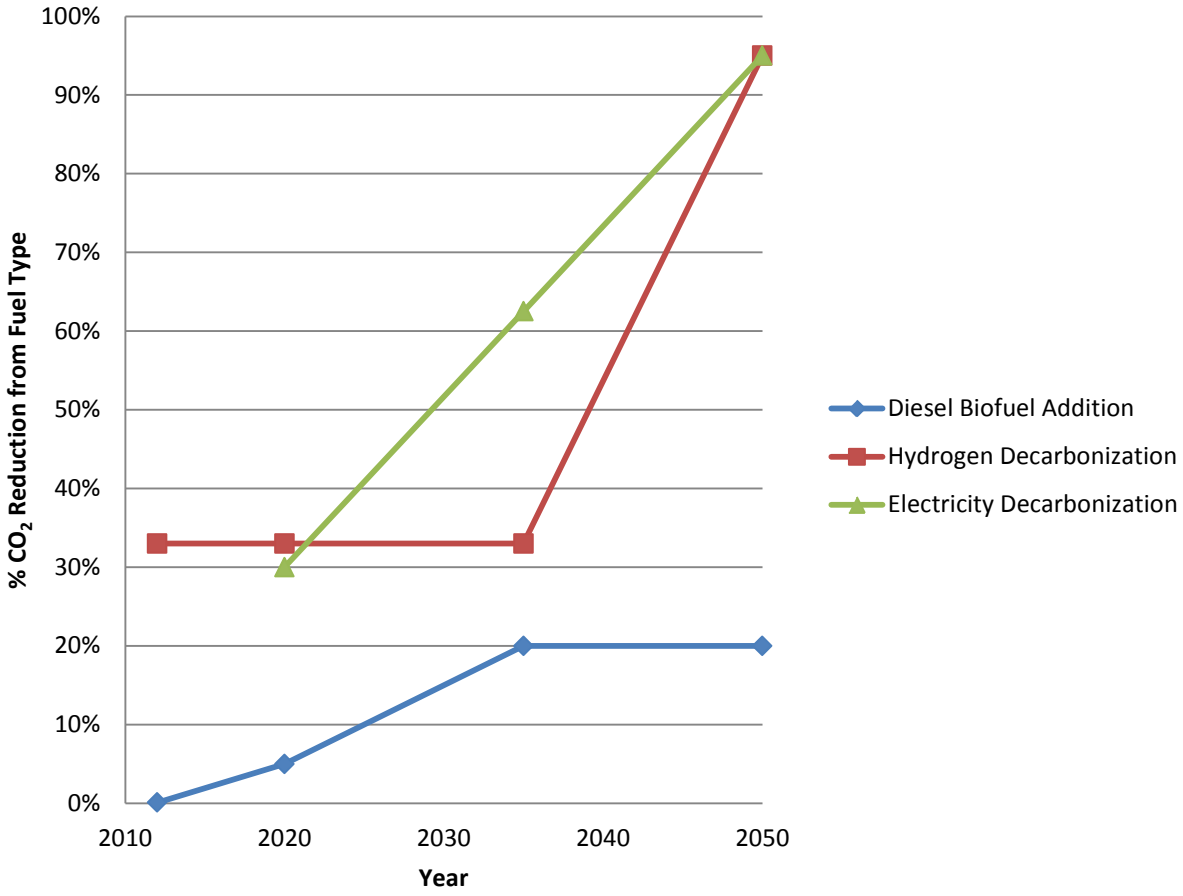
[21] Williams, James H.; DeBenedictis, Andrew; Ghanadan, Rebecca; Mahone, Amber; Moore, Jack, Morrow, William R., III; Price, Snuller; and Torn, Margaret S. 2011. ***The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity.*** *Science,* April 20, 2012.

Figure 2-9: Fuel-related CO_2 Reduction Assumptions



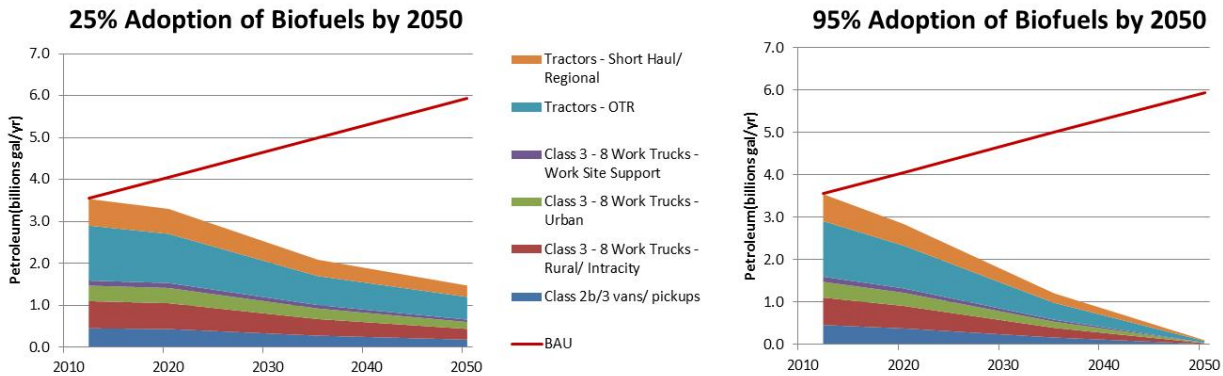
Increased use of biofuels and decarbonization achieved by using renewable energy sources will contribute to the CO_2e reductions projected by the CalHEAT Roadmap. Significant reductions can be achieved through electricity decarbonization, by using clean or renewable energy sources for electric power,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

Source: California Hybrid, Efficient and Advanced Truck Research calculations

The roadmap projections for CO_2equivelent (CO_2e) emissions and petroleum use are based in part on biofuel adoption, assuming a moderate adoption rate of 25 percent 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 2-10. Compared to 2012 levels, this would result in a 6.9 percent reduction in petroleum use by trucks in California by 2020, a 41 percent reduction by 2035, and a 58 percent 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 emissions can be achieved.

Figure 2-10: Impact of Biofuel Adoption on Petroleum Reduction shows reduction curves for petroleum of 25 percent adoption by 2050 on the left and 95 percent 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 percent reduction in petroleum use by 2020, a 66 percent reduction by 2035, and a 97 percent reduction by 2050, compared to 2012 levels.

Figure 2-10: Impact of Biofuel Adoption on Petroleum Reduction



The CalHEAT Roadmap assumes a 25 percent 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.

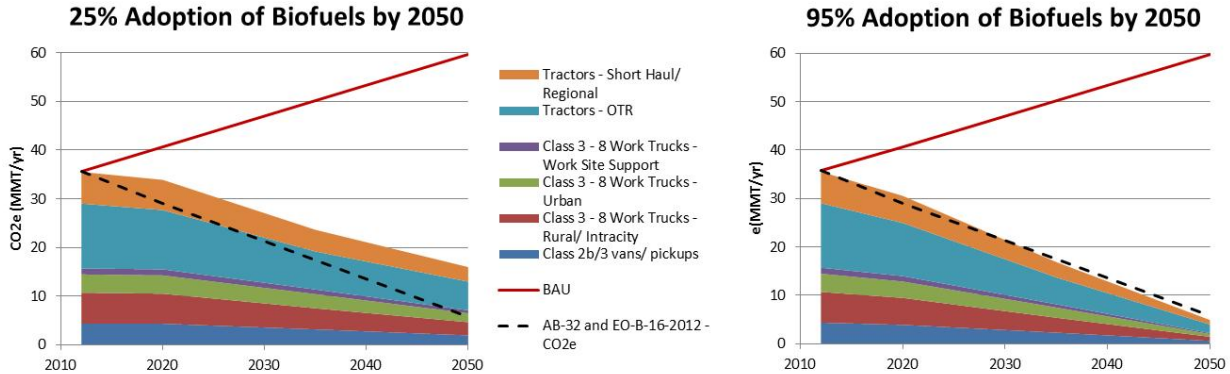
Source: California Hybrid, Efficient and Advanced Truck Center calculations

Impact of Biofuel Adoption on CO_2e Reduction

The impact on CO_2e emissions due to a transition to biofuels is shown in Figure 2-11. The chart on the left shows the curves used for the projections in this roadmap, using a 25 percent 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 percent by 2020, 33 percent by 2035, and 55 percent 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 2-11, which is based on a 95 percent 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 percent reduction of CO_2e in 2050.

Figure 2-11: Biofuel Related Impact on CO_2e Reduction



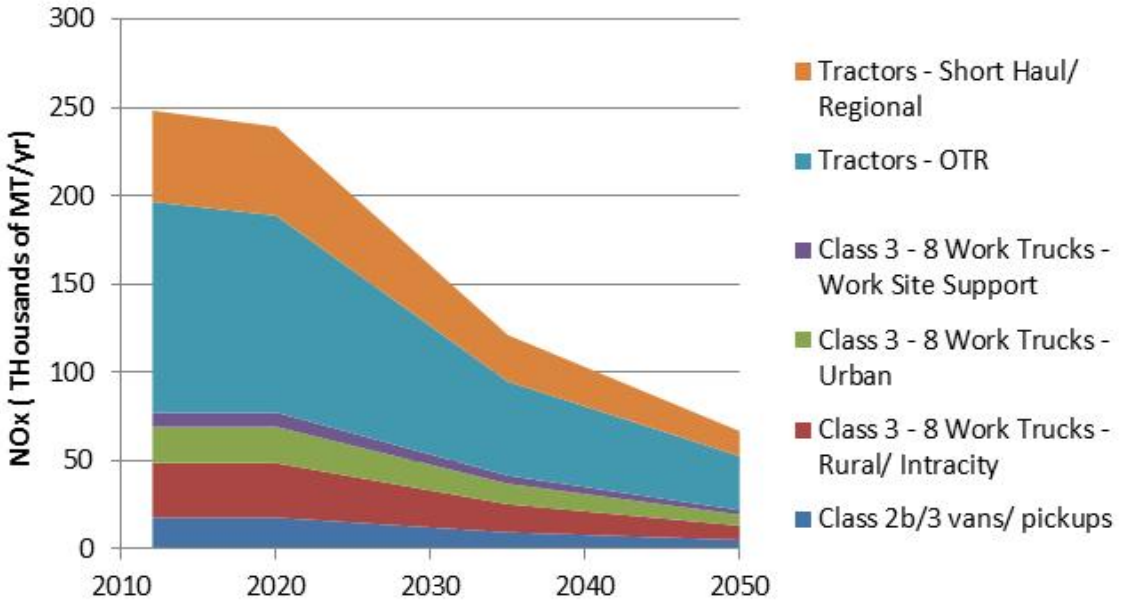
The CalHEAT Roadmap assumes a 25% adoption rate for biofuels by 2050, which would result in a reduction of CO_2e from 36MMT/year in 2012 to 16MMT/year in 2050, as shown in the chart on the left. A higher rate of adoption of biofuel can further reduce CO_2e, as shown in the example on the right, which assumes a 95 percent adoption rate by 2050. At a 95 percent 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.

Source: 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 2-12. On a percentage basis, the reductions are 4 percent by 2020, 51 percent by 2035 and 73 percent 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 2-12: Projected NOx Reductions



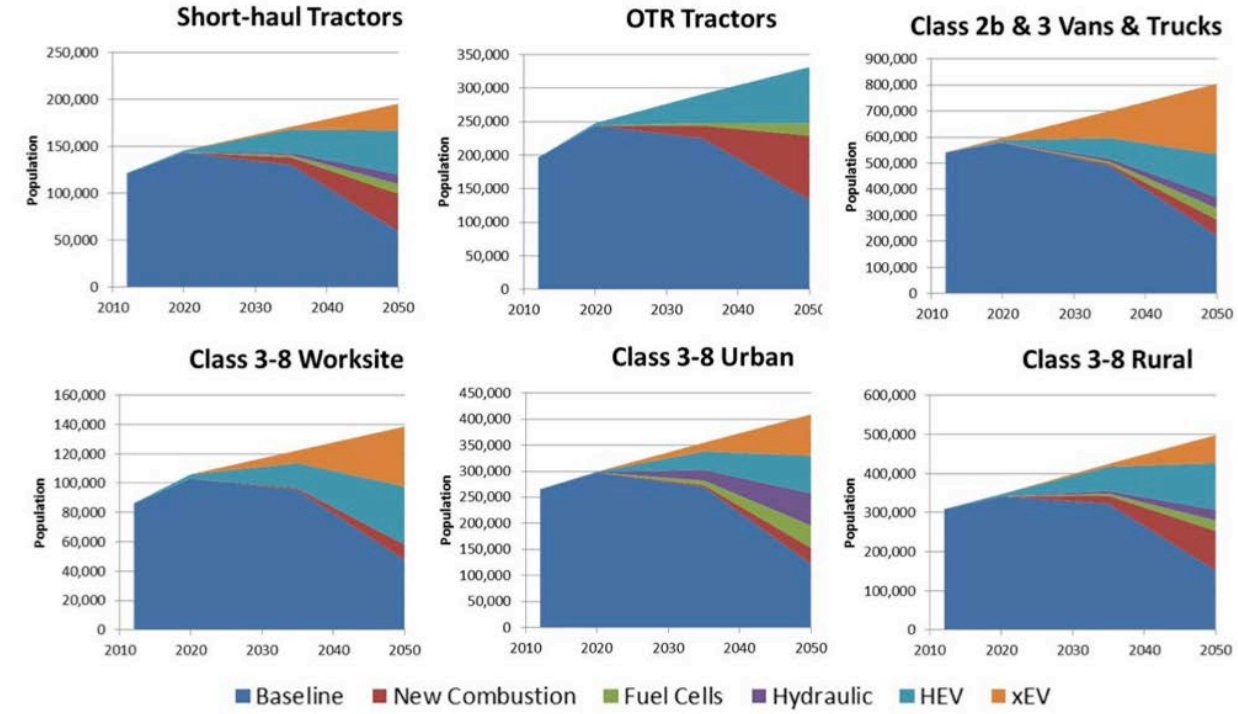
CalHEAT Roadmap projections result in a reduction of NOx, a greenhouse gas that is a precursor to ozone, from 249,000 metric tons per year in 2012 to 67,000 metric tons per year in 2050. The highest reductions will result from short-haul/regional and over-the-road tractors.

Source: California Hybrid, Efficient and Advanced Truck Center calculations

2.2.4.4 Technology Adoption

Projected timelines for technology adoption and the impact by number of vehicles is shown in Figure 2-13 by CalHEAT truck category and in Figure 2-14 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 2-14.

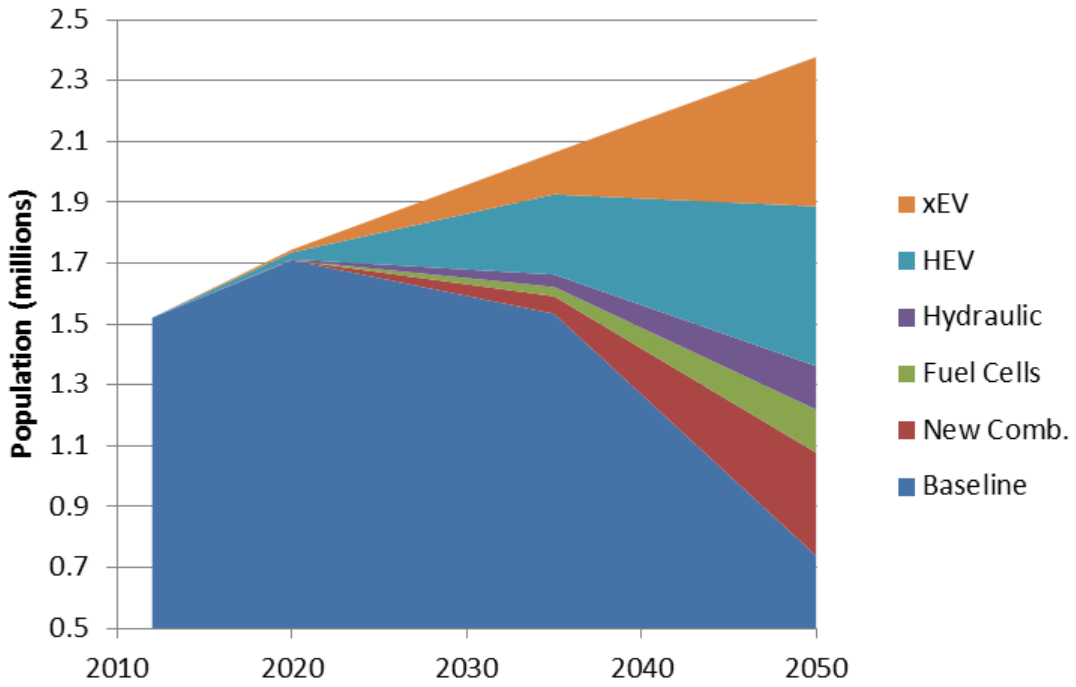
Figure 2 13: Technology Adoption by Truck Category



Projected adoption of CalHEAT roadmap action items by technology group and truck category, shown by number of vehicles affected from 2010 through 2050.

Source: California Hybrid, Efficient and Advanced Truck Research

Figure 2-14: 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

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3 Technology Solutions and Action Roadmaps

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

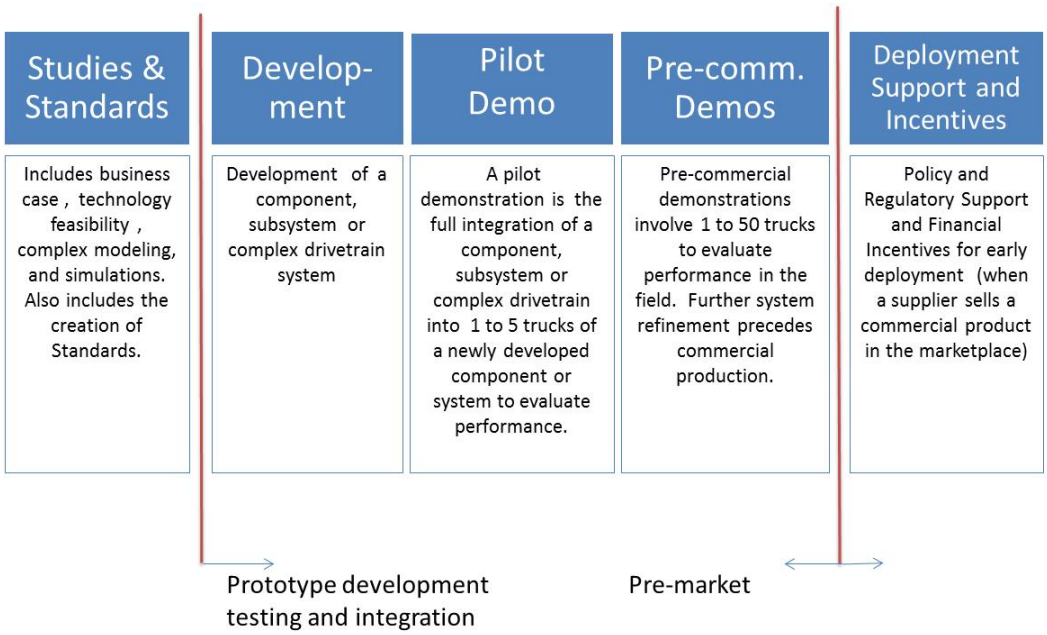
From these pathways, 13 technology strategies were selected as those most likely to provide achievable opportunities to reduce petroleum use and carbon emissions, and increase efficiency. They are shown in shown in Figure 2-17, Summary Roadmap Timelines. Actionable steps with milestones and timelines for technology research, development, demonstration and market introduction were identified for each of the strategies. The overall roadmap includes 66 action items, covering the 13 technology strategies. Each of these technology strategies is addressed in a separate section, beginning with Section 2.3.2, Hybrid Electric..

2.3.1 Introduction to the Roadmap

The CalHEAT roadmap uses five types of actions to accelerate the development and commercialization of technology solutions, detailed in Figure 2 15. "Studies and Standards"

covers 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 provides regulatory or financial support to encourage adoption.

Figure 2-15: CalHEAT Technology Actions

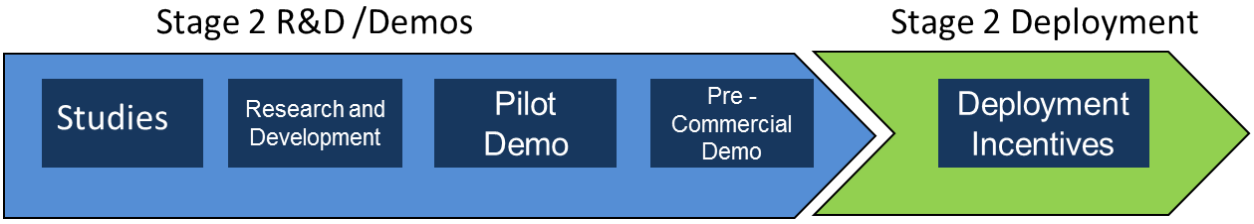


CalHEAT uses five types of actions to accelerate technology solutions in the market.

Source: 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 2-16, 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 2-16: Summary Timeline

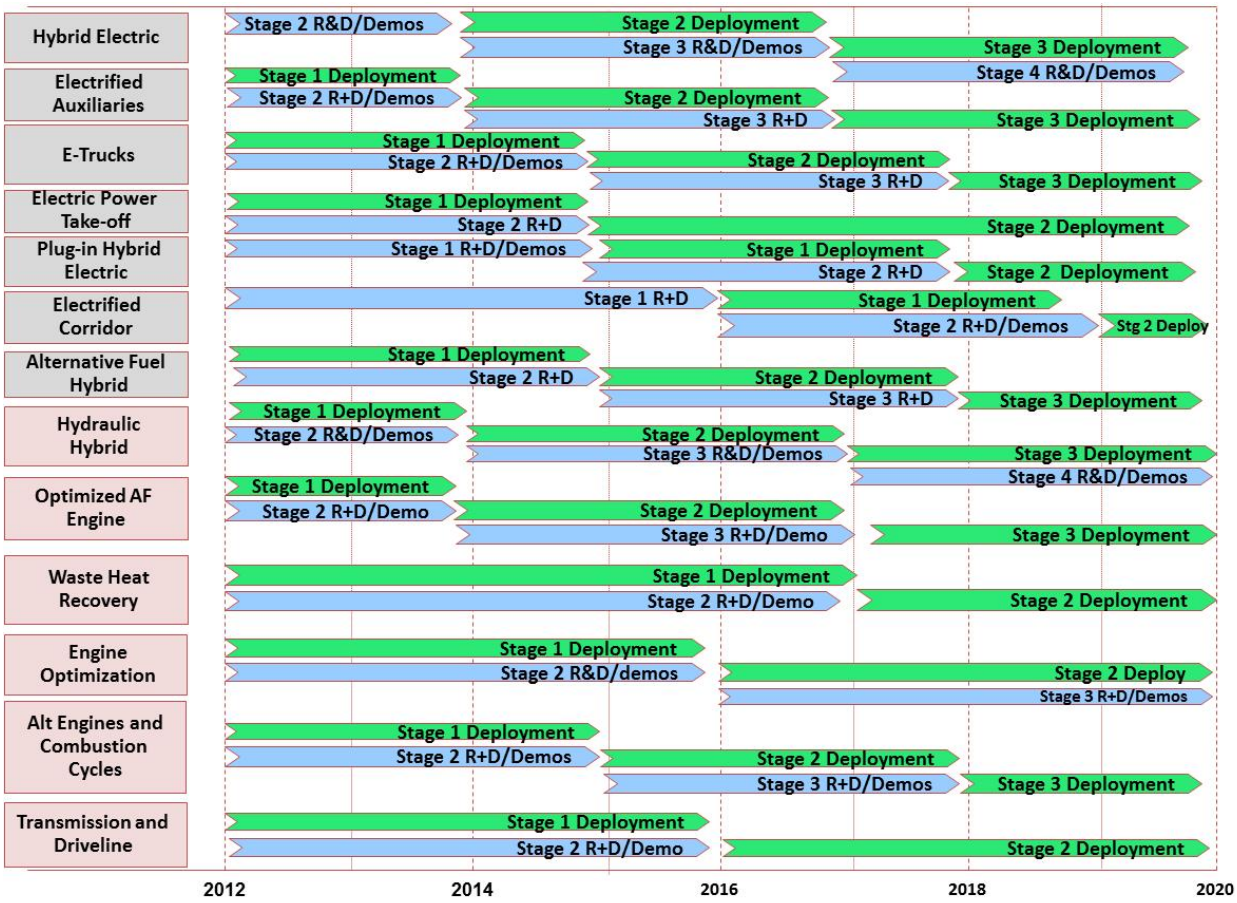


Summary timelines are used in the summary Roadmap timelines and in the 13 technology and action roadmaps that group goals and actions by technology strategy to show the development stages, actions and the period of time projected for each.

Source: California Hybrid, Efficient and Advanced Truck Research Center

An overall summary timeline for the development stages of the roadmap, by technology strategy, is shown in Figure 2-17, 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 2-18.

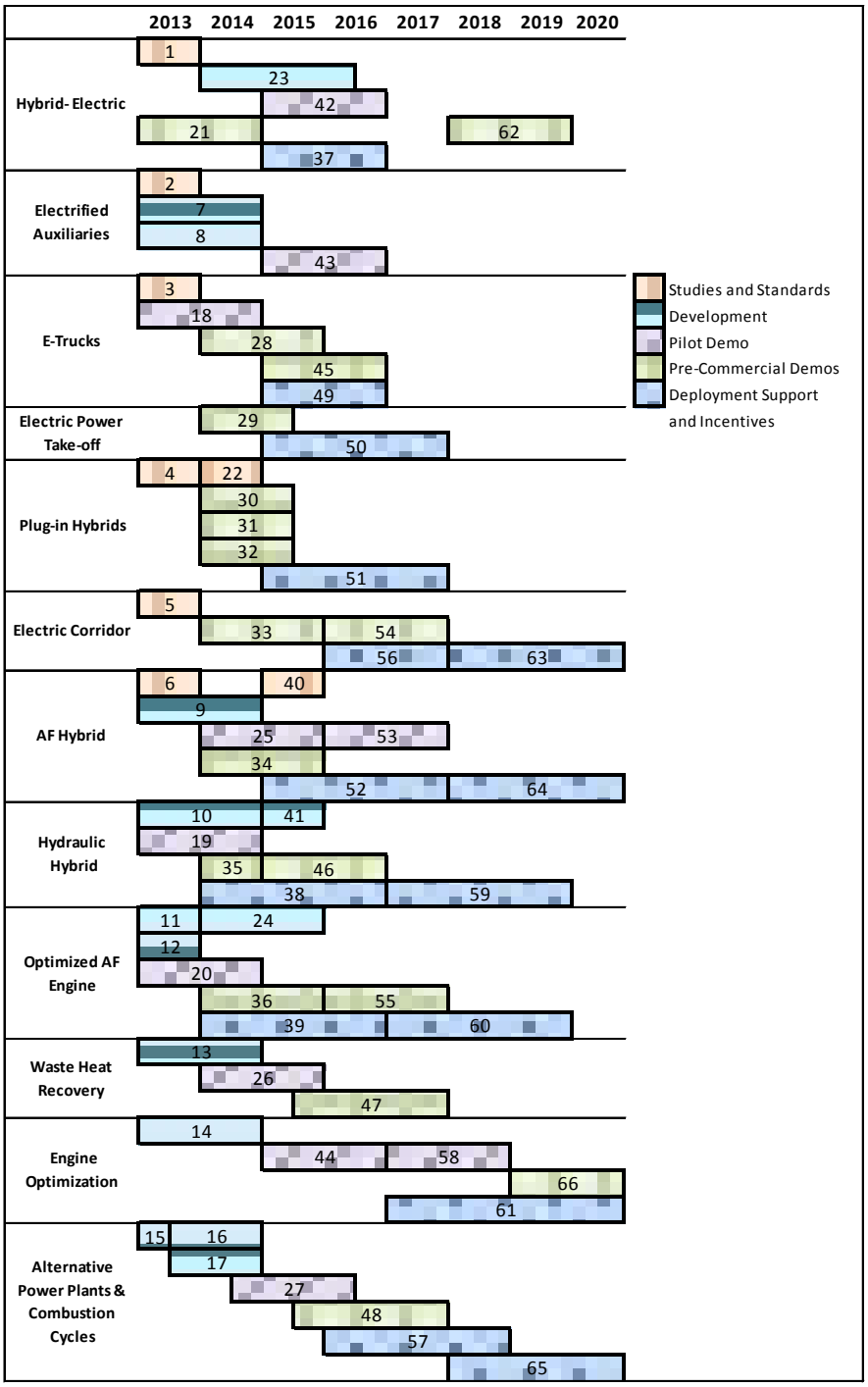
Figure 2-17: Summary Timeline for CalHEAT Roadmap Technology Strategies



Here is the summary roadmap timeline for the 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 percent by 2050 from 2012 compared to "Business as Usual."

Source: California Hybrid, Efficient and Advanced Truck Research Center

Figure 2-18: 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 1, Appendix 2B, for a numerical list, timeline and description.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.2 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 return on investment (ROI) are summarized in four technology/action stages in Figure 2-19, below. The technology improvements for each stage, described in the upper series of boxes, can be achieved through the corresponding actions shown below them.

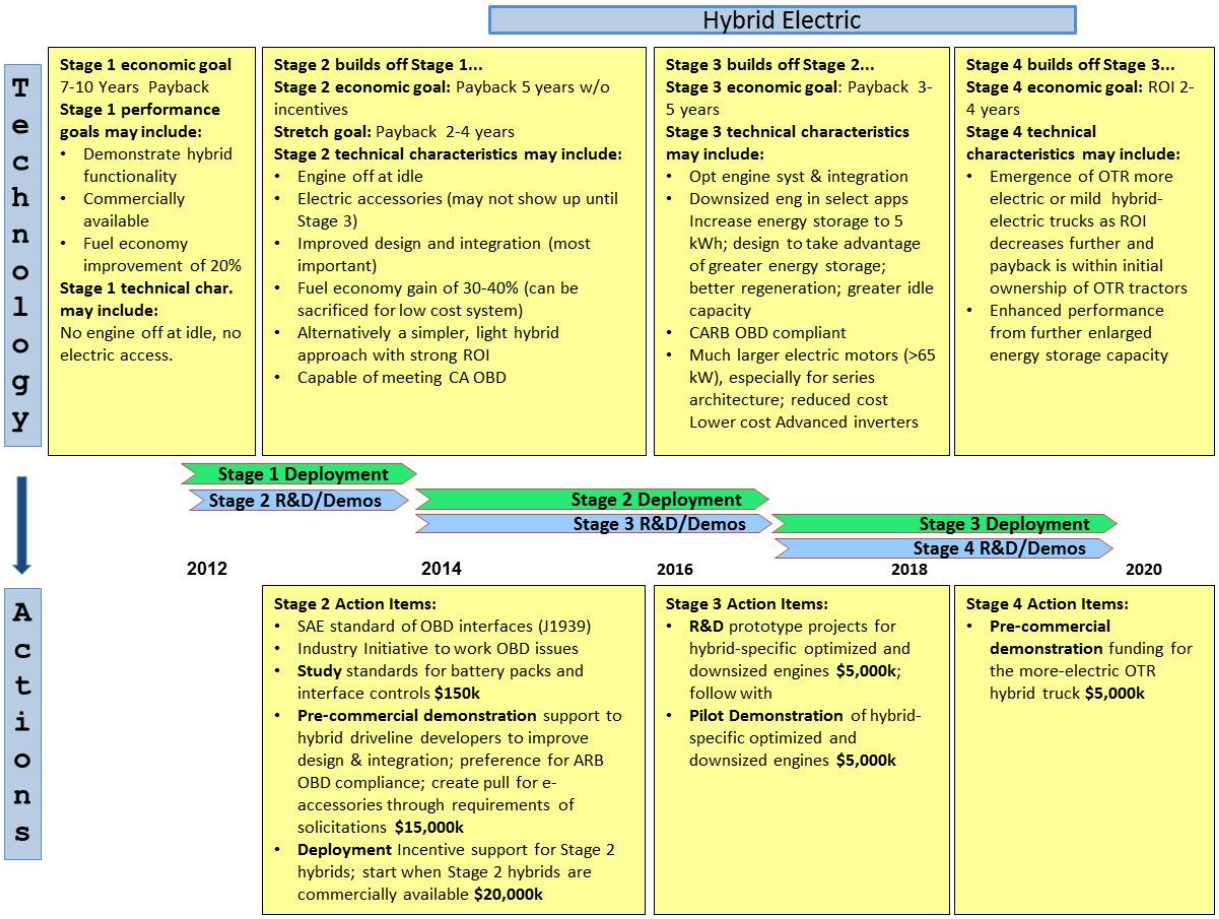
Over the four stages shown in the roadmap, the ultimate goal will be to achieve a two-to-four year ROI. To accomplish this, the strategy will be an evolution of improved levels of system and chassis integration complemented by improvements in energy storage costs and performance.

Characteristics of hybrid trucks that were commercially available in 2012 are shown as Stage 1 technology. They provide a 20 percent 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 percent, and California 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 2-19: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.3 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 percent 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

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

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 and plug-in hybrid trucks; as is idle-off for hybrids; and the further electrification of Class 8 over-the-road tractors.

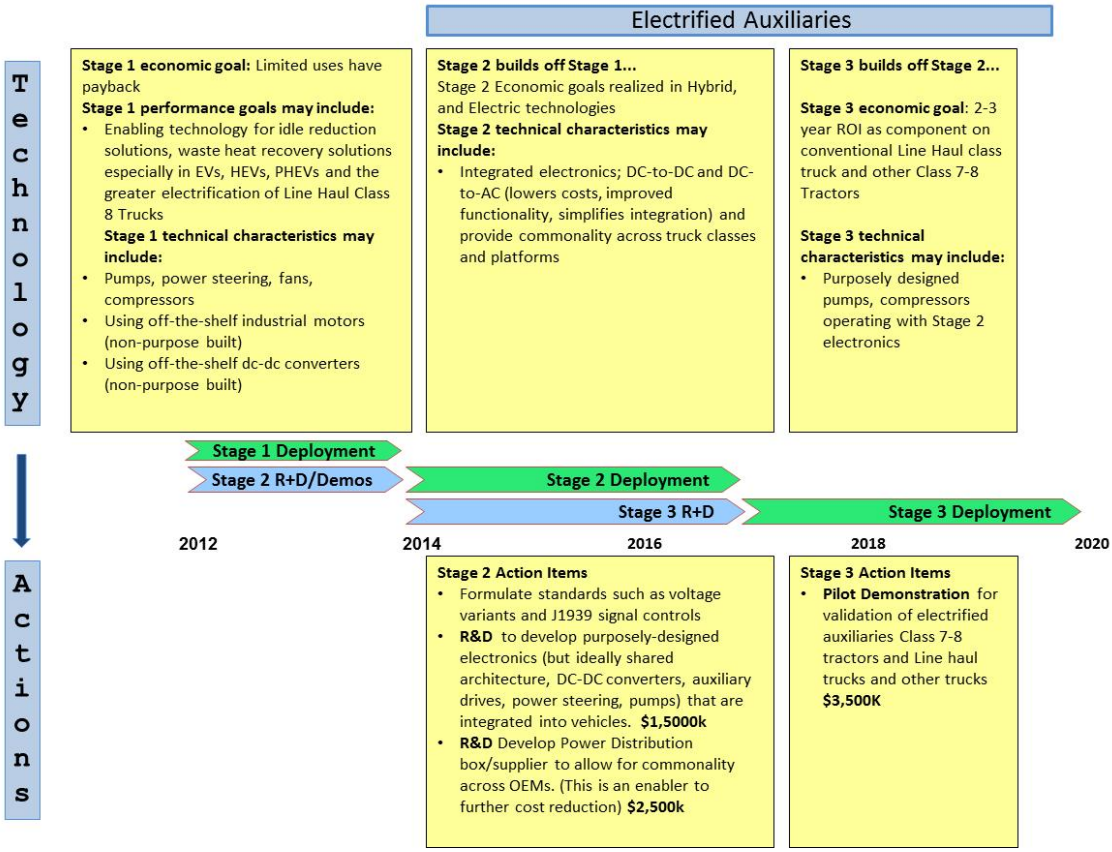
Electrifying of truck engine components is essential in many emerging truck systems because of the efficiency benefit that can be gained. This is true even on otherwise conventional powertrains but becomes especially important with hybrid powertrains and critical when considering the ability for a hybrid vehicle 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 2-20. Stage 1 development was already underway in 2012. The objective of converting auxiliary loads to electric power is to reduce the amount of fuel used by hybrid electric vehicle (HEV) or plug-in hybrid electric vehicle (PHEV) trucks in idle mode to power accessories. The Stage 1 electrified auxiliaries that were commercially available in 2012 are based on off-the-shelf industrial motors and DC-to-DC converters and typically include pumps, power steering, fans, and compressors.

Implemented from 2014 to 2017, Stage 2 targets are the 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 the non-standard voltages across vehicle platforms, so one roadmap action includes the development of standards for voltage variants and J1939 signal controls. Other actions include R&D into 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, from 2017-2020, includes two main goals: (1) to achieve purpose-designed pumps and compressors operating with Stage 2 electronics to improve efficiency and (2) to achieve a two-to-three-year ROI for components on conventional linehaul and other Class 7-8 tractors. Pilot demonstrations for validation of electrified auxiliaries in Class 7-8 tractors and linehaul trucks are projected for 2017 to 2019.

Figure 2-20: 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 linehaul trucks planned for Stage 3, 2018-2019.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.4 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 (EV). 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 this suggests 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 2-21 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. 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.

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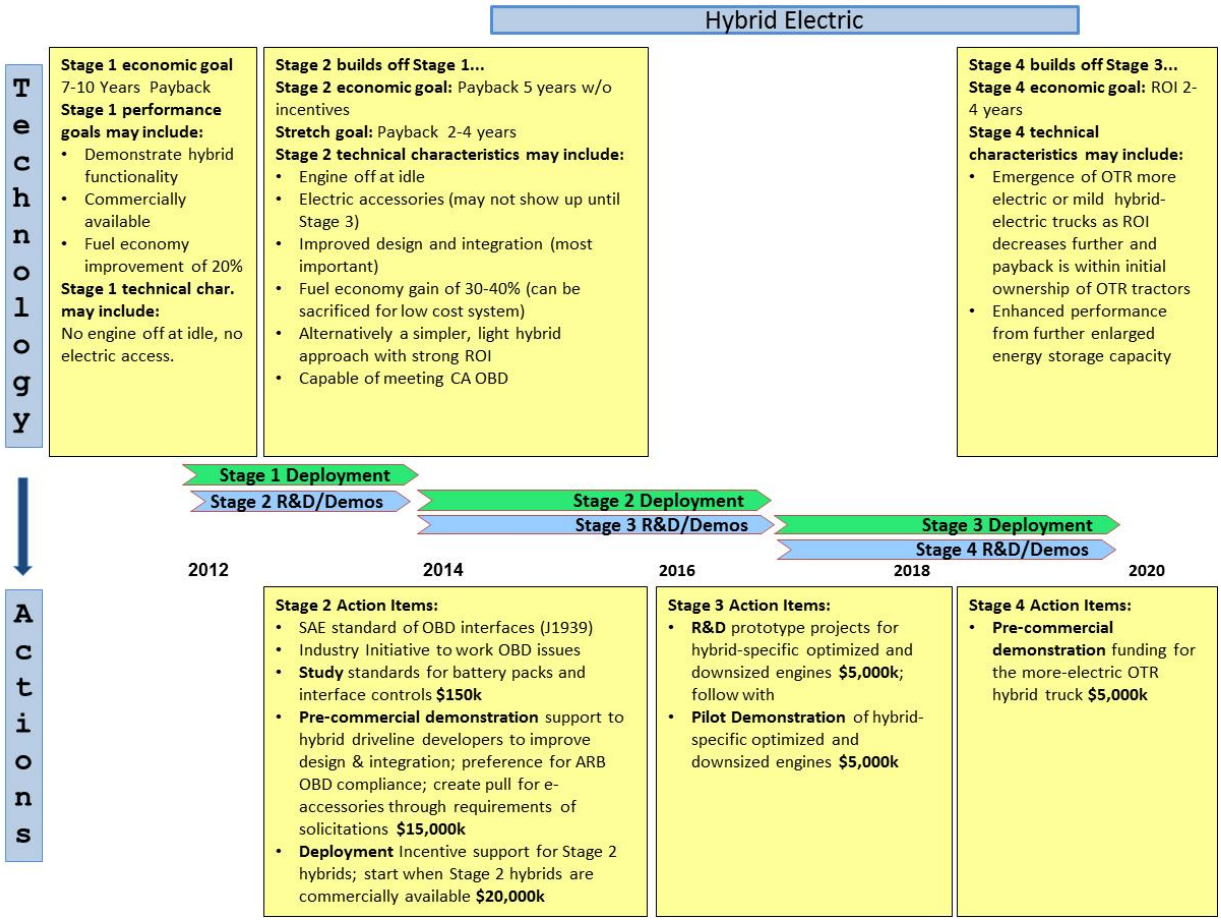
[23] California Energy Commission, ***2009 Integrated Energy Policy Report***, December 2009, http://www.energy.ca.gov/2009_energypolicy/index.html

Figure 2-21: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

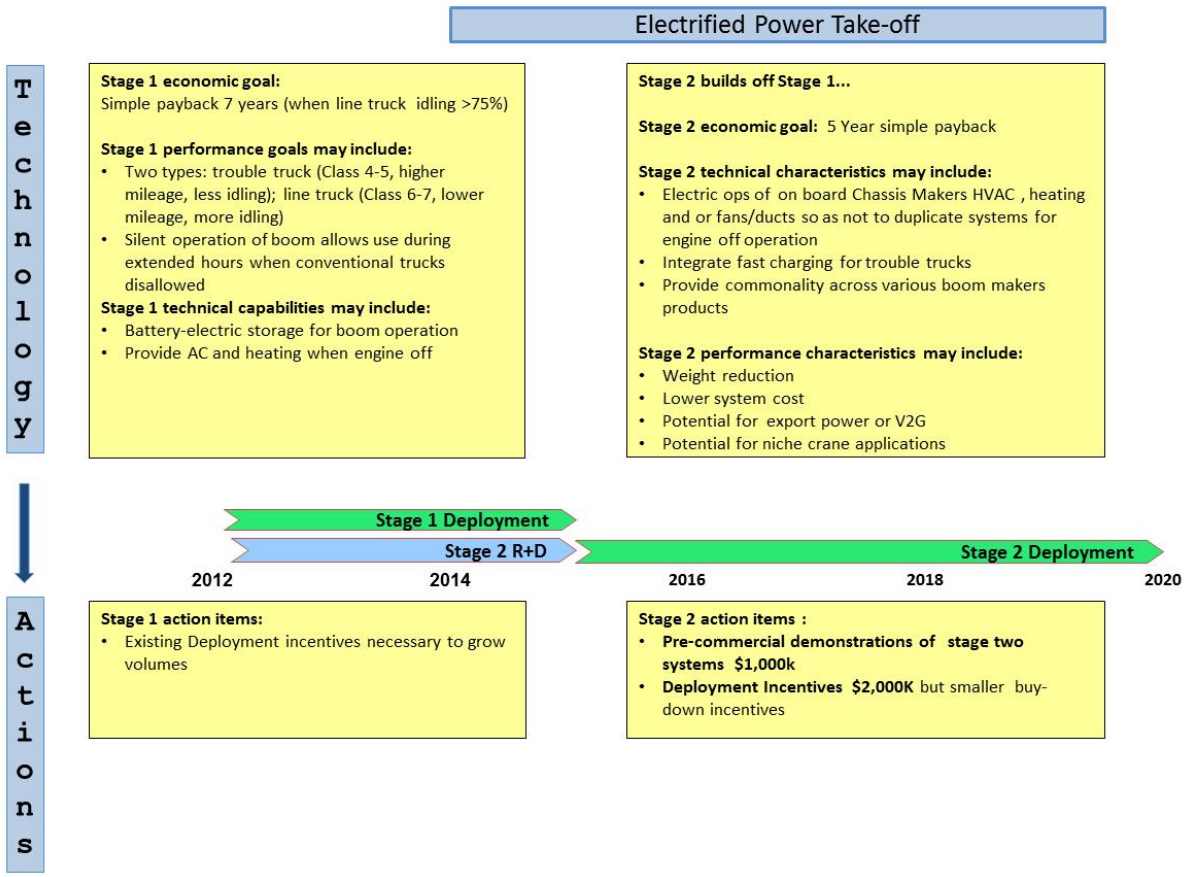
2.3.5 Electrified Power Take-off

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 2 22. 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 2-22: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.6 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 the capture of more braking energy and greater use of electricity to offset combustion fuels.

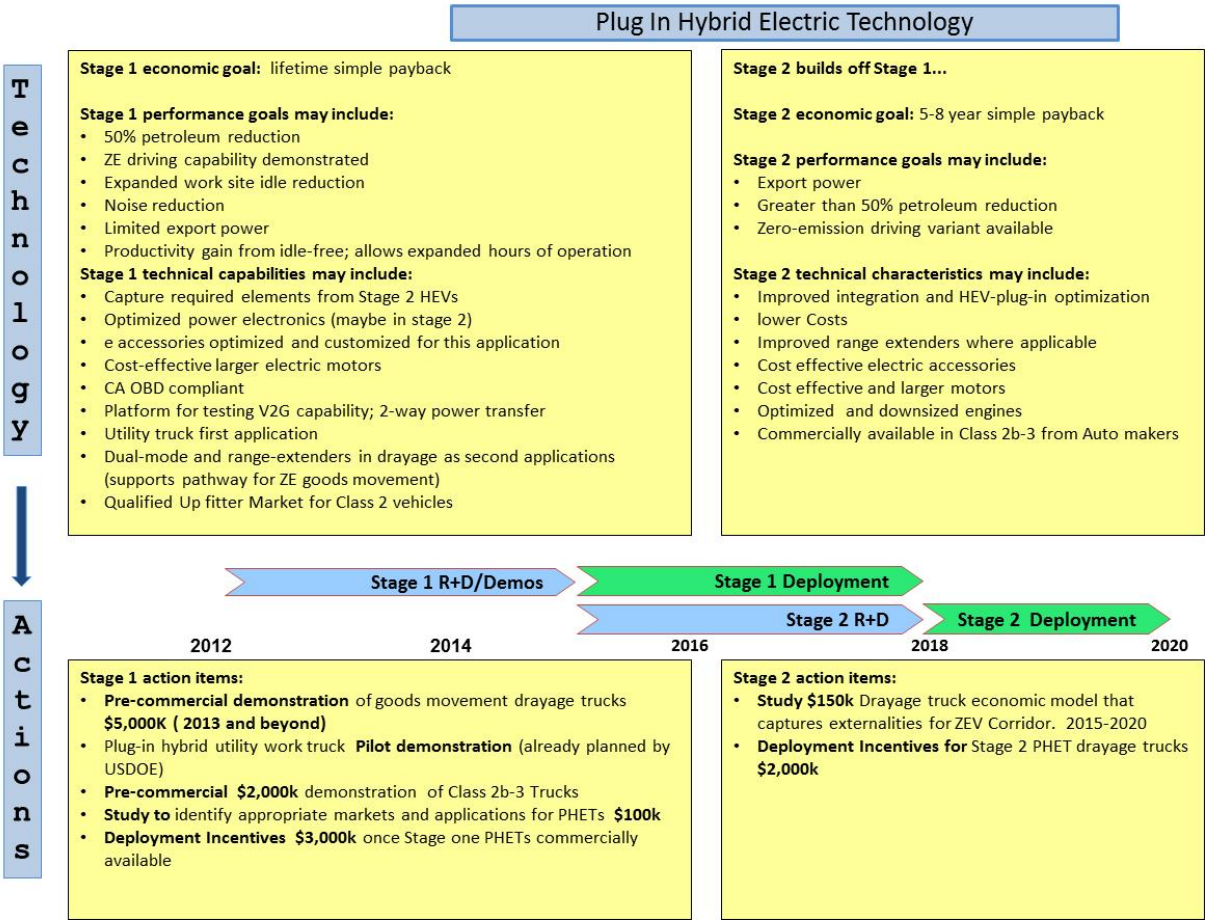
The CalHEAT roadmap identifies two stages for plug-in hybrid electric technology, as shown in Figure 2-23. The economic goal for Stage 1, from 2010 through 2015, is lifetime payback of the incremental cost of the vehicle, compared to a conventional truck, through reduced fuel costs. Stage 1 performance goals include a 50 percent 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 2-19: Hybrid Electric Technology and Action Roadmap, page 2-33. Additionally, larger, cost-effective motors, and California-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 percent 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 2-23: Plug-in Hybrid Technology and Action Roadmap



Plug-in electric hybrids have the potential to reduce petroleum use by 50 percent 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.7 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 engine power. Among the more advanced and complicated strategies to implement are dedicated truck corridors or lanes,

[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

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.

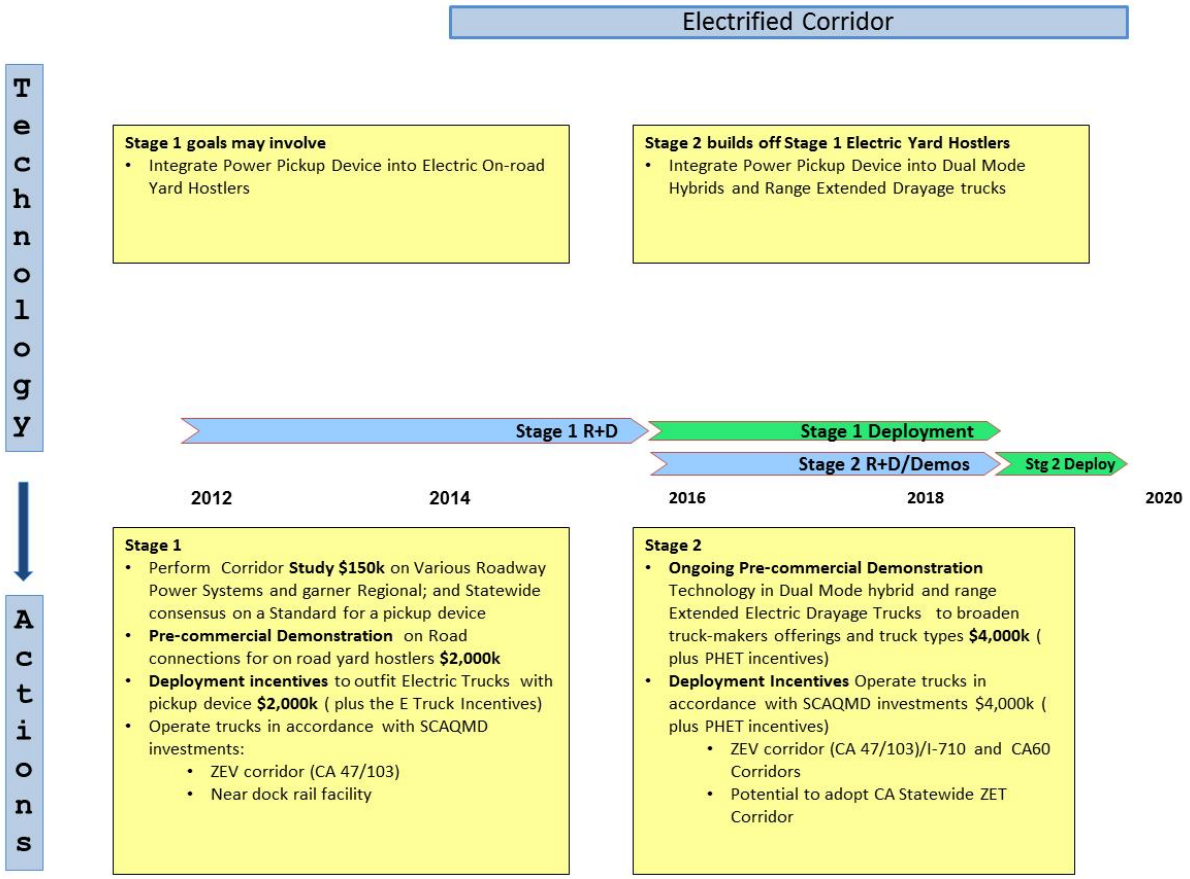
The *Roadmap for Electrified Corridors*, shown in Figure 2-24, identifies areas of development related to external electric power for power pickup devices in on-road yard hostlers and electrified corridors in Stage 1 and integration of a power pickup device into dual-mode hybrids and range-extended drayage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

Figure 2-24: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.8 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 percent 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].

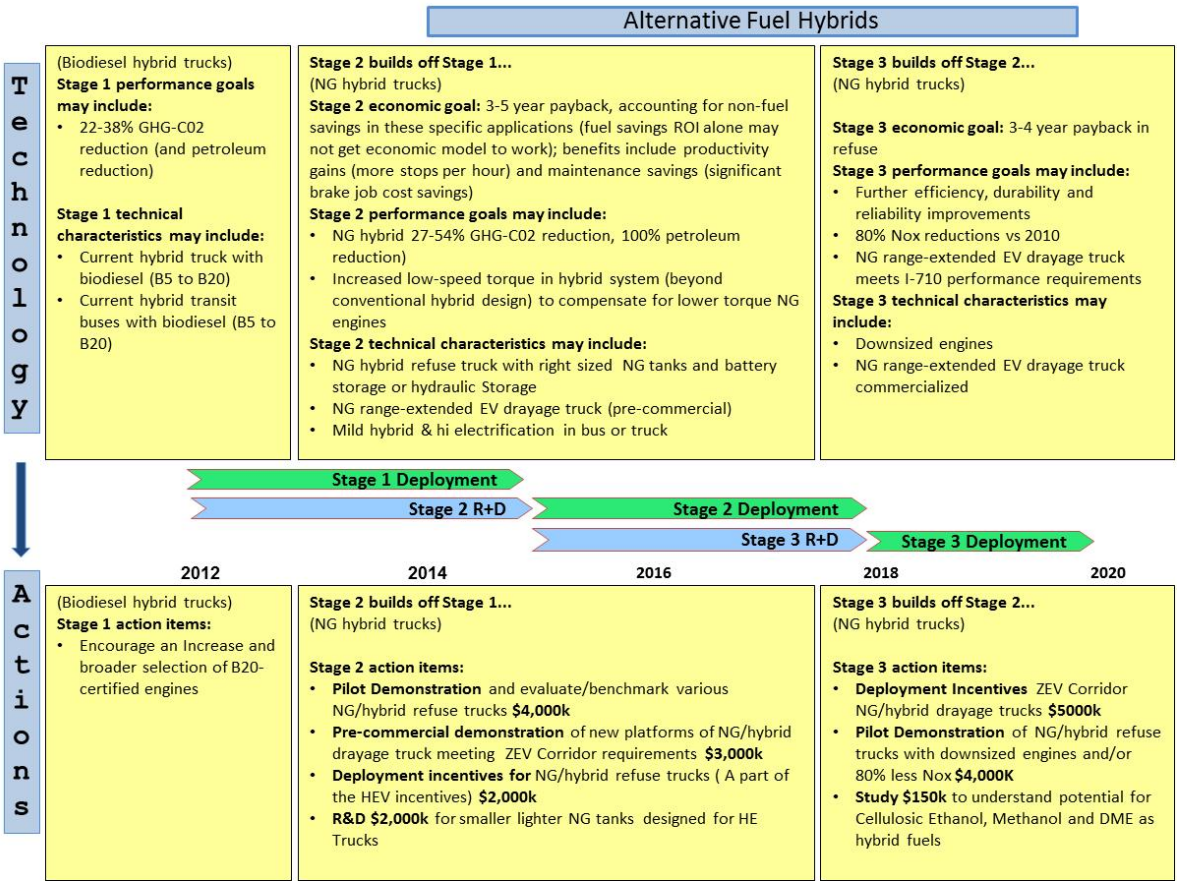
Three stages in the Roadmap have been defined for Alternative Fuel Hybrids, as shown in Figure2-25. Stage 1, 2012-2013, focuses on advances in B5 to B20 biodiesel hybrid trucks and buses (which use fuel containing 5 percent and 20 percent biodiesel, respectively) to achieve 22-38 percent CO_2e reduction, 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 percent reduction in CO_2, 100 percent 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 goals of further efficiency, durability and reliability improvements, an 80 percent 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).

[25] Dr. Lawrence Wnuk, CalHEAT, Barriers and Opportunities in Alternatively Fueled Hybrids.

Figure 2-25: 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, from 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.9 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 in the architecture. Series hybrids have drive wheels that are driven exclusively by the electric or hydraulic motor; the internal combustion

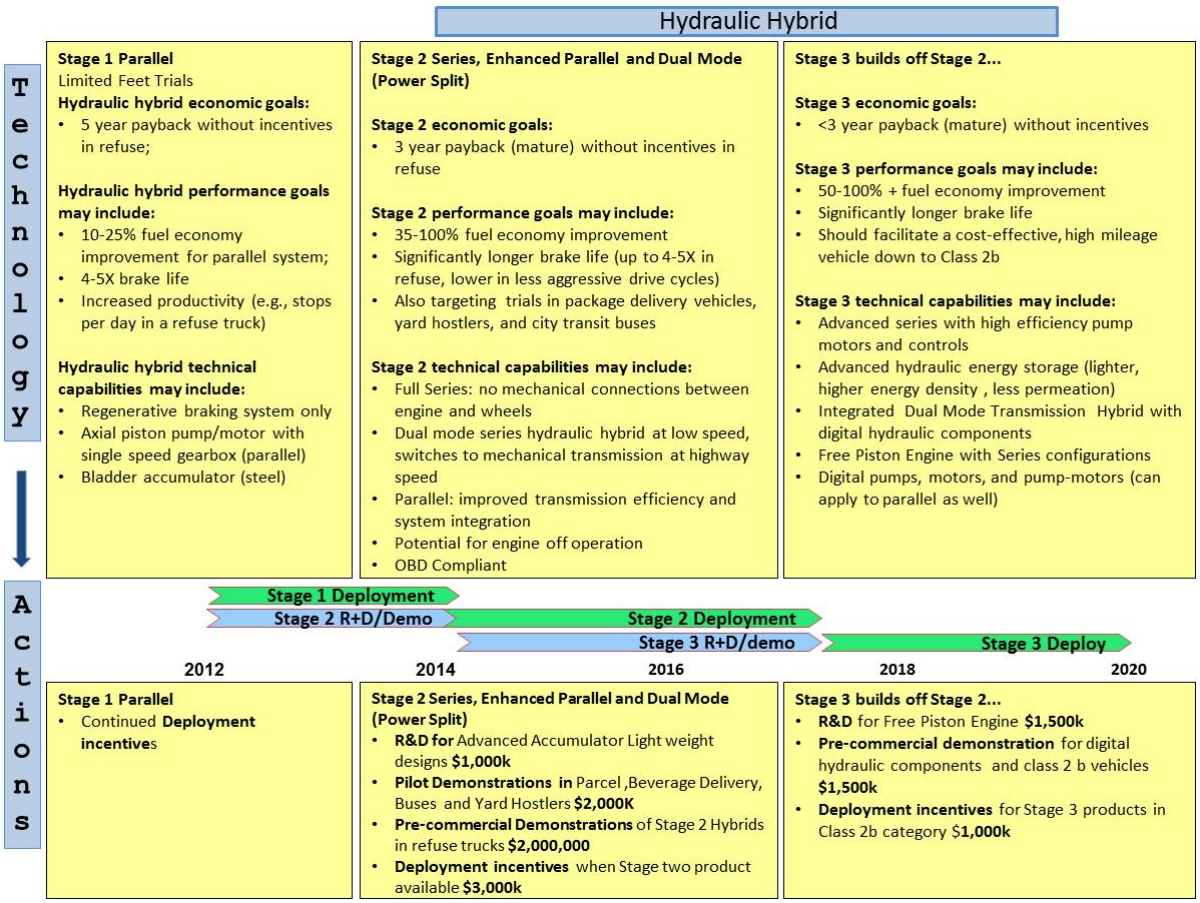
engine serves to keep the system charged but has no direct mechanical link to the drive wheels. In a parallel hybrid, both the electric (hydraulic) motor and the internal combustion engine are linked mechanically to the drive wheel, typically through a shared transmission. Power split, or series-parallel 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 percent electric/hydraulic power to 100 percent 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 2-26. 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 percent fuel reduction from parallel hybrid architectures have been demonstrated, along with a four to five times the 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 35-100 percent 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 percent 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 2-26: 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 percent in Stage 1 to 50-100 percent in Stage 3, and expand applications from primarily refuse trucks to multiple truck categories down to Class 2b by the end of the decade.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.10 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

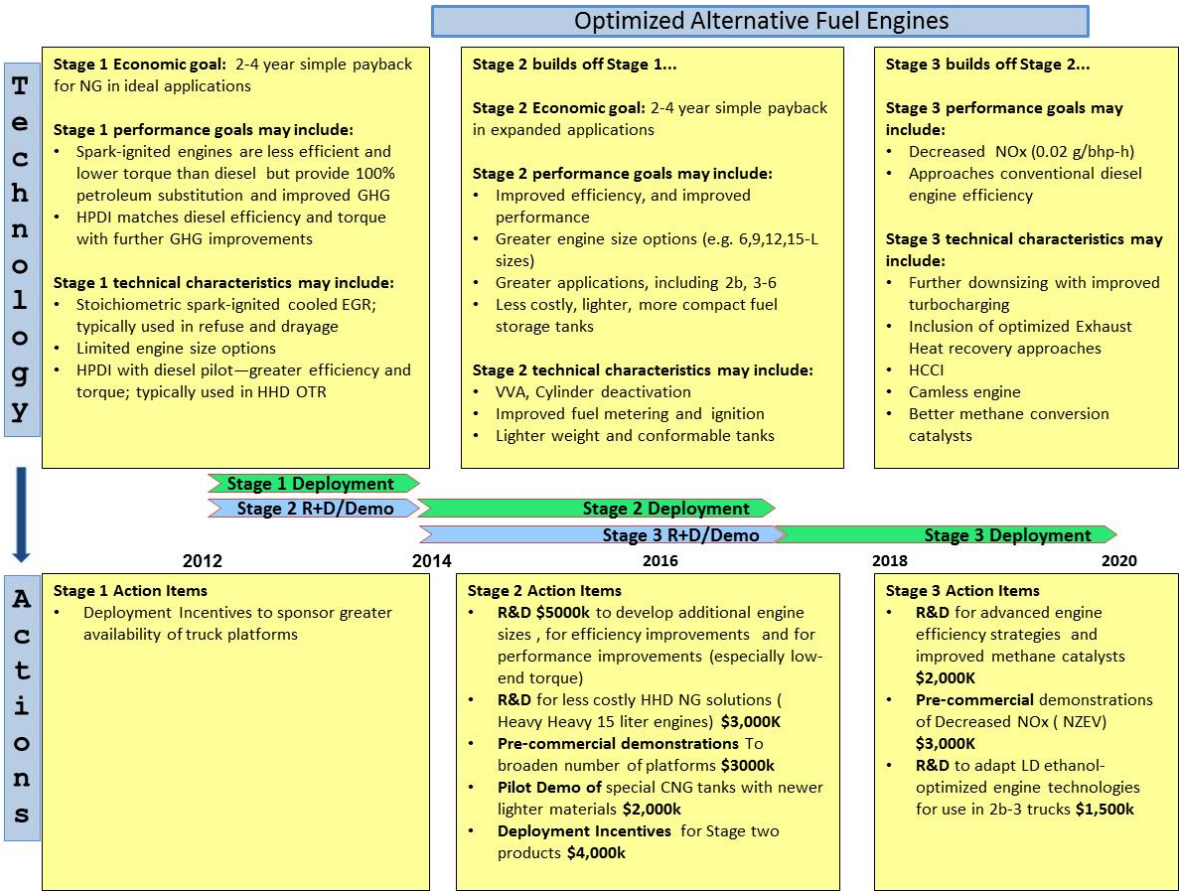
with good fuel consumption, but can be difficult to control across all engine loads and in transient operation. HCCI helps reduce both NOx and particulate matter (PM) emissions, although like other alternative combustion modes, it typically achieves lower thermal efficiency than conventional diesel combustion. 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 2-27, 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 percent 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 2-27: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.11 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 linehaul truck[26] revealed that just 42 percent 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 percent of the fuel consumed and exhaust heat accounts for another 24 percent. 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 percent is not unusual. This would correspond to a roughly 5 percent 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 linehaul 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 percent can be achieved in long-haul 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]

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

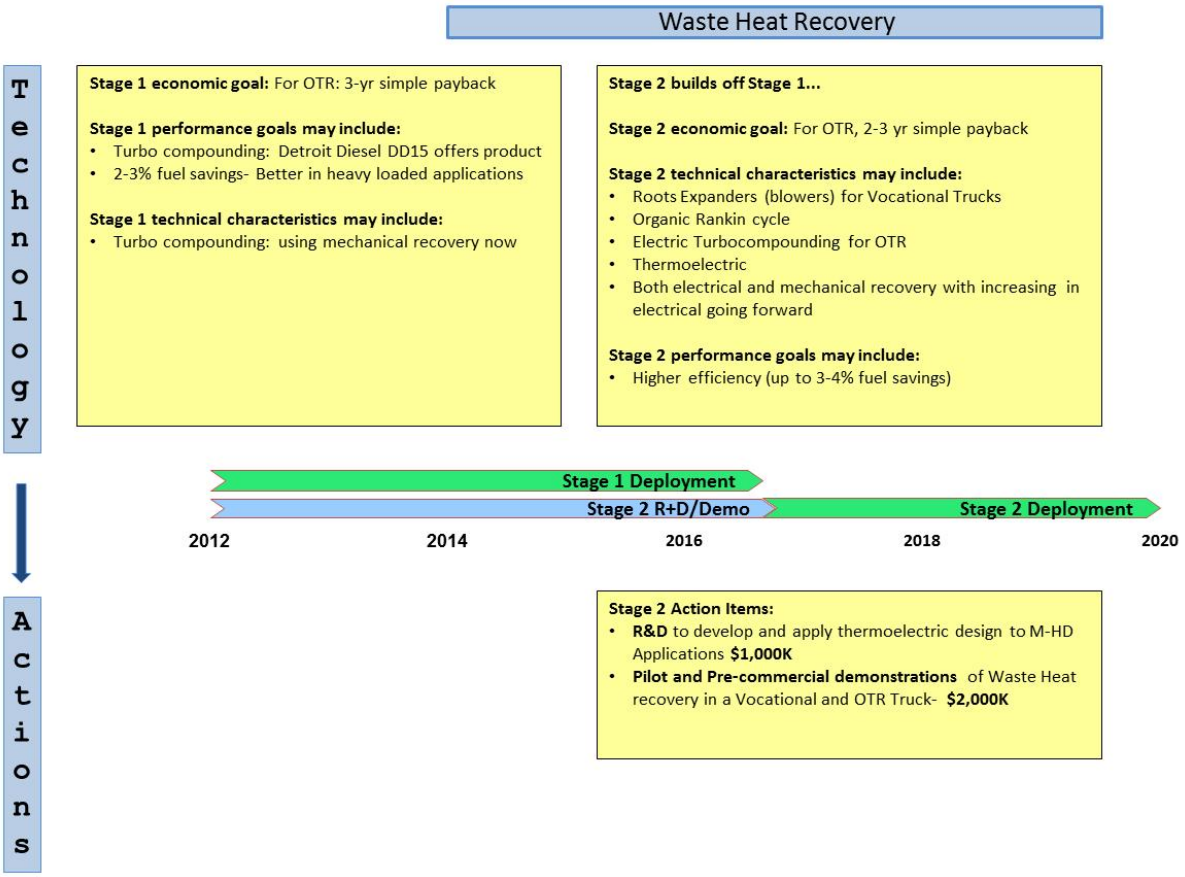
[27] Anthony Grezler, Volvo Powertrain Corporation, ***Diesel Turbo-compound Technology***, ICCT/NESCCAF Workshop presentation, February 20, 2008, slide 5.

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

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 2-28, 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.

Figure 2-28: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.12 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 percent 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 percent to 50 percent by 2010 and 55

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

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

percent 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 longhaul 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 2-29. 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 percent 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 percent BTE corresponding to the DOE Supertruck project developments. Actions for Stage 2 include a pilot demonstration of a 50 percent 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 percent BTE DOE Supertruck, incorporating advanced technologies that may lead to a 200 percent 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 percent BTE Class 8 truck with 200 percent fuel efficiency improvement, and pilot demonstration of an OTR truck with three to ten times lower NOx.

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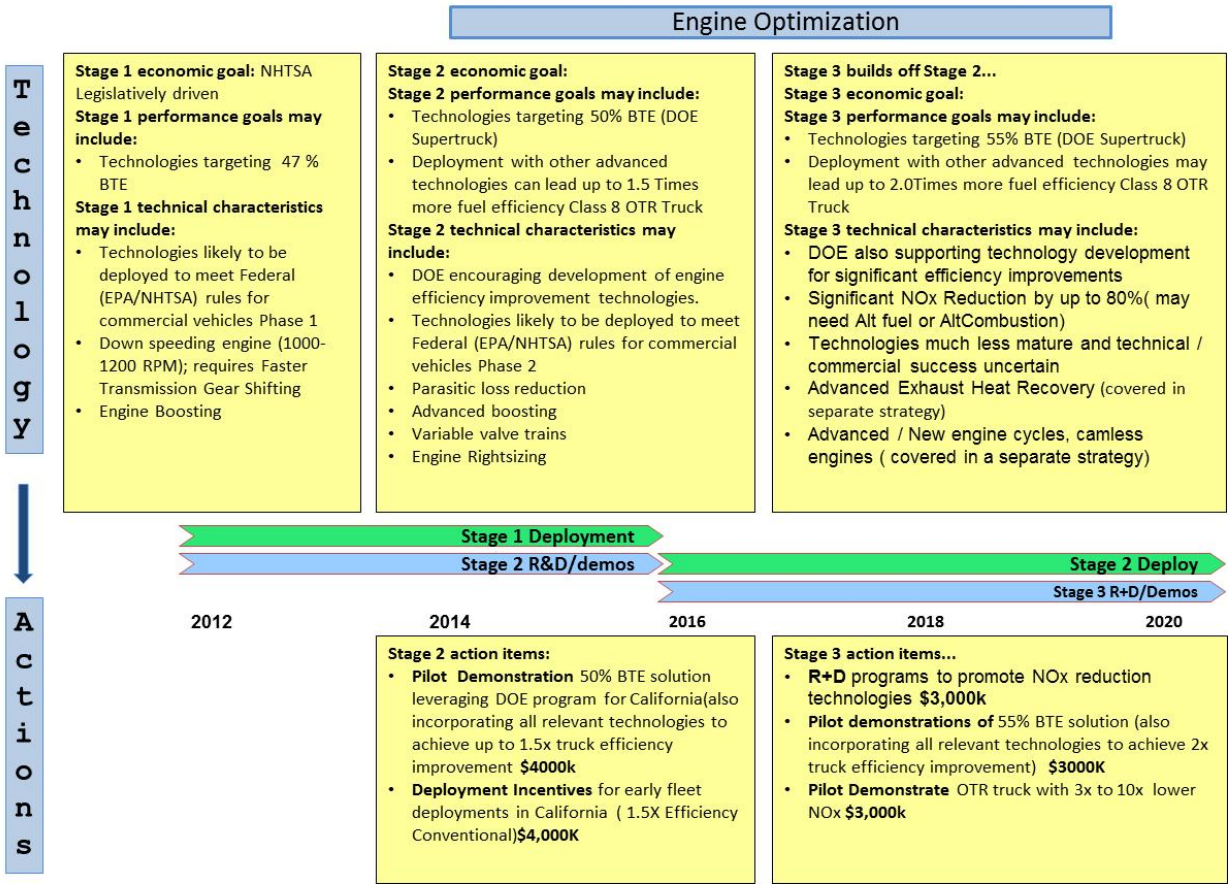
[31] Committee to Review the 21st Century Truck Partnership, Phase 2, National Research Council. ***SuperTruck Program*. *Review of the 21st Century Truck Partnership, Second Report***. Washington, DC: The National Academies Press, 2012.

Figure 2-29: 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 percent baseline efficiency in 2012 to 2013. Stages 2 and 3 influence the Supertruck Program for California and include performance goals of 50 percent BTE in Stage 2 and 55 percent in Stage 3. Stage 2 actions in this roadmap for California include a pilot demonstration of the 50 percent 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 percent BTE Class 8 OTR truck and an OTR truck with 3x to 10x lower NOx.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.3.13 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 percent from 2010 emissions for trucks.

The *Alternative Power Plant and Combustion Cycle Technology and Action Roadmap*, shown in Figure 2-30, 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.

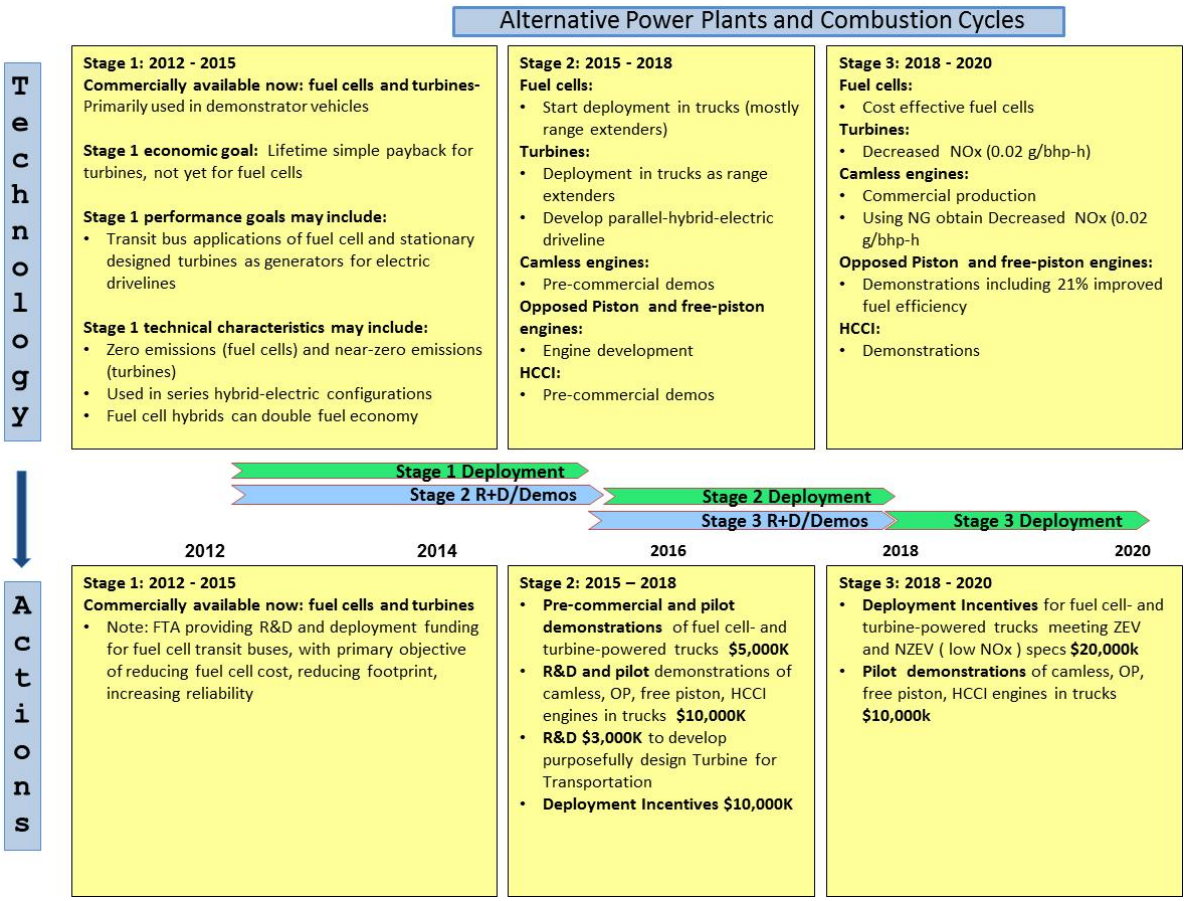
Fuel cells are a zero-emission power source that have shown promise as premium power generators in the 5-10 kW range but have not yet reached the packaging size, weight, and cost range needed for widespread acceptance for on-board power in trucks.

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 from 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 2-30: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

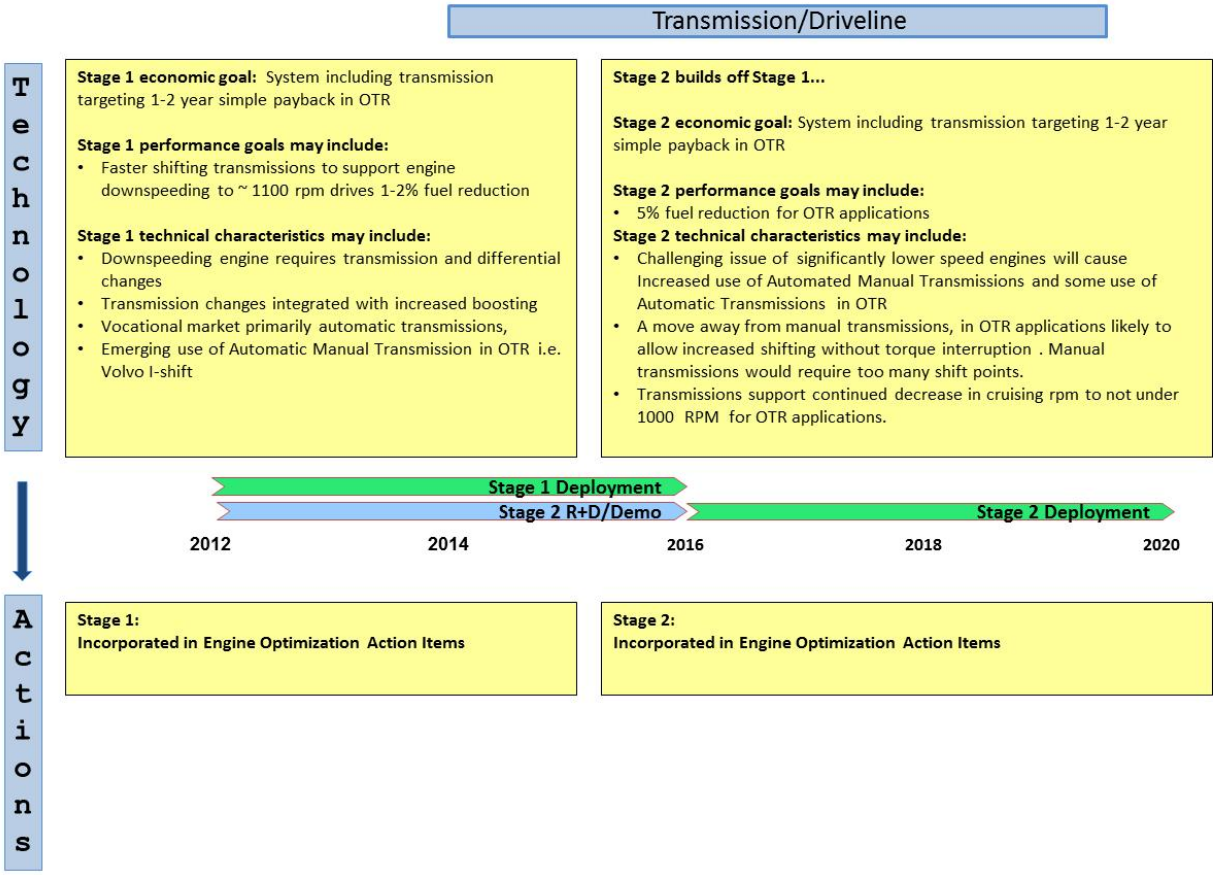
2.3.14 Transmission/Driveline Improvements

The 21st Century Truck Partnership improvements in engine efficiency, discussed above in the "Engine Optimization" section, 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 2-31. 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 percent reduction in fuel use. The technology 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 2-29. Stage 2 calls for a 5 percent 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 2-31: 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

2.4 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 percent reduction in CO_2 e by 2050, and 75 percent

reduction in petroleum use, compared to projected "Business as Usual" levels without these changes.

For CO_2 e, 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 percent 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_2 e and petroleum with a higher adoption rate of biofuels.

Over the same period, NOx emissions are projected to decrease 73 percent, 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 2-32 were identified as having the potential to achieve significant energy and environmental benefits to meet State policy goals.

Figure 2-32: 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.

Source: 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 2B includes a summary of the actions by technology strategy, followed by a numerical list with descriptions; and Appendix 2C 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.

2.4.1 Priority Actions

Critical to the implementation of these 66 roadmap actions is funding. Next steps would be to prioritize and act on the 66-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 percent of CO_2 e 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.

2.4.2 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 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_2 e 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 more electrified over-the-road truck.
- Advanced and highly-efficient combustion technologies and fuel cell solutions.
- Three hundred percent greater vehicle efficiencies leveraging driveline improvements, engine efficiencies, and improved vehicle aerodynamics and rolling resistance.
- Technical assistance to fleets, dealers, and maintenance shops to assure a better understanding of early market adoption issues and 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 eight million annual metric tons of CO_2 e 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 percent 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_2 e emissions projected by the roadmap for 2050, as shown in Figure 2-11: "Biofuel Related Impact on CO_2 e Reduction". 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 percent growth in the business-as-usual projections for CO_2 e. 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:

- 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.
- 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 CO2e 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.

CHAPTER 3:
Testing and Demonstration of Class 8 Trucks

3.1 Executive Summary

The California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center is a California-based resource center for research, development, demonstration, and commercialization of advanced, efficient truck technologies, and systems. This project evaluated the performance of advanced Class 8 urban delivery trucks in a limited demonstration program in Southern California. The primary goal of the project was to evaluate the benefits of heavy-duty hybrid vehicle technology compared to conventional vehicles. The project team consisted of CalHEAT; Daimler Trucks North America LLC (DTNA) as the vehicle supplier; a beverage delivery company as the fleet operator; Eaton Corporation as the hybrid drivetrain supplier; and Telogis Inc. as the data acquisition system supplier. The results provide early benchmark data in expected fuel economy and efficiency improvements from advanced Class 8 beverage delivery trucks and provide the potential savings from this important heavy-duty truck segment.

Four beverage delivery trucks, three hybrids and one conventional diesel were monitored over a 15-month vehicle demonstration and testing period in Los Angeles. During the data collection phase, the hybrid vehicles did show a significant improvement in miles per gallon (MPG) and gallons per hour (GPH). The hybrid trucks showed an average 15.6 percent improvement in fuel economy (MPG) and a reduction of 22.4 percent in fuel consumption rate compared to the conventional diesel in typical operation in the beverage delivery fleet. The trucks were randomly assigned for the field test with duty cycles that were not identical because the team did not want to disrupt the daily operations of the fleet.

To precisely assess the efficiency and emissions of the hybrid truck compared to a conventional truck in a controlled setting, CalHEAT performed a chassis dynamometer test of the hybrid and conventional vehicles at the University of California Riverside College of Engineering Center for Environmental Research & Technology (CE-CERT). Prior to testing, two duty cycles were developed by West Virginia University for the chassis dynamometer testing. Two speed-time driving schedules representing a “heavy” and a “light” vehicle load were developed using data collected from Class 8 beverage delivery tractors operating in Los Angeles.

The hybrid showed higher CO_2 emissions than the conventional engine when a 20-minute key-off wait was used between the test cycles. During discussions with the project team, it was determined a low catalyst temperature may be a potential cause for the unexpected results. The team then decided to perform a second test without the light cycle and replace it with testing the heavy cycle using a 1-minute soak to ensure the catalyst was up to the required temperature. With a 1-minute key-off soak, the CO_2 emissions for the hybrid were significantly reduced. The reduction of the CO_2 emissions with a 1-minute key-off soak seems to confirm that the higher CO_2 emissions occur during conditions when the catalyst has not reached its appropriate “light-off” temperature. All other emissions such as NOx, total hydrocarbons

(THC), methane, and non-methane hydrocarbons (NMHC) for the hybrid were similar or lower than the conventional. It should be noted that the CO_2 emissions for all vehicles tested appear to be well below the certification levels. For fuel economy, the hybrid truck showed an improvement of 30 percent over the conventional truck on the heavy cycle during the test. In addition, a new battery with higher capacity for the hybrid was also tested. The chassis dynamometer test indicated that the larger battery system improved fuel economy performance by an additional 4 percent, resulting in a 34 percent improvement over the conventional unit in fuel economy for the "heavy" duty cycle.

3.2 Background

The California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center is a California-based resource center for research, development, demonstration and commercialization of advanced, efficient truck technologies and systems. The center works as a partnership of diverse stakeholder groups developing and implementing an overall research and a market transformation plan to inform manufacturers and suppliers on clean truck technology status, gaps, and needs for commercialization as well as guide state investment and funding for hybrid, efficient and advanced truck technologies.

Medium- and heavy-duty vehicles are critical to the economy, yet remain a real and growing challenge for fuel use, GHG, and criteria emissions. Medium- and heavy-duty on-road truck traffic serving urban and goods movement needs combined with heavy-duty off-road vehicle use at distribution centers and ports, contribute significantly to fuel use, poor regional air quality, and are a sizable source of greenhouse gas emissions. Class 8 urban delivery trucks are an important category of trucks contributing to the challenge.

This project evaluates the performance of Class 8 urban delivery advanced trucks in a limited demonstration program in Southern California. The primary goal of the project is to evaluate the benefits of heavy-duty hybrid vehicle technology compared to conventional vehicles. The project team consists of CalHEAT; Daimler Trucks North America LLC (DTNA) as the vehicle supplier; a beverage delivery company as the fleet operator; and Telogis Inc. as the data acquisition system supplier. The results provide and benchmark early data in expected fuel economy and efficiency improvements from advanced Class 8 trucks and indicate the potential savings from this important heavy-duty truck segment.

3.3 Project Overview

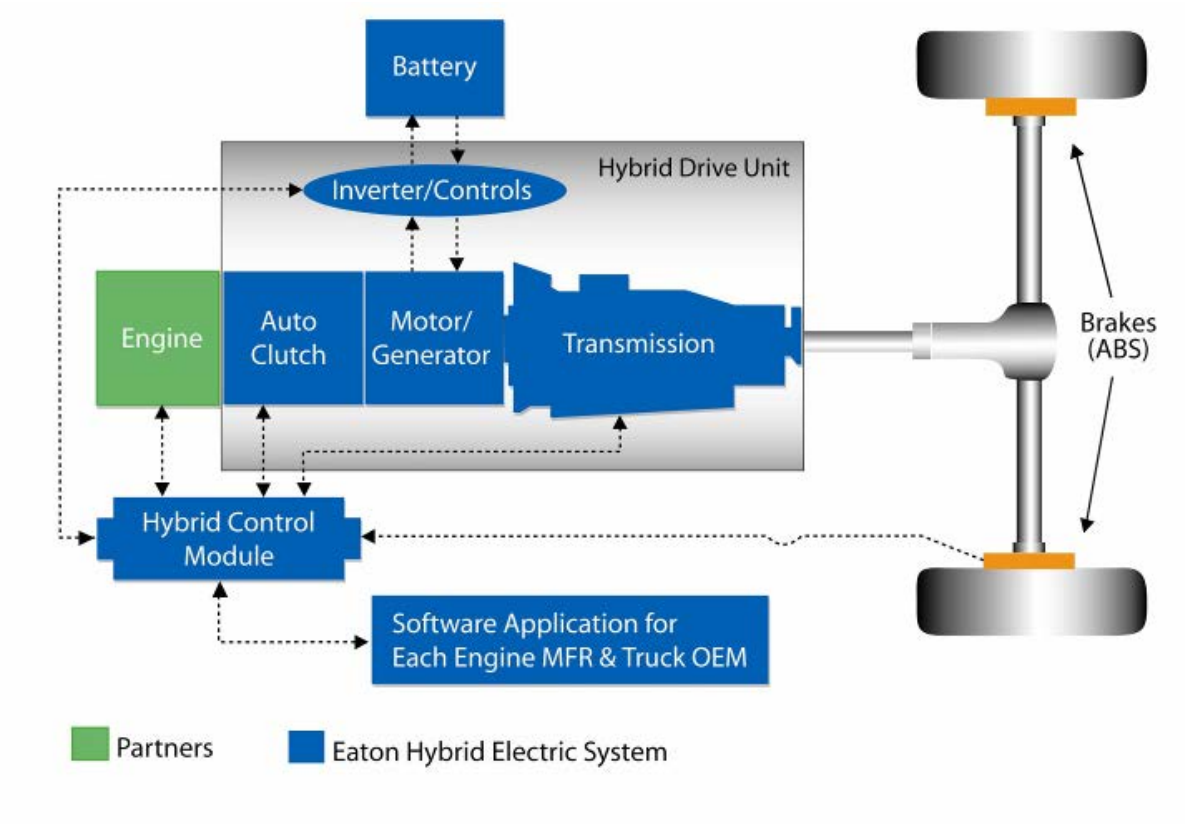
3.3.1 Test Vehicles

Four vehicles were selected from the test fleet for this project, three hybrid trucks (two Freightliner M-2s and one Kenworth T370) and one conventional Freightliner M-2 truck. These trucks are Class 8 short-haul urban delivery tractors with a gross vehicle weight rating of 30,000 lbs. The test vehicles operate within the City of Los Angeles and parts of surrounding areas. The Los Angeles beverage delivery truck fleet operates about 30 beverage delivery trucks with 30-40 drivers depending on volume of deliveries. Typically, each vehicle makes roughly 18-20 deliveries per day for six days a week operating approximately 12 hours a day. In addition, all vehicles undergo a mandatory maintenance inspection and service every 90 days. In addition to

the four field test vehicles, a fifth truck, a hybrid truck was used for the chassis dynamometer test at University of California, Riverside.

In order to quantify and compare the benefits of the hybrid vehicles, all of the vehicles were monitored by a data logging system provided by Telogis to collect vehicle performance information. All of the vehicles utilize 2010 on-road engines and after-treatment systems certified to 2010 emission standards. The beverage delivery trucks in this project utilized the parallel hybrid electric system developed by Eaton. Figure 3-1 below shows the layout of the Eaton hybrid system for delivery vehicles.

Figure 3-1: Eaton Hybrid Electric System Layout



Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 3-1 provides a summary of the specifications for the hybrid and conventional trucks used during the test project.

Table 3-1: Truck Test Fleet

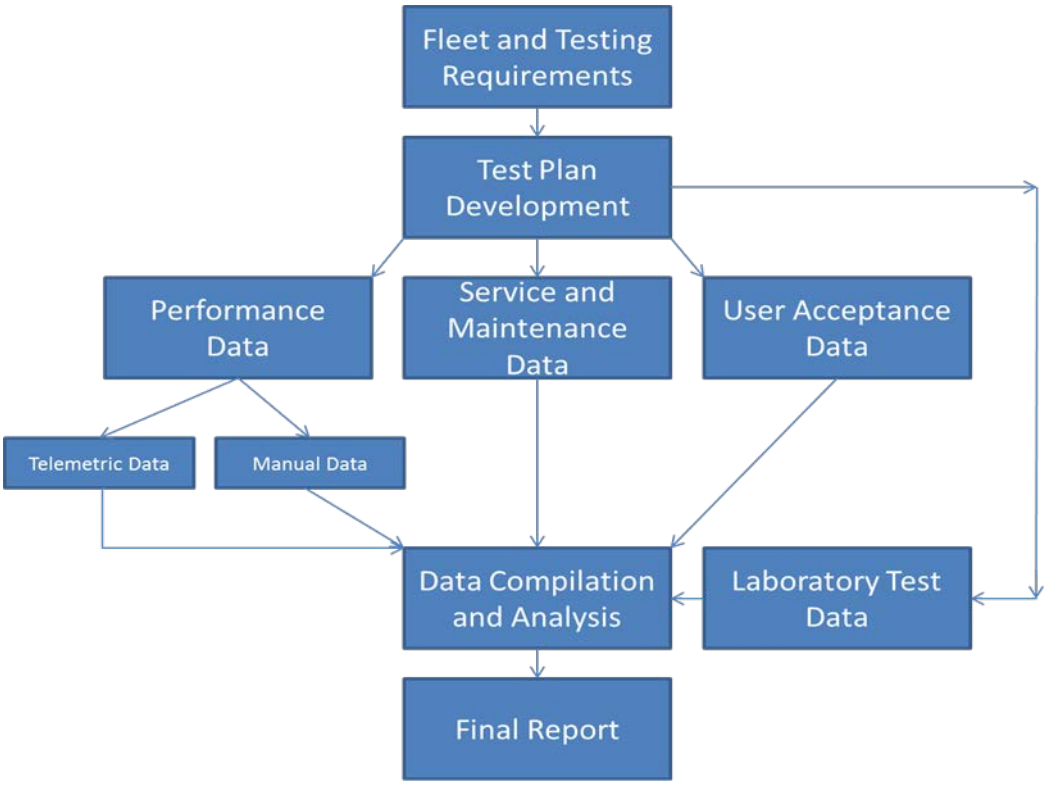
Vehicle ID	Vehicle Make and Model	Engine Make and Model	Transmission Manufacturer	Electric Motor Power	Engine HP and Torque
HYBRID 1	Freightliner M-2 Hybrid	Cummins ISB 6.7	Eaton	40 kW	280 HP 660 LB/FT
HYBRID 2	Freightliner M-2 Hybrid	Cummins ISB 6.7	Eaton	40 kW	325 HP 750 LB/FT
HYBRID 3	Kenworth T370 Hybrid	Paccar PX6-325	Eaton	40 kW	325 HP 750 LB/FT
CONV	Freightliner M-2 (Conventional)	Cummins ISC-300	Allison	NA	325 HP 750 LB/FT
HYBRID 4	Freightliner M-2 Hybrid	Cummins ISB 6.7	Eaton	40 kW	325 HP 750 LB/FT

Source: California Hybrid, Efficient and Advanced Truck Research Center

3.3.2 Data Collection Methods and Elements

An important element of the demonstration project is to determine the capability and reliability of the hybrid beverage delivery trucks in real-life settings and duty cycles during their normal operation. In order to evaluate the performance of the hybrid trucks, CalHEAT developed a test program to perform a comprehensive evaluation of vehicles during a demonstration project. Figure 3-2 depicts the CalHEAT process for data collection and analysis of vehicle performance.

Figure 3-2: CalHEAT Data Collection and Analysis Flow Chart



Source: California Hybrid, Efficient and Advanced Truck Research Center

3.3.2.1 Performance Test

A telemetric data acquisition system was installed to extract the data from the vehicles. CalHEAT worked with Telogis, a data acquisition system supplier, to collect specific parameters accessed by the data loggers. The vehicles were used during their normal routes with the telemetric systems tracking the performance of the vehicles and transmitting the data to the Telogis website through a cellular connection. The data can later be downloaded from the Telogis website through reports provided by Telogis. Utilizing the data loggers, the project team was able to view the various system functions in real time and acquire data for analysis. The data loggers were used during the duty cycle development and performance data collection phase of this project.

Performance testing was conducted between July 2011 and February 2012 and was accomplished by collecting and sorting the telemetric data on vehicle operations. The data acquisition system logged a number of different parameters that were later used to determine the fuel economy benefits of the hybrids vs. the diesel beverage delivery trucks. The parameters collected by the system used in this report were:

- Total Engine Hours
- Total Miles Traveled
- Total Fuel Use

- Total Idle Time
- Derived Average Speed

With the above data collected, CalHEAT analyzed the data to compare average fuel economy for the hybrid and diesel beverage delivery trucks during in-use operations. Fuel economy for the purpose of this test program was measured in gallons per hour (GPH) and miles per gallon (MPG) to provide a better understanding of vehicle use in relation to vehicle fuel economy.

3.3.2.2 User (Driver) Acceptance

Operator acceptance interviews were used to assess drivers' impressions of the performance of the hybrid beverage delivery trucks during in-use operations compared to typical diesel beverage delivery trucks. Due to the subjective nature of driver impressions, a simple, relative rating scheme of "better", "same" or "worse" was used to compare hybrid beverage delivery truck performance characteristics to those of a typical conventional diesel beverage delivery truck.

Interviews were performed by a survey that the hybrid beverage delivery truck drivers were asked to fill out at the middle and at the end of the CalHEAT project. Surveys were filled out at the end of the afternoon shift when the drivers return to the distribution center to maximize survey responses. In addition to the surveys, interviews were conducted with individual drivers or groups of drivers to obtain additional driver comments on the hybrid beverage delivery trucks. Due to timing restraints, not all hybrid beverage delivery truck drivers were able to fill out surveys or be interviewed.

A one-page hybrid beverage delivery truck driver survey form was developed with feedback from the CalHEAT team and Beverage Delivery Fleet Supervisor. The survey questions were designed to cover key vehicle performance areas and other characteristics of the vehicle that would directly affect the driver. The survey contained a total of twelve questions and a space for drivers to record additional comments, beyond the comments provided during the interview, if they so desired. A copy of the Hybrid Driver Survey form is included in Appendix 3A. The specific areas covered by the Hybrid Beverage Delivery Truck Driver Survey questions included:

- Maneuverability at slow speeds
- Pulling power with load
- Acceleration
- Coasting/deceleration
- Braking
- Smoothness of shifting
- In-cab controls
- Interior noise level
- Exterior noise level
- Overall vehicle rating

- Problems with the hybrid drive system
- Additional comments

3.3.2.3 Maintenance and Serviceability

The purpose of collecting service and maintenance data was to assess the reliability, maintainability, and serviceability of the hybrid beverage delivery trucks compared to typical diesel beverage delivery trucks. One of the primary metrics used for this assessment was vehicle availability. In addition, mechanics were asked to provide subjective feedback on various service and maintenance aspects of the hybrid beverage delivery trucks compared to diesel beverage delivery trucks.

Vehicle Availability

Vehicle availability is defined in this report as the percentage of full days each month that a particular vehicle was available to be used. Vehicles undergoing routine maintenance or being repaired were considered "unavailable" until they were put back into service. Please note that beverage delivery trucks, both hybrid and diesel, which were removed from service for emissions testing at University of California, Riverside (UCR) are not included in the data for the month of November 2011. Vehicle availability was tracked via a combination of methods including:

- Vehicle maintenance and service records.
- Discussions with maintenance and service staff.
- E-mails from maintenance staff.

Vehicle availability was determined by cross-referencing the above information for each vehicle in the test group on a monthly basis.

Mechanic Surveys

Mechanics working on the hybrid beverage delivery trucks were asked to fill out a survey at the end of the performance testing period to solicit their feedback regarding maintainability and serviceability aspects of the hybrid beverage delivery trucks compared to typical diesel beverage delivery trucks. The survey questions were designed to cover those aspects of the vehicle design and support that would directly affect the mechanic. The survey contained a total of six questions and a space for mechanics to record additional comments.

For subjective questions, a rating scheme of 1 to 5 was used, 1 being "unacceptable" and 5 being "excellent". A total of seven mechanics filled out the survey at the conclusion of the performance-testing period. A copy of the hybrid Mechanic Survey form is included in Appendix 3B. The specific areas covered by the survey included:

- Start-up problems (i.e. problems noted during the early phases of deployment)
- Hybrid systems and component training
- Design for maintainability

- Design for serviceability
- Quality of manufacturer support
- Trends in service actions over the performance testing period
- Additional comments

3.3.3 Laboratory Test (Emissions Test)

Emissions testing and analysis were performed at the University of California, Riverside's Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT) in Riverside, California.

The research project was built on the application of a transient cycle, especially developed for the beverage delivery trucks by West Virginia University (WVU) and used on the UCR heavy-duty chassis dynamometer. Emissions were measured with CE-CERT's Mobile Emission Lab, and the state of battery charge was monitored while the vehicle followed the transient cycle. Analysis compared the results for both the case of a light load and a heavy load.

3.4 Results

3.4.1 Vehicle Operations Data Summary

Data collected during the eight-month field-testing period were analyzed and summarized below. Please note, HYBRID 1 and Conv were taken out of service for chassis dynamometer testing during November 2011.

Engine Hours

Engine hours were used as a function of hours the vehicles were operated during the test period. The hybrids were not equipped with engine-off during idle so engine hours would be the best representation of how many hours the vehicles were actually used as the engine would be on during all vehicle usage. A summary of engine hours per month for all test vehicles is shown in Table 3-2. The average monthly engine hours for the hybrids ranged from 56.0 to 62.5 engine hours per month with the conventional vehicle averaging 59.2 engine hours per month.

Table 3-2: Summary of Average Monthly Engine-Hours of Test Vehicles

	Average Monthly Engine-Hours (hours)									
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total	Average
HYBRID 1	40.3	67.7	62.8	65.5	NA	78.5	51.8	70.9	437.4	62.5
HYBRID 2	31.5	77.1	86.6	60.8	59.4	59.5	34.2	39.6	448.8	56.1
HYBRID 3	43.1	43.1	24.8	51.5	67.4	64.8	83.4	70.0	448.0	56.0
CONV	37.9	72.6	33.0	48.8	NA	63.2	74.8	83.8	414.1	59.2

*Note: HYBRID 1 and CONV trucks were removed from service for testing during November

Source: California Hybrid, Efficient and Advanced Truck Research Center

Miles Traveled

A summary of miles traveled per month for all test vehicles is shown below in Table 3-3. Please note that the miles traveled per month for all of the vehicles were highly dependent on the duty cycle. The hybrid beverage delivery trucks averaged between 588.5 to 689.7 miles per month. The conventional beverage delivery truck averaged 666.3 miles per month during the test period.

Table 3-3: Summary of Average Monthly Miles Traveled for Test Vehicles

	Average Monthly Miles Traveled (miles)									
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total	Avg
HYBRID 1	482.2	740.7	879.2	782.3	NA	944.5	660.5	948.8	5517.7	689.7
HYBRID 2	574.8	776.1	628.2	590.3	732.6	606.5	334.3	465.4	4708.2	588.5
HYBRID 3	512	512	291.4	543.1	768	764.3	986.1	884.8	5261.7	657.7
CONV	502.1	899.7	398.3	576.6	NA	835.1	940.1	1178.1	5330.0	666.3

*Note: HYBRID 1 and CONV trucks were removed from service for testing during November

Source: California Hybrid, Efficient and Advanced Truck Research Center

Fuel Use

A summary of fuel used per month for all test vehicles is shown in

Table 3-4. Please note that the amount of fuel used per month for all of the vehicles was highly dependent on the duty cycle. The hybrid beverage delivery trucks averaged between 103.9 to 114.5 gallons per month. The conventional beverage delivery truck averaged 131.3 gallons per month during the test period.

Table 3-4: Summary of Fuel Use for Test Vehicles

	Average Monthly Fuel Used (gallons)									
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total	Ave
HYBRID 1	77.9	123.0	127.5	127.7	NA	158.0	106.6	158.0	886.7	110.8
HYBRID 2	85.9	140.9	130.5	107.4	121.4	106.2	60.4	78.9	831.5	103.9
HYBRID 3	93.4	93.4	48.5	95.9	137.2	125.1	169.3	153.0	915.8	114.5
CONV	97.3	180.6	77.5	119.4	NA	163.1	191.7	220.6	1050.2	131.3

*Note: HYBRID 1 and CONV trucks were removed from service for testing during November

Source: California Hybrid, Efficient and Advanced Truck Research Center

Vehicle Route Characteristics

Upon further inspection, CalHEAT monitored the vehicles to understand their route driving characteristics to try to understand the differences in the data provided above. In Table 3-5 and

Table 3-6 we see the variation in percentage of the time the vehicle spends idling and the difference in average speed. Please note the average speed was derived from the average miles traveled and average engine hours as the team felt it gave a better overall picture of average speed.

Table 3-5: Average Idling Hours per Month (Hours) and Overall % Idling for All Test Vehicles

	Average Monthly Idling Hours (hours)									
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total	% Idling
HYBRID 1	7.3	7.4	9.4	9.6	NA	13.9	8.1	11.0	68.9	15.6%
HYBRID 2	2.8	25.0	43.7	19.0	11.2	22.5	11.2	8.6	144.0	32.1%
HYBRID 3	15.0	15.0	11.7	22.2	23.5	23.2	34.3	32.9	177.8	39.7%
M2 CONV	5.1	7.3	6.3	6.5	NA	12.0	14.8	11.7	63.6	15.3%

*Note: HYBRID 1 and CONV trucks were removed from service for testing during November

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 3-6: Monthly Average Speeds for Test Vehicles

	Monthly Average Speed (MPH)								
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Avg Speed
HYBRID 1	12.0	10.9	14.0	12.0	NA	12.0	12.8	13.4	12.5
HYBRID 2	12.2	10.1	7.2	9.7	12.3	10.2	9.8	11.8	10.5
HYBRID 3	11.9	11.9	11.8	10.6	11.4	11.8	11.8	12.6	11.7
CONV	13.3	12.4	12.1	11.8	NA	13.2	12.6	14.1	12.9

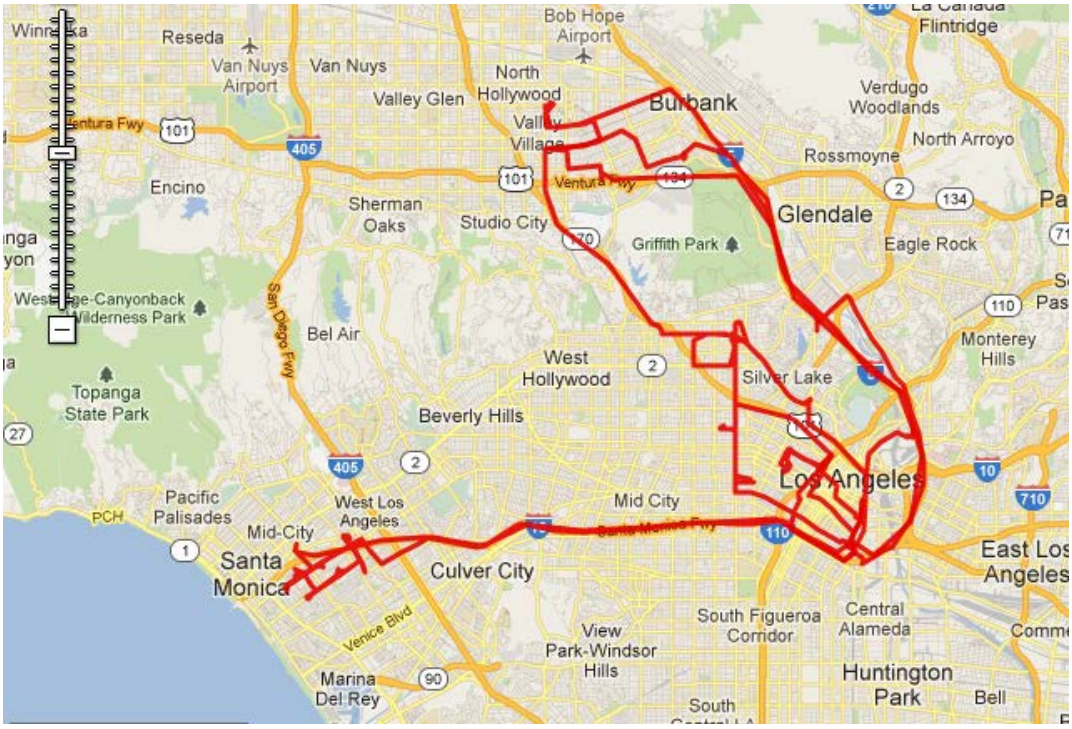
*Note: HYBRID 1 and CONV trucks were removed from service for testing during November

Source: California Hybrid, Efficient and Advanced Truck Research Center

From the data, we see that there is a difference in the idling percentages and average speed for the four vehicles. During the performance-testing period of the project, CalHEAT did not want to disrupt the day-to-day operations of the fleet. Therefore, the vehicles were placed into the fleet's pool of vehicles, which allowed the vehicles to be selected randomly based on delivery regions. Utilizing data from the GPS and randomly selecting days, we found the vehicles operated in different areas of the Los Angeles Basin, which resulted in the different duty cycles.

HYBRID 1, HYBRID 3 and CONV all operate out of the facility in downtown Los Angeles. Figure 3-3 depicts a sample of the routes taken by the three vehicles.

Figure 3-3: Sample Routes for Vehicles Operating Out of Downtown Los Angeles Facility

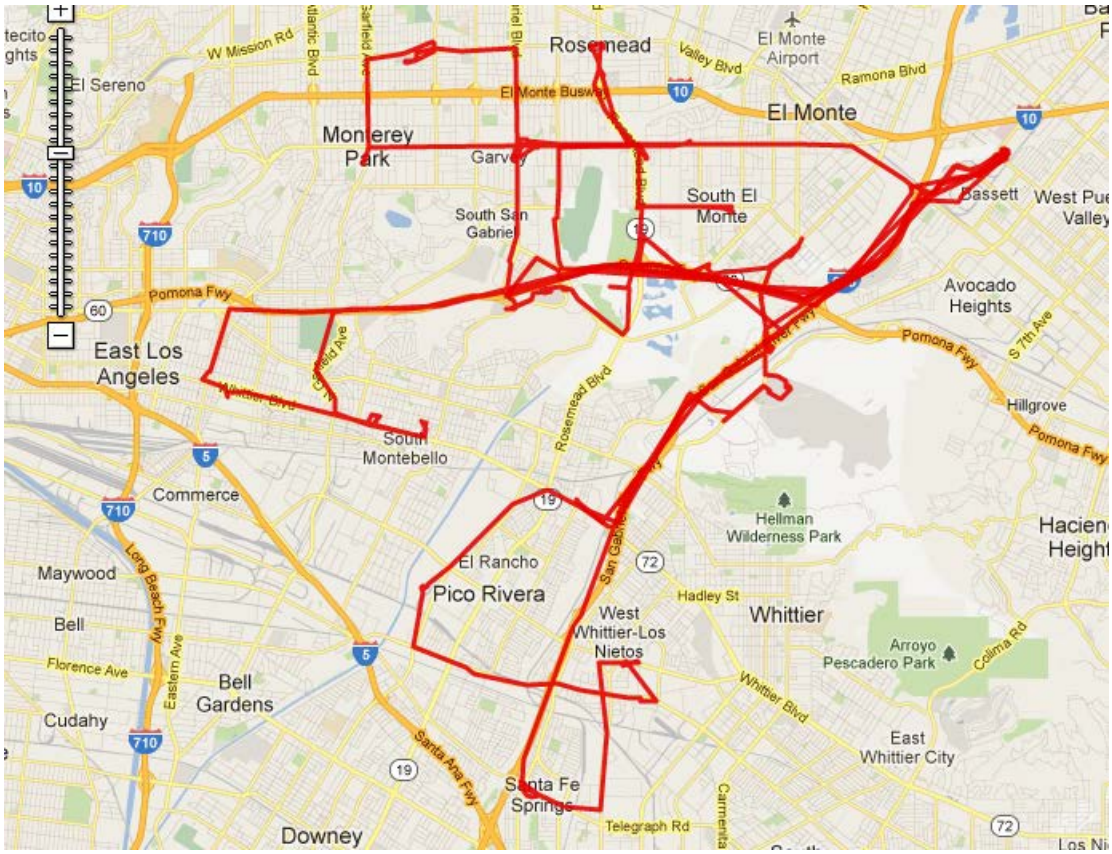


Source: California Hybrid, Efficient and Advanced Truck Research Center

HYBRID 3 operated more in the downtown areas compared to HYBRID 1 and CONV. This explains its high idling percentage and lower average speed of HYBRID 3 compared to the others. Meanwhile, HYBRID 1 and CONV were found to spend more time traveling further away from the congested streets of downtown LA with more freeway traveling, which resulted in lower idling percentage and higher average speeds.

HYBRID 2 operated in a different area compared to the other test vehicles which resulted in different vehicle operation characteristics. HYBRID 2 operated out of another facility in the San Gabriel Valley of Los Angeles County. HYBRID 2 made more deliveries on surface streets which led to higher idling percentage and lower average speeds. Figure shows the typical routes for M2 HYBRID 2.

Figure 3-4: Sample Routes for Vehicles Operating Out of the San Gabriel Valley Facility



Source: California Hybrid, Efficient and Advanced Truck Research Center

3.4.2 Fuel Economy Results

Miles per Gallon (MPG)

Using the vehicle operational data above, the fuel economy (MPG) of each vehicle was calculated and provided in Table 3-7.

Table 3-7: Summary of Average Monthly MPG for Test Vehicles

	Average Monthly MPG								
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Average
HYBRID 1	6.19	6.02	6.90	6.12	NA	5.98	6.20	6.01	6.22
HYBRID 2	6.69	5.51	4.81	5.50	6.04	5.71	5.54	5.90	5.66
HYBRID 3	5.48	5.48	6.01	5.66	5.60	6.11	5.82	5.78	5.75
CONV	5.16	4.98	5.14	4.83	NA	5.12	4.91	5.34	5.08

Source: California Hybrid, Efficient and Advanced Truck Research Center

Gallons per Hour (GPH)

A summary of the average monthly fuel consumption rate in gallons per engine operating hour for all test vehicles is shown in Table 3-8 below.

Table 3-8: Summary of Average Monthly GPH for Test Vehicles

	Average Monthly GPH								
Vehicle #	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Average
HYBRID 1	1.94	1.82	2.03	1.95	1.94	2.01	2.06	2.23	2.01
HYBRID 2	2.73	1.83	1.51	1.76	2.04	1.79	1.76	1.99	1.85
HYBRID 3	2.17	2.17	1.95	1.86	2.04	1.93	2.03	2.19	2.04
CONV	2.57	2.49	2.35	2.45	NA	2.58	2.56	2.63	2.54

Source: California Hybrid, Efficient and Advanced Truck Research Center

3.4.2.1 Field Data Collection Conclusions

Table 3-9 shows the individual hybrid truck improvements over the conventional truck. Isolating each vehicle, we see the fuel economy benefits of the hybrid beverage delivery truck ranges from 11.6 percent improvement to 22.6 percent. In addition, the GPH benefits ranges from 19.6 percent to 26.9 percent.

Table 3-9: Individual Hybrid Truck vs. Conventional Truck Improvements

HYBRID 1	
MPG	GPH
22.6%	-20.8%
HYBRID 2	
MPG	GPH
11.6%	-26.9%
HYBRID 3	
MPG	GPH
13.3%	-19.6%

Source: California Hybrid, Efficient and Advanced Truck Research Center

The variation in fuel economy and fuel consumption rates is primarily due to the difference in duty cycle of each vehicle. As discussed earlier, CalHEAT did not want to disrupt the day-to-day operations of the fleet and the vehicles were placed into the fleet's pool of vehicles. The regions varied between routes such as the low speed and high percentage of idling characteristic of driving in downtown Los Angeles to routes that include freeway driving with less idling.

From the data, we see that the operation of the vehicles played a key role in the difference in fuel economy and fuel consumption rates of the vehicles. Despite the difference in duty cycle of the vehicles, the hybrid vehicles did show an improvement in MPG and GPH regardless of the duty cycle. As noted above, the hybrids showed an improvement in fuel economy (MPG) ranging from 19.6 percent to 22.6 percent. The hybrids also showed a reduction of 19.6 percent to 26.9 percent in fuel consumption, a rate which showed the hybrids were more efficient compared to the conventional diesel in typical operation at the fleet. However, utilizing the idling percentage and derived average speed, we find that a direct comparison can be made between HYBRID 1 and CONV. Both of the vehicles operate in similar routes with similar idling percentages and derived average speeds. When comparing the HYBRID 1 and CONV, the hybrid showed a 22.6 percent improvement in MPG and a 20.8 percent in GPH. Due to the difference in duty cycle, CalHEAT performed a chassis dynamometer test at University of California, Riverside. The main goal of the chassis dynamometer test is to assess and compare the efficiency and emissions of the hybrid truck compared to a conventional truck in a controlled laboratory setting (see Section 3.5).

3.4.3 User (Driver) Acceptance Results

3.4.3.1 Six-Month Driver Survey

A results summary of the first hybrid beverage truck driver survey given at the end of the third month is provided in Table 3-10. A total of 17 driver surveys were filled out during the first performance testing period. Results for each of the twelve (12) items in the survey are expressed as percentages of the total responses for each of the three possible ratings ("better",

"same" or "worse") for comparison to diesel beverage delivery trucks. Questions 11 and 12 were included in the driver survey that was not directly related to the driver evaluation of the trucks.

Table 3-10: Summary of Hybrid Driver Survey Results at Six Months

Overall Hybrid Truck Performance Parameters	**% Breakdown**		
	Better	Same	Worse
1. Maneuverability at slow speeds	23.5%	52.9%	23.5%
2. Pulling power with Load	0.0%	11.8%	88.2%
3. Acceleration	0.0%	11.8%	88.2%
4. Coasting/Deceleration	53.3%	40.0%	6.7%
5. Braking (stops load quickly and smoothly)	82.4%	17.6%	0.0%
6. Smoothness of shifting under acceleration	82.4%	17.6%	0.0%
7. In-cab controls (convenience and functioning of switches, controls, etc.)	64.7%	35.3%	0.0%
8. Interior noise level	88.2%	11.8%	0.0%
9. Exterior noise level	82.4%	17.6%	0.0%
10. Overall vehicle rating	64.7%	23.5%	11.8%
11. Any problems with the hybrid drive system?	4%	12%	
12. Are you interested in additional training on how to drive the hybrids more efficiently?	5%	10%	

Source: California Hybrid, Efficient and Advanced Truck Research Center

3.4.3.2 Project End Driver Survey

A final driver survey was performed at the end of the performance-testing period. A total of 12 driver surveys were filled out at the end of the project. Results for each of the twelve items in the survey are provided in Table 3-11.

Table 3-11: Summary of Hybrid Driver Survey Results at Project End

Overall Hybrid Truck Performance Parameters	% Breakdown		
	Better	Same	Worse
1. Maneuverability at slow speeds	58.3%	16.7%	25.0%
2. Pulling power with Load	0.0%	33.3%	66.7%
3. Acceleration	0.0%	33.3%	66.7%
4. Coasting/Deceleration	25.0%	66.7%	8.3%
5. Braking (stops load quickly and smoothly)	58.3%	33.3%	8.3%
6. Smoothness of shifting under acceleration	16.7%	16.7%	66.7%
7. In-cab controls (convenience and functioning of switches, controls, etc.)	91.7%	8.3%	0.0%
8. Interior noise level	66.7%	33.3%	0.0%
9. Exterior noise level	75.0%	25.0%	0.0%
10. Overall vehicle rating	41.7%	33.3%	25.0%

Source: California Hybrid, Efficient and Advanced Truck Research Center

3.4.3.3 Additional Driver Comments

Additional driver comments were provided during the interview. Comments were grouped into three basic categories—Performance; Comfort, Convenience, and Safety; and the general Additional Comments. Individual items within each category were further categorized as either positive or negative depending on the nature of the comment. Many of the same comments appeared several times indicating a common perception or experience among different drivers. A summary of driver comments arranged by category is provided below.

Vehicle Performance

Positive

- Hybrids performs well on flat roads, not grades
- Smooth acceleration
- Performs well when vehicle is empty but performance gets worse driving under heavy loads or up a grade.
- Smooth coasting
- Once the vehicle is up to speed, it drives well
- Shifts late on a few units

Negative

- Pulling power is horrible, especially driving up a hill
- Driving up a hill, big difference is felt

- Requires the driver to anticipate gear changes driving up hill
- Automatic transmission doesn't downshift going up hill
- Liquids are hard to transport as the liquid moves in unison. Any jerkiness in the vehicle movement can be felt. Cargo also falls
- Driving up California State Route 2 (SR 2), a road with high grade, the trucks cannot reach 35 MPH ascending hills.
    - Typically drives up at 15-20MPH with the hazard lights on
    - Semis are going faster
- Vehicle is jerky during downshifting
- Slightly bigger turning radius
- Transmission doesn't shift correctly on a hill. No power on hill

Vehicle Comfort, Convenience, and Safety

Positive

- Very smooth
- Vehicle really quiet
- New models are quieter
- Very quiet and gets a lot of attention from pedestrians

Negative

- Large blind spots on the Kenworth Hybrids
- Needs to stop vehicles to clean out DPF

Additional Comments

- If the problems during acceleration and driving up hill can be fixed, the vehicle will be much better
- Overall good vehicle
- Hybrid truck drives better in traffic
- Drive the hybrid for smoothness
- Drive the diesel for power
- Needs more power

3.4.3.4 Driver Survey Conclusions

The results from the first and second surveys were generally positive with the drivers viewing the hybrid beverage delivery truck as equal to or better than the conventional truck on most vehicle characteristics including overall vehicle rating. While a majority of the feedback provided by the drivers of the hybrid utility truck were positive, the features of the hybrid beverage delivery truck that was rated most consistently as "worse" was for pulling power with load and acceleration. The survey showed that 88 percent of the drivers felt that both pulling power with load and acceleration were poor. In addition, the drivers complained about the pulling ability of the trucks up a grade when under load, for example, traveling up SR 2 from downtown Los Angeles to Glendale, the drivers noted the top speed of the truck was at around 20-30 MPH, well below the 65 MPH speed limit. The features of the hybrid beverage delivery truck most consistently rated the same or better than the diesel beverage delivery trucks were coasting, braking, smoothness of shifting under acceleration, in-cab controls, interior noise level, and exterior noise level. Around two-thirds of the drivers also rated the overall vehicle as "better" than conventional diesel beverage delivery trucks.

For the second survey performed at the end of the project performance testing period, the results were similar to the first survey with the majority of drivers noting the hybrid trucks provided poor performance in acceleration and pulling power with load. While most of the other items showed a majority of scores as "better" or "same", smoothness of shifting under acceleration went from a favorable score where 82 percent of drivers rated as "better" to 67 percent of drivers rating it as poor. A majority of the drivers noted an issue with the shifting that resulted in the low scores for "smoothness of shifting under acceleration" category. The issue, as a majority of the drivers noted, is that the transmission does not upshift at times, which causes the trucks to stay in the same gear at high revs. The drivers noted that when this happens, they need to switch to manual mode to upshift. CALSTART asked the lead mechanic's opinion regarding this issue and the response was that the issue arises from driver error. When the driver parks the truck and turns off the engine in gear, a trouble code is generated by the transmission with leads to the vehicle not shifting to prevent further damage. The lead mechanic noted that a simple clearing of the trouble code will fix the problem.

3.4.4 Service and Maintenance Evaluation

3.4.4.1 Vehicle Availability Results

CalHEAT requested the work orders from the maintenance staff but due to the sensitive nature of the documents, the request was denied and therefore, detailed analysis cannot be performed on the availability of the vehicles for this report. However, the primary goal of this project is to evaluate the hybrid beverage delivery trucks against their conventional counterpart. CalHEAT was able to perform a quick assessment of the hybrid and conventional beverage delivery truck availability by not including loss of availability due to driver errors. From the interviews, it was found that all of the test vehicles drivetrains were extremely reliable. By not including problems caused by driver errors, CalHEAT found the vehicles to have 100 percent availability during the project demonstration period.

Service and Maintenance Conclusions

Based on the discussions with the maintenance staff at the end of the project, the average availability of the hybrid beverage delivery trucks over the eight-month performance testing period was 100 percent based on hybrid drivetrain and engine reliability. By comparison, the average availability of the diesel beverage delivery truck was also 100 percent.

While the hybrid beverage delivery trucks and the diesel hybrid delivery truck availability were 100 percent, they made up only a small sample of the overall fleet.

3.4.4.2 Hybrid Mechanic Survey Results

A summary of hybrid mechanic survey results is provided below. A total of seven hybrid driver surveys were filled out by mechanics who worked on the hybrid beverage delivery trucks during the eight-month performance testing period.

Question 1 of the survey was: "Describe any hybrid beverage delivery truck problems observed during the early part of the demonstration period that were subsequently corrected by the manufacturer:"

It should be noted that the three vehicles in the test fleet did not have any problems observed during the early part of the demonstration project. However, the test vehicles are a small portion of the fleet in Los Angeles. CalHEAT interviewed the lead mechanic to obtain further information on other issues that arose with other hybrid trucks in the fleet. Problems with explanations associated with the hybrid trucks are listed below.

For the test vehicles, no problems associated with the hybrid drive system were observed during the early part of the demonstration project. However, other vehicle issues were observed and are described below.

- Shifting issues as described by the drivers in the driver surveys. The lead mechanics noted that the issue is largely due to driver error. Turning off the truck while it is in gear and not in neutral caused the problems. A code is generated to prevent shifting when the trucks are not turned off properly.
- Trailer air hose damage is also due to driver error. The drivers have been notified that the air hoses are not able to support the stretching caused during "jack knifing" the trailer (positioning the trailer perpendicular to the tractor).

Questions 2 – 6 of the survey asked the mechanic to rate various maintenance and service characteristics of the hybrid beverage delivery trucks on a scale of one to five where 1 was "unacceptable" and 5 was "excellent". A summary of the responses is given in Table 3-12.

Table 3-12: Summary of Hybrid Mechanic Survey Results for Questions 2 – 6

Hybrid Mechanic Survey Question	Average Rating
Hybrid systems and component training	4.6
Design for maintainability	4.3
Design for serviceability	4.3
Vehicle manufacturer support	3.9
Hybrid system manufacture support	4.3

Source: California Hybrid, Efficient and Advanced Truck Research Center

Question 7 of the survey was: "Describe any trends observed regarding non-routine service actions associated with the hybrid beverage delivery trucks including the long-term effectiveness of corrective actions:"

Responses to Question 7 are summarized as follows:

- Hybrid trucks are currently set up very similar to comparable diesel trucks with the exception of the hybrid system components.
- No work has been performed on hybrid system components as all hybrid-related work was performed by Eaton.
- Mechanics have been trained and are currently transitioning to perform more work on the hybrid system.
- Mechanics have, to a limited extent, performed battery swaps on the hybrid truck fleet.
- The mechanic staff does check hybrid battery system air filter and coolants to ensure proper operation of hybrid system as well as other preventative maintenance work.

Question 8 of the survey provided a space for additional comments. Responses to Question 8 are provided below:

- The hybrid trucks are extremely reliable.
- Very positive experience with the hybrid trucks.
- Compared to the previous trucks in the old fleet, the hybrids are a great plus.
- Most issues were caused by driver error; more driver training can reduce errors.
- Trucks are very straightforward and basic, easy to service.
- Mechanics are able to diagnose issues with the trucks, including the hybrid drive system with confidence.

Mechanic Survey Conclusions

Based on the mechanic surveys, 100 percent of the mechanics gave the hybrid beverage delivery trucks a rating of "acceptable" or "good" scores regarding hybrid training, maintainability, serviceability and manufacturer support. Interviewing the mechanics, the maintenance staff

performs routine maintenance on the hybrid beverage delivery trucks every 90 days as required by the fleet during the eight-month performance testing period. It should be noted that mechanics were generally not responsible for service actions on the hybrid systems beyond routine maintenance. During the test period, the hybrid system was covered under warranty or due to the hybrid system being relatively new, any service to the hybrid system was performed by Eaton representatives.

CalHEAT staff attended an Eaton Roadranger Mechanics Training class on July 6-7, 2011. In interviews conducted right after the training, mechanics said the classes were very informative in helping them understand how to service, troubleshoot, and take precautions when servicing the hybrid system. When performing the survey, the mechanics felt the training was highly effective and scores of "good" to "excellent" were provided.

3.5 Emissions Testing

3.5.1 Duty Cycle Development

This portion of the report was derived from the HTUF-WVU report, "Development of Heavy Duty Driving Schedules for Class 8 Beverage Delivery Trucks" found in Appendix 3C.

Two speed-time driving schedules were developed using data collected from Class 8 beverage delivery tractors operating in Los Angeles. Two driving schedules were developed representing a "heavy" and a "light" vehicle load. The two duty cycles were developed for vehicle emissions and fuel economy evaluation while the vehicle was operated over the duty cycles developed using a chassis dynamometer.

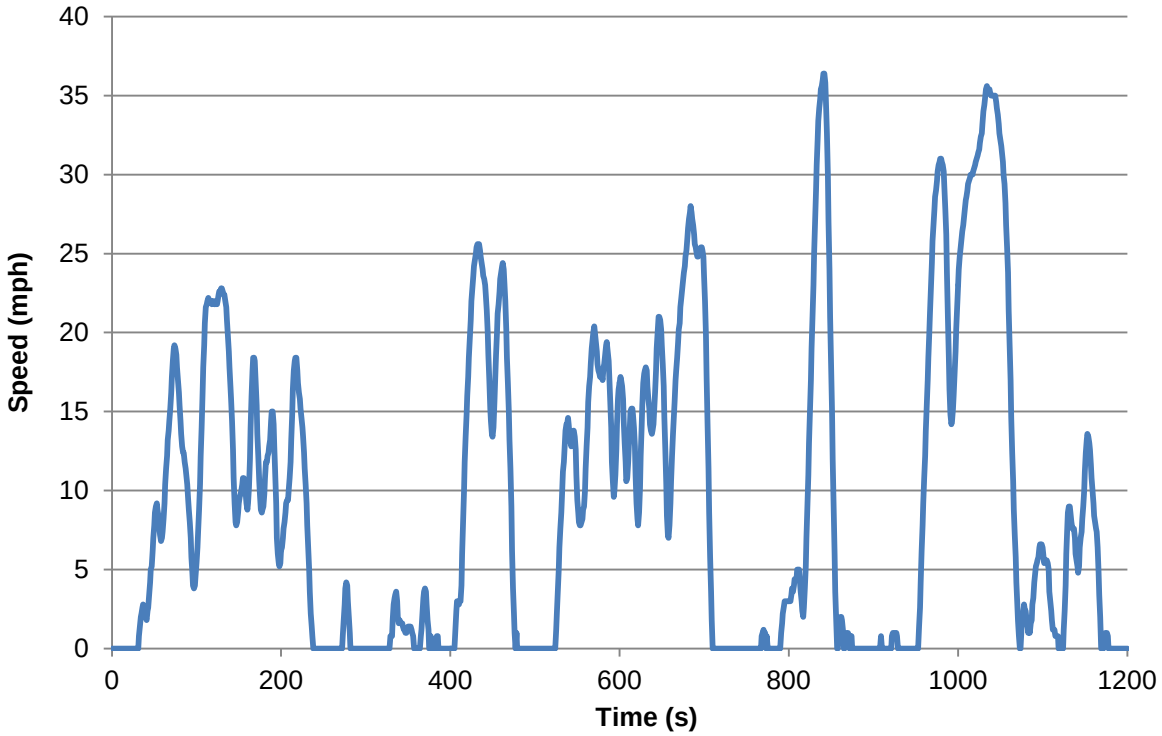
3.5.1.1 Duty Cycle Development Procedure

Data used to develop the duty cycles were logged from two Class 8 tractors used in beverage delivery service in Los Angeles. Data collected by CalHEAT included global positioning system (GPS) latitude, longitude, and speed while the vehicles were operated over their typical delivery routes. One of the vehicles was a conventional diesel-powered tractor while the other was powered by a hybrid-electric drivetrain. Data were collected between December 11, 2010 and March 4, 2011 and represented over 900 miles of operation.

Data for the conventional and hybrid tractors was collected with Telogis GPS fleet tracking. The Telogis system continuously monitored each vehicle between December 11, 2010 and March 4, 2011 and recorded continuous vehicle position and speed information. The data were then downloaded as "Fleet Reports" which consisted of time-stamped data points including the vehicle location (address), latitude, longitude and speed. Vehicle load weights were also determined through vehicle delivery logs.

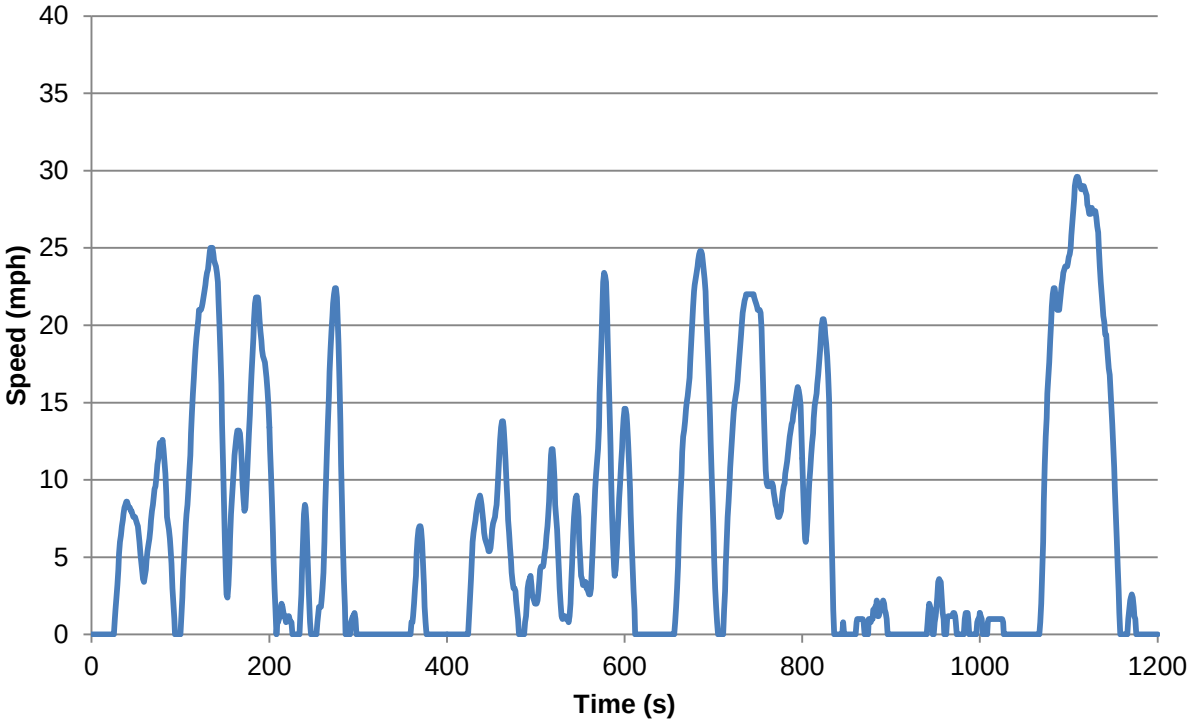
Data was then provided to West Virginia University (WVU) to develop candidate driving schedules by synthesizing randomly combined microtrips, or driving segments, from the "heavy" and "light" speed-time data sets until duty cycles with the desired duration (1200 seconds) were formed.

Figure 3-5: Driving Schedule Composed of Microtrips from Activity Classified as "Heavy"



Source: California Hybrid, Efficient and Advanced Truck Research Center

Figure 3-6: Driving Schedule Composed of Microtrips from Activity Classified as "Light"



Source: California Hybrid, Efficient and Advanced Truck Research Center

3.5.1.2 Duty Cycle Data Collection Issues

According to WVU, developing the duty cycle using data collected from GPS was problematic. For example, when insufficient satellites are visible to the GPS receiver as a result of tunnels, bridges, and nearby buildings, the receiver might record data points with the last known latitude and longitude and a speed of zero. In addition to data points with suspect speed information, there were frequent data dropouts where the parameters, normally recorded at a frequency of 1Hz, would be missing. Another issue with the GPS data was resolution of speed to 1-mph increments that, without processing, would result in extremely discontinuous data. Data processing consisted of four distinct operations and included (1) identifying data segments with anomalous information; (2) determining if the segment was repairable; (3) removing anomalous segments that were not repairable and repairing those that were and; (4) applying a data smoothing algorithm to reduce effects of low resolution speed data.

Acceleration rates of the candidate driving schedules were examined by the Center for Environmental Research and Technology at the University of California- Riverside and found to be acceptable for use on their chassis dynamometer.

3.5.1.3 Duty Cycle Discussion

Two driving speed-time driving schedules for use in evaluating emissions and fuel economy from beverage delivery tractors were developed with each driving schedule being composed of segments of in-use speed-time activity data collected from conventional and hybrid beverage

delivery tractors while operating in the Los Angeles area. Each driving schedule was selected from a group of speed-time driving schedules developed from parent (heavy and light) data based on how well its average speed, standard deviation of speed, percent idle, and percent creep compared to its parent data set. The "heavy" driving schedule was developed using activity data when the vehicle was engaged in outbound activity and in the first half of its daily delivery schedule while the "light" driving schedule was developed using inbound activity from the second half of its daily delivery schedule. The assumed loading for the heavy driving schedule was 38,975 lbs. and, for the light driving schedule, 30,825 lbs. The driving schedules have been forwarded to UC Riverside CE-CERT for review for use on their chassis dynamometer. CE-CERT's initial review found both driving schedules to deceleration and acceleration rates which were acceptable for use on their chassis dynamometer. Table 3-13 below shows the characteristics of the two duty cycles developed.

Table 3-13: Light and Heavy Duty Cycle Characteristics

ID	$_{AVG}$ (mph)	$_{SDev}$(mph)	%Creep	%Idle
Light	10.66	5.36	20.8	33.5
Heavy	11.97	5.97	21.1	32.3

Note: %Creep is defined as the percentage of time the vehicle operates at speeds below 4 MPH and greater than 0 MPH. %Idle is the defined as the percentage of the time the vehicle is idling with the engine on.

Source: California Hybrid, Efficient and Advanced Truck Research Center

3.5.2 Chassis Dynamometer testing

This portion of the final report is derived from UCR CE-CERT's report, "Assessment of the Emissions and Fuel Economy of a Class 8 Conventional and Class 8 Hybrid Truck: Chassis Dynamometer Testing" found in Appendix 3D.

3.5.2.1 Dynamometer Testing Purpose

Emissions testing and analysis was performed at the University of California, Riverside's Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT) in Riverside, California.

The chassis dynamometer test was built on the application of a transient cycle, specifically developed for the beverage delivery trucks by West Virginia University as noted earlier. The duty cycle was used on the UCR heavy-duty chassis dynamometer with prior approval by CE-CERT staff. Emissions were measured with CE-CERT's Mobile Emission Lab and the state of the battery charge monitored while the vehicle followed the transient cycle. Analysis compared the results for both the case of a light load and a heavy load.

Originally, two vehicles from the beverage delivery fleet were tested, one conventional truck, and one hybrid truck. During the first test, HYBRID 1 was tested and the results were inconclusive as the results showed unusual CO_2 emissions for both cycles. Due to the lack of specific emission system temperature parameters being collected during the test, a solid conclusion could not be reached to explain the unusual results. The team cannot confidently

state whether it was an error in the testing or if it was caused by vehicle issues. Therefore, the results were omitted from this report, and a second test was performed using another hybrid truck similar to that used in the beverage fleet to attempt to understand operational characteristics of the hybrid system and eliminate the possible unique test result from the first test. For the second test, a non-service Freightliner hybrid truck was tested with the desired emission system temperature parameters being collected. Also, since Eaton provided a new high capacity battery (approximately 5 kWh vs. roughly 2 kWh) for the hybrid, the team focused on just the "heavy" duty cycle to test the hybrid with the old and new battery packs.

Table 3-14 provides a summary of the specifications for the trucks used during the chassis dynamometer testing. The technologies were all designed to meet 2010 emissions standards, and included both selective catalytic reduction (SCR) and diesel particulate filter (DPF) after-treatment systems. The hybrid vehicles were selected to have power levels similar to those of the conventional vehicle to provide the most comparable test conditions as possible. The Freightliner hybrid truck was a version of the hybrid vehicle similar to the hybrid beverage delivery trucks currently being operated at the test fleet. The fuel for all of the trucks was commercial ultra-low sulfur diesel (ULSD) fuel.

Figure 3-7: Testing of Hybrid Class 8 Beverage Delivery Trucks at UCR CE-CERT

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 3-14: Chassis Dynamometer Test Vehicles

Vehicle Make and Model	Engine Make and Model	Transmission Manufacturer	Electric Motor Power	Engine HP and Torque	Fuel	Odometer	Exhaust After treatment
Conventional Diesel Truck							
Freightliner M-2 2010 (CONV)	Cummins ISC-300 8.3L	Allison	NA	300 HP 860 LB/FT	ULSD	13,848	DPF & SCR
Freightliner Hybrid Truck							
Freightliner M-2 2010 Hybrid (HYBRID 4)	Cummins ISB 6.7L-325	Eaton	40 kW	325 HP 750 LB/FT	ULSD	1,467	DPF & SCR

DPF = diesel particulate filter; SCR – selective catalytic reduction
‡ Tested with 370 and 350.4 nominal voltage battery

Source: California Hybrid, Efficient and Advanced Truck Research Center

Results

Fuel Economy Results

Table 3-15: Chassis Dynamometer Fuel Economy Test Results

	Carbon Balance Fuel Economy (mpg)	
	Using Engine Control Module	Using CO2 Emissions
M2 Conventional, Heavy Cycle		
Average	4.68	4.18
Std. Dev.	0.12	0.06
Freightliner Hybrid, New (5 kWh) Battery, 20 minutes between Heavy Cycles		
Average	6.27	6.53
Std. Dev.	0.21	0.35
%Improvement	34.13%	56.22%
Freightliner Hybrid, Old (2 kWh) Battery, 20 minutes between Heavy Cycles		
Average	6.08	6.56
Std. Dev.	0.06	0.21
%Improvement	30.06%	56.80%

Source: California Hybrid, Efficient and Advanced Truck Research Center

This table shows that, using output from the engine control module (ECM) as well as a measure of CO_2 emissions, the hybrid has higher fuel economy on an MPG basis than the conventional engine for the heavy cycle. The hybrid showed an emission-based increase in fuel economy of 56.2 percent and an ECM-based improvement of 34.1 percent for the new 5 kWh battery with a 20-minute key-off soak between cycles. With the old 2 kWh battery, and the 20-minute key-off soak, the hybrid showed a fuel economy improvement of 56.8 percent using CO_2 emissions and a 30.1 percent increase in fuel economy using the ECM. This is consistent with previous studies that have shown fuel economy reductions for similar hybrid configurations and indicates that the in-use fuel economy improvements with the hybrid technology can be significant.

Emissions results

Table 3-16: Chassis Dynamometer Emissions Results

	Emissions (g/mile)					
	THC	CH4	NMHC	CO	NOx	CO2
Conventional, Heavy Cycle						
Average	-0.08	0.03	-0.11	0.14	3.01	2380.38
Std. Dev.	0.00	0.01	0.01	0.08	0.90	36.21
Freightliner Hybrid, New Battery, 20 minutes between Heavy Cycles						
Average	-0.14	0.00	-0.14	0.16	3.02	1526.49
Std. Dev.	0.10	0.04	0.06	0.03	0.49	81.20
% Improvement	-84.5%	105.0%	-36.5%	-18.3%	-0.2%	35.9%
Freightliner Hybrid, New Battery, 1 minute between Heavy Cycles						
Average	-0.27	-0.05	-0.22	-0.08	1.76	1336.29
Std. Dev.	0.00	0.01	0.01	0.03	0.32	23.99
% Improvement	-242.0%	292.9%	-106.7%	154.4%	41.6%	43.9%
Freightliner Hybrid, Old Battery, 20 minutes between Heavy Cycles						
Average	-0.15	0.00	-0.15	0.31	2.39	1518.72
Std. Dev.	0.11	0.06	0.05	0.01	0.45	47.50
% Improvement	-95.9%	107.8%	-44.4%	-125.6%	20.6%	36.2%
Freightliner Hybrid, Old Battery, 1 minute between Heavy Cycles						
Average	-0.29	-0.07	-0.22	-0.17	2.05	1403.65
Std. Dev.	0.00	0.01	0.00	0.00	0.15	29.25
% Improvement	-268.0%	359.3%	-109.3%	226.7%	31.9%	41.0%

Source: California Hybrid, Efficient and Advanced Truck Research Center

Unexpectedly, the hybrid showed higher CO_2 emissions than the conventional engine when a 20 minute key-off soak was used between the test cycles. During discussions with the project team, it was determined that a low catalyst temperature may be a potential cause for the unexpected results. The team then decided to perform a second test without the light cycle and replace it with testing the heavy cycle using a 1-minute soak to ensure the catalyst was up to the required temperature. With a 1-minute key-off soak, the CO_2 emissions for the hybrid were significantly reduced. The reduction of the CO_2 emissions with a 1-minute key-off soak seems to confirm that the higher CO_2 emissions occur during conditions when the catalyst has not reached its appropriate "light-off" temperature. It should be noted that the CO_2 emissions for all vehicles tested appear to be well below the certification levels. The emissions results cannot be directly

compared with certification results since the certifications are done on an engine dynamometer using a measurement of g/bhp-hr, as opposed to on a vehicle chassis using measurements of g/mi.

Also unexpectedly, the THC and NMHC emissions were negative for all test conditions. This is due in part to the emissions levels being close to the background levels in the dilution tunnel. This may also indicate that the catalyst destroys 100 percent of the THC and NMHC emitted by the engine and some of the THC and NMHC in the ambient air. The average CH_4 emissions were negative for the Freightliner hybrid for all test conditions, so the catalyst on this truck may also be capable of destroying 100 percent of the engine-emitted CH_4 and some of the CH_4 in the ambient air. The NO_x emissions for the hybrid were approximately the same as those from the conventional vehicle for the 20-minute key-off soak with the new battery, and lower than the conventional vehicle for the 20-minute key-of soak with the old battery and lower for both batteries for the 1-minute key-off soak.

3.5.2.2 Dynamometer Test Conclusions

Using the old 2kWh battery, the hybrid truck showed an improvement of 30 percent over the conventional truck on the heavy cycle. The chassis dynamometer test indicated that the larger battery system improved fuel economy performance by an additional 4 percent, resulting in a 34 percent improvement over the conventional unit. This is better than the demonstrated fuel economy improvements that were noted in the field testing of the vehicles due to the controlled environment of the dyno test.

As discussed earlier, in the first dyno test, there were some contradictory results shown in the emissions of CH_4, CO_2, and NOx which were higher in the hybrid vehicle than they were in the conventional. The CO_2 was particularly much higher than expected and caused the team to question its source. The team members consisting of representatives from CalHEAT, UCR, Eaton, Freightliner, and Cummins s decided to perform the test again as the team cannot confidently identify where the problem came from.

It was suggested that spikes in the emissions were possibly due to the hybrid engine operating at a lower load during transients with the hybrid system absorbing some of the load and the after-treatment system being too cool to react to a transient load change. It was difficult to determine if this was the case from the initial test data since diesel oxidation catalyst (DOC) temperature was not directly monitored.

Therefore, it was determined that it would be best to accomplish another dynamometer test and better instrument the catalyst to understand its relationship to the emissions results. Although the original vehicle was not available for the test, a matching vehicle was used and would also help determine if the previous results were unique to one vehicle. Eaton pointed out that they would be up-fitting this vehicle with a larger battery and newer software, so the team decided to take advantage of this and acquire data on both the original hybrid and upgraded battery configurations.

Although it may not be technically valid to compare the second dyno test data with the first test due to different ambient conditions and the considerable intervening time, we can draw some

general conclusions. First, during both the first and second dyno tests there were CO_2 spikes evident in the data when there were 20-minute cool downs allowed between runs. Data from the second test with the DOC instrumented indicates that the spikes occurred during a hard acceleration transient from low speed to a higher speed before the DOC had warmed to above approximately 200^0 C. This most likely occurs in the hybrid because the electric motor shares some of the acceleration power required, lessening the load on the internal combustion engine, increasing the time to warm up for the catalyst.

Based on the results of testing, it could be suggested that, in order to ensure hybrid emissions are consistently lower than conventional vehicles across all operational regimes, improvement in the integration of the exhaust after-treatment system with the hybrid system should be implemented, while maintaining drivability and fuel efficiency of the vehicle.

3.6 Conclusion

The three hybrid trucks (two Freightliner M-2s and one Kenworth T370) showed improvements in fuel economy over the conventional Freightliner M-2 truck. The real-world-operation MPG improvements on the three hybrids ranged from 11.6 percent to 22.6 percent. While a number of variables can contribute to the range of fuel economy benefits, the difference may be primarily due to the difference in the duty cycle of the test vehicles operating within the City of Los Angeles and parts of surrounding areas. Despite the difference in duty cycles, the hybrid vehicles showed an improvement over the conventional with an average fuel economy improvement of about 16 percent.

In addition to testing for the fuel economy benefits of the hybrids, two surveys and interviews were conducted with drivers to determine the usability of the hybrid beverage delivery trucks. While a majority of the feedback provided by the drivers of the hybrid utility truck was positive, the features of the hybrid beverage delivery truck that were rated most consistently as "worse" were for pulling power with load and acceleration. Others features of the hybrid beverage delivery truck most consistently rated the same or better than the diesel beverage delivery trucks were coasting, braking, smoothness of shifting under acceleration, in-cab controls, interior noise level, and exterior noise level. The results were generally positive with the drivers viewing the hybrid beverage delivery truck as equal to or better than the conventional truck for most vehicle characteristics including overall vehicle rating.

Mechanics were also surveyed and interviewed to determine the serviceability of the hybrid trucks. Based on the mechanic surveys, 100 percent of the mechanics gave the hybrid beverage delivery trucks a rating of "acceptable" or "good" regarding hybrid training, maintainability, serviceability, and manufacturer support. In addition, as part of the evaluation for service and maintenance, vehicle availability was also considered. Based on the discussions with the maintenance staff at the end of the project, the average availability of the hybrid beverage delivery trucks over the 8-month performance testing period was 100 percent based on hybrid drivetrain and engine reliability. The average availability of the diesel beverage delivery truck was also 100 percent.

Finally, in order to assess the efficiency and emissions of the hybrid truck compared to a conventional truck in a controlled laboratory setting, CalHEAT performed a chassis dynamometer test at University of California, Riverside. The hybrid showed higher CO_2 emissions than the conventional engine when a 20-minute key-off soak was used between the test cycles. During discussions with the project team, it was determined a low catalyst temperature may be a potential cause for the unexpected results. The team then decided to perform a second test without the light cycle and replace it with testing the heavy cycle using a 1-minute soak to ensure the catalyst was up to the required temperature. With a 1-minute key-off soak, the CO_2 emissions for the hybrid were significantly reduced. The reduction of the CO_2 emissions with a 1-minute key-off soak seems to confirm that the higher CO_2 emissions occur during conditions when the catalyst has not reached its appropriate "light-off" temperature. All other emissions such as NOx, THC, methane, and NMHC for the hybrid were similar to or lower than those of the conventional truck. It should be noted that the CO_2 emissions for all vehicles tested appear to be well below the certification levels.

The hybrid truck showed an improvement of 30 percent over the conventional truck on the heavy cycle. The chassis dynamometer test indicated that the larger battery system improved fuel economy performance by an additional 4 percent, resulting in a 34 percent improvement over the conventional unit.

CHAPTER 4:
Testing and Demonstration of Plug-In Parcel Delivery Vehicles

4.1 Executive Summary

This final report presents results, findings and recommendations of the testing and demonstration of battery electric parcel delivery trucks operated by a large parcel delivery fleet in Los Angeles, CA. This report presents the results of a comprehensive performance evaluation of three battery electric truck models (see Figure 4-1) using information and data from in-use data collection, on road testing and chassis dynamometer testing.

Figure 4-1: A Navistar eStar, a FCCC MT E-Cell and a Smith Electric Newton Step Van

E-Truck Performance Evaluation

Seven trucks were selected for the in-use data collection activity. Five of the trucks were battery electric trucks or E-Trucks (four Navistar eStars and one Freightliner Custom Chassis MT E-Cell). From March 26 to December 18, 2012, the four Navistar eStars drove a combined total of 9,082 miles and consumed 9,496 kWh for an average AC energy consumption of 1.05 AC kWh per mile, equivalent to 35.8 MPG. From June 26 to December 18, 2012, the FCCC MT E-Cell covered 1,306 miles and consumed 1,986 kWh for an average AC energy consumption of 1.52 AC kWh per mile, equivalent to 24.7 MPG. The vehicles covered between 220 and 330 miles per month and consumed between 230 and 360 AC kWh per month. Most of the days, the eStars drove less than 30 miles per day and used less than 20 percent of the battery capacity.

Two conventional diesel trucks (Isuzu Reach Vans) were used to collect baseline data for comparison. For a period of three weeks, the two Isuzu Reach Vans drove a combined total of 844 miles. Their lifetime fuel economy was between 10.9 and 11.5 MPG.

Data showed that E-Trucks are more efficient than conventional diesel vehicles, with E-Truck efficiency being up to 4 times better than the fuel efficiency of similar diesel vehicles. E-Trucks are also cheaper to operate since they are more efficient and are generally fueled with cheap electricity. E-Truck yearly fuel cost is up to 80 percent lower than diesel fuel cost. With no tailpipe emissions, E-Trucks are cleaner to operate than vehicles fueled with fossil fuels. On a well-to-wheel basis, E-Trucks emit up to 70 percent less greenhouse gases when recharged with California electricity. Using domestically produced electricity, E-Trucks use almost no crude oil.

One prototype FCCC MT E-Cell was tested by the Electric Vehicles Technical Center of Southern California Edison over two routes designed on local street roads. The main goal of this task was to evaluate the maximum vehicle range, energy consumption from the grid in kWh in mile and total charging time following a controlled testing process.

Table 4-1: Summary of MT E-Cell on-road testing data

	Urban Range Test **Min. Payload**	**Urban Range Test** **Max. Payload**	**Delivery Route** **Min. Payload**
Duration of Drive	2h 52min	2h 15min	3h 28min
Total Distance Travelled	67.6 miles	56.2 miles	56.5 miles
Low Indicator Range	53.6 miles	44.9 miles	45.6 miles
Power Limiting Range	66.1 miles	55.8 miles	54.5 miles
Charge Duration (bulk of the charge)	13h 15min	13h 45min	13h 20min
Total Charge Energy	66.8 AC kWh	67.5 AC kWh	67.4 AC kWh
AC Energy Consumption	0.99 AC kWh/mile	1.20 AC kWh/mile	1.19 AC kWh/mile

The total vehicle range was measured between 56 and 68 miles depending on the payload and duty cycle. Vehicle efficiency was calculated between 1.0 and 1.2 AC kWh/mile, equivalent to 31.3 and 37.6 MPG.

Charging duration was measured as about 13 hours and 30 minutes to reach the bulk of the charge and can take up to 17 hours and 30 minutes to reach a full charge. A continuous power draw of 260 to 300 W was recorded after the charge was completed and until the vehicle was unplugged.

A Smith Electric Newton Step Van was tested on a chassis dynamometer at the Center for Environmental Research and Technology of the University of California, Riverside over two standardized drive cycles (the Hybrid Truck Users Forum Parcel Delivery Class 4 – HTUF4 and the Orange County Bus Cycle – OCBC) as well as a steady state range test. The main goal of this task was to evaluate maximum vehicle range, energy consumption from the grid in kWh per mile and total charging time.

Table 4-2: Summary of the chassis dynamometer main results

Test Cycle	Overall AC Energy Consumption	Equivalent MPG	Total Driving Range
HTUF4	0.81 AC kWh/mile	46.4 MPGe	110.7 miles (estimated)
OCBC	0.88 AC kWh/mile	42.7 MPGe	101.9 miles (estimated)
Steady State	0.98 AC kWh/mile	38.4 MPGe	91.6 miles (measured)

The Newton Step Van reached the best equivalent fuel economy and the lowest energy consumption on the HTUF4 drive cycle. Total driving range was estimated as 110.7 miles. The OCBC drive cycle, with more accelerations and decelerations, is a more intensive drive cycle and thus, equivalent fuel economy was lower and energy consumption higher than for the HTUF4 cycle. Total driving range was estimated as 101.9 miles. As expected, the Newton Step Van had the lowest equivalent fuel economy and the highest energy consumption on the steady state range test. Total driving range was measured as 91.6 miles.

The bulk charge duration (battery SOC goes from 0 to 100 percent) took about 13 hours and total charge duration took about 14 hours and 20 minutes (battery SOC goes from 0 to 100 percent and battery current drops to 0). A continuous power draw of 65 to 140W was measured after the charge was completed and until the vehicle was unplugged.

E-Truck User Acceptance

In order to assess the user acceptance of the E-Trucks, we conducted surveys and interviewed several fleet staff. Comparisons were made between electric and conventional trucks to determine the advantages and disadvantages during normal everyday use. Driver surveys assessed the performance of the E-Trucks and the mechanics surveys assessed their serviceability and maintainability.

The user acceptance surveys and interviews revealed several E-Truck specific issues on the Navistar eStar. Particularly, drivers noted the long time needed to start the vehicle. However, complaints also originated from vehicle design issues, unrelated to E-Truck specific characteristics. The eStar had design characteristics that were not fully adapted to parcel delivery operation and as a result, driver operations were considerably slowed down compared to a conventional vehicle. The user acceptance surveys and interviews also revealed a gap in

driver training. With the eStar in particular, there were more than a few new operating steps that drivers needed to assimilate.

Service and Maintenance

The E-Trucks encountered several issues that made them generally less available than conventional diesel trucks. Since these vehicles were early production vehicles and had limited in-service experience, maintenance issues were anticipated to arise during the project performance period. Fleet mechanics had limited experience with E-Truck maintenance procedures and thus, all major repairs were handled by the E-Truck manufacturers. In addition, E-Truck manufacturers carried a limited inventory of spare parts.

From general maintenance costs and maintenance intervals data, we estimate that for an E-Truck operating from the downtown Los Angeles facility, maintenance savings would be around $250 per year, or 2-3¢ / mile for a vehicle that drives about 10,000 miles per year without including brakes and tires savings. For a vehicle that drives about 15,000 miles per year and including some brake and tire savings, we estimate that maintenance savings would be around $1,300 per year, or equivalent to 8-10¢ / mile.

E-Truck Charging

Based on the in-use data collection, on-road testing, and chassis dynamometer testing, a comprehensive analysis of E-Truck charging was developed to evaluate E-Truck charging patterns in parcel delivery operation and assess the impacts of E-Trucks charging on the building where they are recharging as well as on the local and state grid.

Typical charge duration for the FCCC MT E-Cell was measured between 12 and 14 hours to achieve the bulk of the charge and over 17 hours to achieve a full charge. Maximum charging current was recorded at 23.2 A (AC) and maximum grid charging power at 5.6 AC kW. A continuous power draw of 260 to 300 W was recorded after the charge was completed and until the vehicle was unplugged.

Total charge duration for the Navistar eStar was estimated between 12 and 13 hours. Maximum charging current was recorded at 24.3 A (DC) and maximum grid charging power was estimated at 8.8 AC kW.

At a continuous charging current of 32A, typical charge duration for the Smith Electric Newton Step Van was measured at about 13 hours to achieve the bulk of the charge and 14 hours and 20 minutes to achieve a full charge. Maximum charging current was recorded at 17 A (DC) and maximum grid charging power at 6.7 kW. A continuous power draw of 65 to 140W was measured after the charge was completed and until the vehicle was unplugged.

Findings and Recommendations

The findings of this report confirm the good fit of E-Trucks for parcel delivery applications previously identified by the CalHEAT roadmap. This report also informs fleets and E-Truck manufacturers on the overall performance of E-Trucks, provides insights on how the technology can be improved on the one hand and better used on the other hand and gives

information to the CalHEAT roadmap to outline actionable steps on the electrification pathway identified by the roadmap. The key findings and recommendations of this report fall into five major categories:

Performance:

Table 4-3: Summary of E-Truck performance key findings

E-Truck Performance Key Findings	Report Section(s)
Operating conditions impact E-Truck performance	4.4.2 – 4.4.3
AC energy consumption is a better measure of overall vehicle efficiency	4.4.1 – 4.4.3
E-Trucks are more efficient and cheaper to operate	4.4.3 – 4.4.4
E-Trucks are cleaner to operate on a well-to-wheels basis	4.4.3 – 4.4.4
Different data collection methods exist to evaluate E-Truck performances	4.4.1 – 4.4.3

Recommendations:

1. Further testing should be carried out to better understand the impact of operating conditions on E-Truck performance.
2. AC kWh/mile should be used to compare the efficiency of E-Trucks with other vehicles.
3. Appropriate data collection techniques should be used to provide better performance data on E-Truck deployment projects.

Maintenance:

Table 4-4: Summary of E-Truck maintenance key findings

E-Truck Maintenance Key Findings	Report Section(s)
E-Trucks need strong maintenance repair networks	0
E-Trucks have lower maintenance costs	0

Recommendations:

1. Local and regional maintenance repair networks as well as spare parts inventories need to be developed in correlation with E-Truck sales. In addition, fleet mechanics need to be trained to diagnose and service E-Truck maintenance issues.

2. A more complete analysis is needed to further investigate and understand the potential maintenance savings of E-Trucks.

Fleet deployment:

Table 4-5: Summary of E-Truck fleet deployment key findings

E-Truck Fleet Deployment Key Findings	Report Section(s)
Train E-Truck drivers	4.4.5 – 4.5.2
Assign "early-adopter" drivers	4.5.2

Recommendations:

1. Drivers operating E-Trucks should be trained and coached to adapt their driving techniques to E-Trucks to take advantage of regenerative braking for instance.
2. "Early adopters" drivers should be selected first for E-Truck deployment project in order to build a positive experience.

Charging:

Table 4-6: Summary of E-Truck charging key findings

E-Truck Charging Key Findings	Report Section(s)
Charging infrastructure is an important component of any E-Truck deployment project	0
Charging time depends on charging infrastructure	0
E-Truck "stand-by" power can negatively impact overall energy consumption	4.4.2 – 4.4.3 – 0
Impacts of E-Truck charging will be focused on building and local grid infrastructure	0

Recommendations:

1. Fleet managers should carefully plan E-Truck deployments to minimize charging infrastructure costs.
2. The charging current should be specified to guarantee vehicle availability.
3. Further testing should be carried out to better understand the origin of the stand-by current draw of E-Trucks when plugged in but not charging and explore ways to reduce its impact on overall E-Truck efficiency.
4. Demand response strategies should be implemented to take advantage of low energy prices such as Time-of-Use pricing and avoid penalties such as demand charges.

5. Electric utilities and companies deploying E-Trucks need to work together to share the costs of local infrastructure upgrades in a way that is fair for ratepayers and acceptable for utility cost recovery structures but does not deter companies from deploying E-Trucks.

Business case:

Table 4-7: Summary of E-Truck business case key findings

E-Truck Business Case Key Findings	Report Section(s)
Use E-Trucks on higher mileage routes	4.4.1 - 0
Incentives for purchase play a crucial role for the early E-Truck market	0
Right-sizing E-Truck battery is a viable cost reduction pathway	0
Future battery prices will make E-Trucks more cost competitive	0
Vehicle-To-Grid could improve the business case for E-Trucks	0

Recommendations:

1. E-Trucks should be deployed on routes with daily mileage greater than 50 miles.
2. Incentive funding needs to be available at this early stage of the E-Truck market.
3. Fleets, battery and E-Truck manufacturers should work together to develop, test and demonstrate E-Trucks with scalable battery packs.
4. Fleets, battery and E-Truck manufacturers should work together to reduce battery costs.
5. Fleets, battery and E-Truck manufacturers should work together to develop, test and demonstrate V2G options for E-Trucks in delivery applications.

4.2 Introduction

The California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center was established in 2010 by the Energy Commission to perform research in planning, commercializing and demonstrating truck technologies for efficient medium- and heavy-duty vehicles. This project was part of a larger research and demonstration effort within the CalHEAT Research Center and focused on evaluating the performance of plug-in electric parcel delivery trucks in Southern California. Battery electric trucks or E-Trucks are expected to play an important role in the future of medium and heavy-duty transportation in California and will help the State achieve its long term goals of reducing petroleum use and greenhouse gas (GHG) emissions and improving air quality.

4.2.1 Purpose of the Report

This report presents the testing and demonstration results of E-Trucks in parcel delivery application. The goal of the report is twofold. First, the testing and demonstration of E-Trucks provide information to the CalHEAT roadmap to outline actionable steps on the electrification pathway identified by the roadmap (see section 0).

The second goal is to inform fleets and E-Truck manufacturers on the overall performance of E-Trucks and provide insights on how the technology can be improved on the one hand and better used on the other hand. E-Truck technology is relatively new to the market, as commercial E-Trucks have been introduced only in the past few years. By providing unbiased, third-party assessment of this technology, we believe this report will offer relevant, timely and valuable information to the industry.

This project evaluated the performance of several E-Truck models that are presented in Section 4.3. A comprehensive performance evaluation is covered in Section 4.4 which includes review of information from in-use data collection, on-road testing and chassis dynamometer testing. User acceptance is detailed in Section 4.5 followed by a preliminary reliability and maintenance evaluation of E-Trucks in Section 4.6. E-Truck charging is covered in detail in Section 4.7. Finally, a business case analysis for E-Trucks is detailed and main findings and recommendations are presented in Section 4.8.

4.2.2 CalHEAT Roadmap and Electrification of Transportation

The CalHEAT Research Center was established to support commercialization and demonstration of truck technologies that will help California meet or exceed its 2020 goals in petroleum reduction, carbon reduction, and air quality standards, and identify longer term goals through 2050. The CalHEAT roadmap focuses on medium- and heavy-duty vehicle technology strategies and identifies action items to help mitigate emissions and improve efficiency of trucks [1]. Overall, the action items focus on 13 technology strategies which are grouped broadly into (1) electrification strategies, (2) engine or driveline efficiency strategies, and (3) chassis, body and roadway systems. Electrification technology strategies are particularly important as they are seen as the principal way to reduce petroleum dependence and decrease emissions. The electrification technology strategies include the following:

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

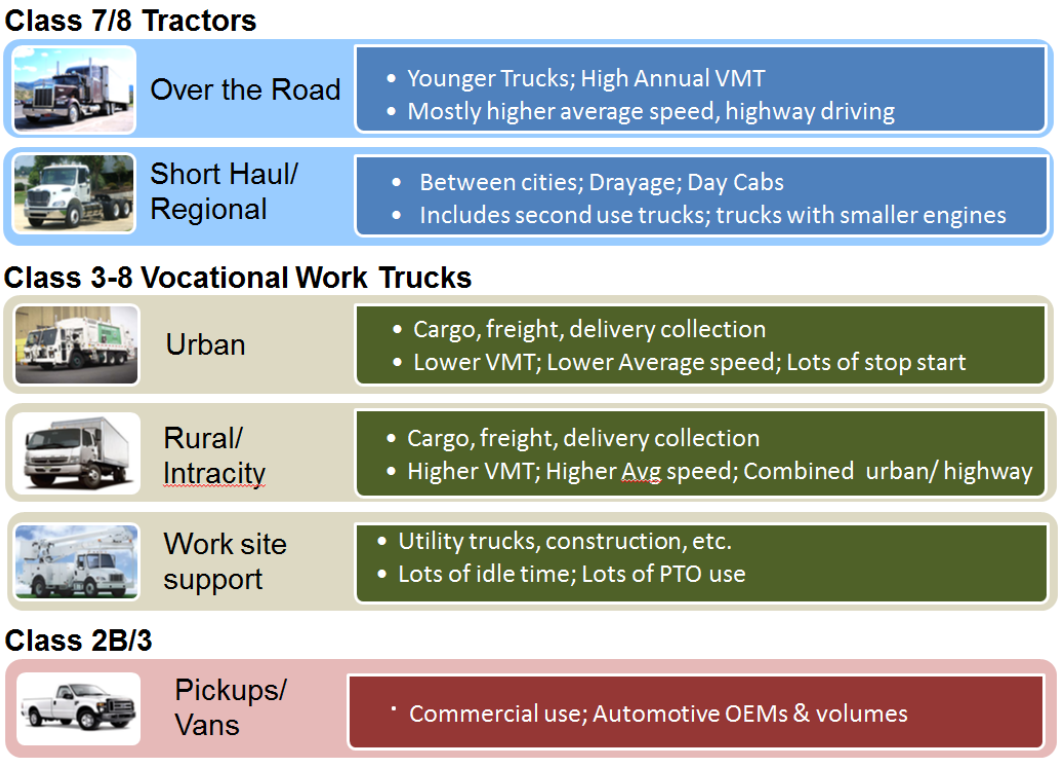
The findings and recommendations of this report support the E-Truck technology strategy of the CalHEAT Roadmap. Although E-Trucks remain significantly more expensive than conventional vehicles, have limited driving range and require a dedicated charging infrastructure, they provide transportation with no tailpipe emissions and well-to-wheel emissions defined by the source of the electricity used to recharge the batteries.

The roadmap identified three technology stages for E-Trucks. Stage 1 is the current stage, Stage 2 would follow in the 2013-2017 timeframe, and Stage 3 from 2017-2020. The main goals of Stage 2 and 3 are to reduce the payback period to 5-8 years and finally to 3-5 years. This would be accomplished with the achievement of the following technical capabilities:

- Improved integration of the electric driveline.
- Optimization of system design.
- Development of standards for battery packs in multiple sizes.
- Fast charging.
- Controlled V2G and smart charging.
- Energy storage compatible with rapid charging.
- Option for cost effective use of smaller batteries.
- Secondary market for energy storage.

To better understand the impact of different technology strategies, the roadmap identified six truck categories to classify the various types of medium and heavy-duty vehicles used in California. The truck categories were defined by vehicle weight, vocation and duty cycle characteristics. The six different CalHEAT trucks categories are described in Figure 4-2.

Figure 4-2: CalHEAT truck classifications, by weight and application [1]



The roadmap identified that E-Trucks will play a noticeable role in the Class 3-8 Vocational Work Trucks - Urban category. This truck category includes delivery applications such as cargo, freight and package delivery and is characterized by lower vehicle miles travelled, lower average speed and high number of stops. Therefore parcel delivery vehicles are good candidates for testing and demonstrating the benefits of E-Trucks.

4.2.3 Battery Electric Trucks for Parcel Delivery

According to the truck inventory of California vehicles carried out by the CalHEAT Research Center, there were about 253,000 Class 3-8 work-urban trucks in California in 2010. They represented 17 percent of the total truck population in California and were responsible for 11 percent of the yearly total truck greenhouse gas (GHG) emissions [1]. This report focused on Class 3-4 vocational work trucks - urban and we estimated that there were about 70,000 of them in the state. If 10 percent of these Class 3-4 vocational work trucks - urban were E-Trucks, we estimate that it would represent 224,000 barrels of oil saved and a reduction of 56,700 metric tons of GHG emitted in the atmosphere every year.[32]

[32] We assumed E-Trucks would replace diesel trucks driving 15,000 miles per year with a 12 MPG fuel economy. We also assumed that producing and burning 1 gallon of diesel emits 12.9 kg of CO_2 equivalent on a well-to-wheel basis, while the carbon intensity of California electricity is 0.45 kg of CO_2 equivalent per kWh. We also assumed that 1,000 gallons of diesel required 25.7 barrels of oil to be produced and transported, while 1,000 kWh of California electricity requires 0.0125 barrels of crude oil to be produced [4].

As of June, 2013, 382 vouchers had been funded for electric vehicles through the California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), including 329 for medium- and heavy-duty electric trucks [2]. Although this number may not be representative of the number of E-Trucks currently on the road, it is a good estimate of the state of the E-Truck market in California. In addition, since its first year in 2010, the California HVIP has been responsible for about 75 percent of E-Trucks sales in the U.S. [3].

A number of E-Truck models dedicated to parcel delivery are currently commercially available. The list below provides a brief description of the characteristics for each model.

Boulder Electric DV500

Address:

1460 Overlook Drive

Lafayette, CO 80026

Website:

http://www.boulderev.com/

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
Up to 100 miles	LiFePO4 72 kWh	11,500 lbs. Class 3	4,000 lbs.	534 ft^3 15.1 m^3	75 mph	Yes

EVI Walk-In Van

Address:

1627 Army Court, Suite 1

Stockton, CA 95206

Website:

http://www.evi-usa.com/

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
Up to 90 miles	LiFeMgPO4 99 kWh	16,001 & 23,000 Class 5 & 6	-	662 & 970 ft^3 18.7 & 27.5 m^3	65 mph	Yes

FCCC MT E-Cell Plug-In EV Truck

Address:

552 Hyatt St.

Gaffney, SC 29341

Website:

http://freightlinerchassis.com/

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
65-90 miles	LiFeMgPO4 78-99 kWh	14,001 & 26,000 Class 4 to 6	-	-	65 mph	No

Smith Electric Newton Step Van

Address:

12200 N. W. Ambassador Drive,

Kansas City, MO 64163

Website:

http://www.smithelectric.com/

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
Up to 80 miles	LiFePO4 80 kWh	16,500 Class 5	5,570 lbs.	684 ft^3 19.4 m^3	~63 mph	Yes

The CalHEAT roadmap identified the delivery application as a good fit for E-Trucks [1]. The following characteristics make E-Trucks and parcel delivery a good match:

- Vehicles operate in dense urban areas characterized by low speeds and stop-and-go operation.
- Vehicles operate on a fixed route covering less than 100 miles per day.
- Vehicles return to the same depot every day where they can be recharged.
- Vehicles can be recharged overnight.
- Electric motors are able to produce maximum torque at low speeds, giving E-Trucks strong driving characteristics, particularly in stop-and-go or urban driving situation.
- Electric motors also offer the ability to operate with very low noise, an advantage in certain delivery applications.

To the best of our knowledge, this report is the most comprehensive testing and demonstration study of E-Trucks in parcel delivery application to date. While other evaluation efforts have involved a large number of vehicles across a wider region, they did not analyze E-Truck performance with the same level of detail. For instance, the U.S. Department of Energy supported two E-Truck performance evaluation projects both managed by the National Renewable Energy Laboratory (NREL):

1) $32M for Smith Electric Vehicles to develop and deploy approximately 500 electric medium-duty trucks with a 100 mile range, and

2) $39.2M for Navistar, Inc. to develop, validate, and deploy 950 advanced battery electric delivery trucks with a 100 mile range.

As of December 31st, 2012, about 200 Smith Electric Newtons were reporting data in 14 states across the nation. Table 4-8 below summarizes some keys parameters of the Smith Newton Vehicle Performance Evaluation. Vehicles were deployed among different truck vocations including delivery [5].

Table 4-8: Summary of the NREL Smith Newton Vehicle Performance Evaluation [5]

Reporting Period	Number of Vehicles	Vehicle days driven	Charge Energy	Total Miles	Avg. Miles Per Day	Overall AC Energy	Overall DC Energy
10/1/2011 - 4/30/2012	187	7996 days	546,408 AC kWh	249,670 miles	31.2 miles/day	2.19 AC kWh/mile	1.72 DC kWh/mile

As of March 31st, 2013, over 100 Navistar eStars were reporting data across the nation. Table 4-9 below summarizes the key parameters of the Navistar eStar Vehicle Performance Evaluation. Vehicles were deployed among several delivery fleets, including parcel delivery [6].

Table 4-9: Summary of the NREL Navistar eStar Vehicle Performance Evaluation [6]

Reporting Period	Number of Vehicles	Vehicle days driven	Charge Energy	Total Miles	Avg. Miles Per Day	Overall AC Energy	Overall DC Energy
7/1/2012 - 3/31/2013	104	6480 days	89,003 AC kWh	96,434 miles	14.9 miles/day	1,01 AC kWh/mile	0.92 DC kWh/mile

4.3 Test Vehicles and Fleet Operations

4.3.1 Description of Test Vehicles

Three different E-Truck models were used for this project: two MT E-Cell All-Electric Delivery Vans from Freightliner Custom Chassis Corporation, four eStars from Navistar and one Newton Step Van from Smith Electric Vehicles. The sections that follow provide descriptions for each vehicle model and their technical characteristics.

4.3.1.1 FCCC MT E-Cell All-Electric Delivery Van

Model Year	2010
Chassis Manufacturer	FCCC
Powertrain Manufacturer	Enova
Battery Manufacturer	Tesla Motors

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
80 to 100 miles	Li-ion 55.5 kWh	14,200 Class 4	4,200 lbs.	550 ft^3 15.5 m^3	55-60 mph	No

Introduced in 2010, the MT E-Cell All-Electric Delivery Van was the result of a joint initiative to develop an all-electric commercial chassis between Enova Systems (EV controls, traction motor, gear box and battery management system), Tesla Motors (battery technology) and FCCC (chassis) [7]. In 2012, the alliance was ended and FCCC now commercializes the MT E-Cell with different partners (see Section 4.2.3). Only 4 units were built and 2 commercialized in this now defunct configuration. Table 4-10 lists the specifications for the MT E-Cell.

Table 4-10: FCCC MT E-Cell vehicle characteristics [8]

Traction Motor	
Peak power	160 HP (120 kW)
Peak torque	479 lb-ft (648 Nm)
Dimensions	
Tires	225/70 R19.5
Wheelbase	138 in.
Overall Length	257 in.
Overall Width	88 in.
Overall Height	118 in.
Cargo Area Length	144 in.
Cargo Area Width	86 in.
Cargo Area Height	83 in.
Rear Loading Floor Height	32 in.
Rear Door Opening Height	60 in.
Rear Door Opening Width	72 in.
Charging	
Connector	NEMA l6-30 charging connector
Charger type	On-board charger for traction battery 220V single phase
Advertised charging time	6 to 8 hours for a full charge

For this project, one E-Cell was in service at the selected facility (named Unit E). In addition, one prototype E-Cell (named Prototype Unit) was made available by FCCC for the road testing done by Southern California Edison (see Section 4.4.2).

4.3.1.2 Navistar eStar

Model Year	2010
Chassis Manufacturer	Navistar
Powertrain Manufacturer	Modec
Battery Manufacturer	A123

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle

Up to 100 miles	Li-ion 80 kWh	12,100 Class 3	4,000 lbs.	417 ft^3 11.8 m^3	50 mph	Yes

The Navistar eStar, a joint venture between Navistar and Modec (a now defunct UK electric vehicle manufacturer), was an all-electric delivery van first introduced in fleet operation in the United States in May 2010. The Navistar eStar project was part of a U.S. Department of Energy program to manufacture and distribute a zero-tailpipe-emission light-duty commercial electric vehicle in the United States. With more than 300 units in service delivered by Modec in Europe and over 100 units delivered by Navistar in the U.S., the Navistar eStar is a widely adopted E-Truck [6] [9]. In March 2013, Navistar disclosed that it had discontinued its eStar electric van [10]. Table 4-11 lists the specifications for the eStar.

Table 4-11: Navistar eStar vehicle characteristics [8]

Traction Motor	
Peak power	102 HP (76 kW)
Peak torque	221 lb-ft (300 Nm)
Dimensions	
Tires	215/75 R17.5
Wheelbase	142 in.
Overall Length	250 in.
Overall Width	77 in.
Overall Height	106 in.
Cargo Area Length	168 in.
Cargo Area Width	74 in.
Cargo Area Height	77 in.
Rear Loading Floor Height	26 in.
Rear Door Opening Height	70 in.
Rear Door Opening Width	61 in.
Charging	
Connector	SAE J1772 charging standard
Charger type	On-board charger for traction battery 220V single phase
Advertised charging time	Approximately 8 hours for a full charge

For this project, four Navistar eStars (named Unit A, B, C & D) were in service at the selected facility.

4.3.1.3 Smith Electric Newton Step Van

Model Year	2012
Chassis Manufacturer	Smith Electric
Powertrain Manufacturer	Smith Electric
Battery Manufacturer	A123 Systems

Advertised Range	Battery	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
Up to 80 miles	LiFePO4 80 kWh	16,500 Class 5	5,570 lbs.	684 ft^3 19.4 m^3	~63 mph	Yes

The Smith Electric Newton Step Van is the latest addition to the Smith Electric product line-up and is one of the latest all-electric trucks to be introduced to the U.S. market. At the end of 2012 nearly 200 Smith Electric Newton vehicles in several configurations (box, refrigerated box, utility boom and stake bed) had been deployed across the United States [5]. Almost 100 were deployed in California alone [2]. Table 4-12 lists the specifications for the Newton Step Van.

Table 4-12: Smith Electric Newton Step Van vehicle characteristics [8]

Traction Motor	
Peak power	180 HP (134 kW)
Peak torque	480 lb-ft (650 Nm)
Dimensions	
Tires	225/70 R19.5
Wheelbase	153.5 in.
Overall Length	274 in.
Overall Width	96 in.
Overall Height	119 in.
Cargo Area Length	156 in.
Cargo Area Width	94 in.
Cargo Area Height	81 in.
Rear Loading Floor Height	36 in.
Rear Door Opening Height	75 in.
Rear Door Opening Width	62 in.
Charging	
Connector	SAE J1772 charging standard
Charger type	On-board charger for traction battery 240V single phase
Advertised charging time	6 to 8 hours for a full charge

For this project, one Smith Electric Newton Step Van was made available by the partner fleet for chassis dynamometer testing done at the Center for Environmental Research and Technology of the University of California, Riverside.

Not all vehicles were used in the same way during this project testing and demonstration. Table 4-13 below summarizes the vehicles used for this project and their roles in the different components of the project.

Table 4-13: Vehicle assignment for the performance evaluation and testing

Vehicles	**Performance Evaluation & Testing**
FCCC MT E-Cell Unit E Prototype Unit	 In service On-road testing
Navistar eStar Unit A / B / C / D	 In service
Smith Electric Newton Step Van	Chassis dynamometer testing

The FCCC MT E-Cell is a Class 4 truck. While it has the smallest battery of the three vehicles tested (55.5 kWh), its performance is comparable to or better than similar conventional diesel trucks with high peak power (160 HP) and peak torque (479 lb.-ft.). Lastly, it does not meet the SAE J1772 recommendations for vehicle charging.

The Navistar eStar is a Class 3 truck and has the smallest payload and cargo volume of the three vehicles tested. It is also less powerful with low peak power (102 HP) and peak torque (221 lb.-ft.). With a top speed of 50 MPH, it is only suited for city roads and cannot operate at highway speeds. The eStar is SAE J1772 compliant.

The Smith Electric Newton Step Van is a Class 5 truck and has the largest payload and cargo volume of the three vehicles tested. With the highest peak power (180 HP) and peak torque (480 lb.-ft.) in this study, its performance is comparable to or better than diesel engines used in similar conventional trucks. It is also SAE J1772 compliant.

4.3.2 Description of Conventional Parcel Delivery Vehicles

A wide variety of conventional vehicles are available for parcel delivery operations. These vehicles are generally separated in 3 categories [11]:

Walk-in vans

Also known as step vans, walk-in vans are particularly well suited for parcel delivery in dense urban areas, with their quick and easy access to cargo. They generally are driven below 15,000 miles per year (or 60 miles per day) [11]. Because of this duty cycle, this vehicle type is well suited for alternative fuels and advanced technologies such as hybrid electric, hydraulic hybrid, CNG and battery electric. Examples of walk-in vans include the MT-45 and MT-55 chassis from FCCC and the Isuzu Reach Van.

Figure 4-3: The MT-45 walk-in van from FCCC

Large vans

Large vans typically drive between 15,000 and 45,000 miles per year (or between 60 and 180 miles per day) [11]. They generally drive at higher average speeds and make fewer deliveries per day than walk-in vans. Examples of large vans include the Sprinter Cargo Van from Mercedes-Benz and the 2014 Ford Transit.

Figure 4-4: The Sprinter Cargo Van from Mercedes-Benz[33]

Panel Vans

Panel vans typically drive over 45,000 miles per year (or over 180 miles per day) [11]. They generally drive at higher average speeds and make fewer deliveries per day than walk-in vans and large vans. Examples of panels vans include the Chevrolet Express Cargo Van or GMC Savana and the Ford E Series Cargo Van.

Figure 4-5: The Chevrolet Express Cargo Van[34]

4.3.3 Description of General Fleet Operation

The five vehicles that were evaluated in parcel delivery service (one MT E-Cell and four eStars) were based in a facility located in downtown Los Angeles, CA. Figure 4-6 shows an aerial picture of the downtown Los Angeles area where the parcel delivery facility where the E-Trucks were based was located. Situated about three miles southwest of the Los Angeles financial district and close to the University of Southern California campus, vehicles from this facility serve a large number of business customers within a 20 mile radius of the depot. In the dense urban area that is downtown Los Angeles, vehicles operating from this facility generally drive

[33] Photo from http://www.mbsprinterusa.com/sprinter/cargo-van

[34] Photo from http://trialx.com/curetalk/wp-content/blogs.dir/7/files/2011/06/cars/2004_Chevrolet_Express_2500_Cargo-1.jpg

less miles per day than comparable facilities located in depots serving less dense suburban areas.

General operating hours for this facility are from 8 a.m. to 8 p.m., with deliveries occurring mostly in the morning and pick-ups in the afternoon.

Figure 4-6: Aerial photo of the downtown Los Angeles area[35]

With over 100 vehicles involved in pick-up and delivery, the downtown Los Angeles depot is an average-size depot for the partner fleet. Vehicles used at this facility are fairly representative of typical parcel delivery operations, with walk-in vans (FCCC MT-45 and MT-55 and Isuzu Reach Van), large vans (Mercedes Sprinter) and panel vans (Ford E Series). However, this facility has been used by the partner fleet as a test bed for alternative technologies such as hybrid electric and is one of the first to have received E-Trucks.

4.4 E-Truck Performance Evaluation

This section discusses the performance of E-Trucks based on in-use data collection (manual and using data loggers), on-road testing, and chassis dynamometer testing. The Navistar eStar and FCCC MT E-Cell vehicles were monitored during the in-use data collection. A prototype MT E-Cell underwent on-road testing, and a Smith Electric Newton Step Van was used for the chassis dynamometer testing. The results provide a comprehensive overview of the performance of commercial E-Trucks in parcel delivery applications in comparison to each other and in comparison to conventional vehicles normally used in this application.

[35] Photo from http://www.photopilot.com

4.4.1 In-Use Data Collection

4.4.1.1 Methodology

Manual Data Collection

We recorded mileage and grid electricity consumption from each E-Truck in operation at the downtown Los Angeles facility: four Navistar eStars (Unit A, Unit B, Unit C and Unit D) and one FCCC E-Cell (Unit E). Both mileage and electricity consumption were read regularly from the end of March to mid-December 2012.

Each vehicle was assigned a specific parking space within the facility and each parking space had a corresponding submeter measuring AC kWh consumed. Mileage was read from the vehicles odometer and grid electricity consumption was read from the assigned submeter (Figure 4-7).

Figure 4-7: eStar dashboard (left) and meters measuring kWh consumption (center & right)

Data Acquisition System

Each E-Truck was equipped with data loggers installed by the vehicle manufacturers to continuously record vehicle, powertrain and battery data during daily vehicle operations. Two conventional diesel trucks were equipped with data acquisition systems provided and installed by CALSTART staff to collect vehicle and route information.

On-Road Testing

One prototype MT E-Cell was made available by FCCC for the on-road testing done by Southern California Edison. Information about the on-road testing and the methodology used can be found in Appendix 4A.

Chassis Dynamometer Testing

For this project, one Smith Electric Newton Step Van was made available by the partner fleet for chassis dynamometer testing done at the University of California, Riverside. More information about the chassis dynamometer testing can be found in Appendix 4B.

4.4.1.2 Results & Discussions

Manual Data Collection

Table 4-14 below presents the summary of the data that was collected for a period of about 10 months.

Table 4-14: Summary of eStar and E-Cell manual data collection

	eStar				**MT E-Cell**
	Unit A	Unit B	Unit C	Unit D	Unit E
Start	3/26/2012	3/26/2012	3/26/2012	3/26/2012	6/26/2012
Finish	12/18/2012	12/18/2012	12/18/2012	12/18/2012	12/18/2012
Miles	1883	2035	2818	2346	1306
AC kWh		3962	3005	2529	1986
AC kWh/mile		1.01	1.07	1.08	1.52

During the data collection period, it was noticed that two eStars (Unit A & B) were exchanging their assigned parking spots, making it difficult to allocate the energy measured to the truck that consumed it. It was decided that the energy measured for these two vehicles would be merged.

We also realized that the submeter used to measure energy for the MT E-Cell was not wired correctly, giving incoherent energy measurements. The issue was reported to fleet management, who had a contractor rewire the submeter. Therefore, all the MT E-Cell data before June 26, 2012 was not usable.

From March 26 to December 18, 2012, the four Navistar eStars drove a combined total of 9,082 miles and consumed 9,496 kWh for an average AC energy consumption of 1.05 AC kWh per mile. From June 26 to December 18, 2012, the FCCC MT E-Cell covered 1,306 miles and consumed 1,986 kWh for an average AC energy consumption of 1.52 AC kWh per mile. Vehicles covered between 220 and 330 miles per month and consumed between 230 and 360 AC kWh per month.

Data Acquisition System

FCCC MT E-Cell

Despite several attempts, we were not able to extract the data from the proprietary data acquisition system installed on this vehicle. Therefore no data was available to analyze.

Navistar eStar

Data collected between March 16 and December 7, 2012 from each eStar was available for analysis. For unit A, nine months of data was available, whereas unit B had only seven months of data was available and unit C & D only six months. Table 4-15 below presents the summary of data that was collected on the four eStars.

Table 4-15: Summary of Navistar eStar data acquisition system data

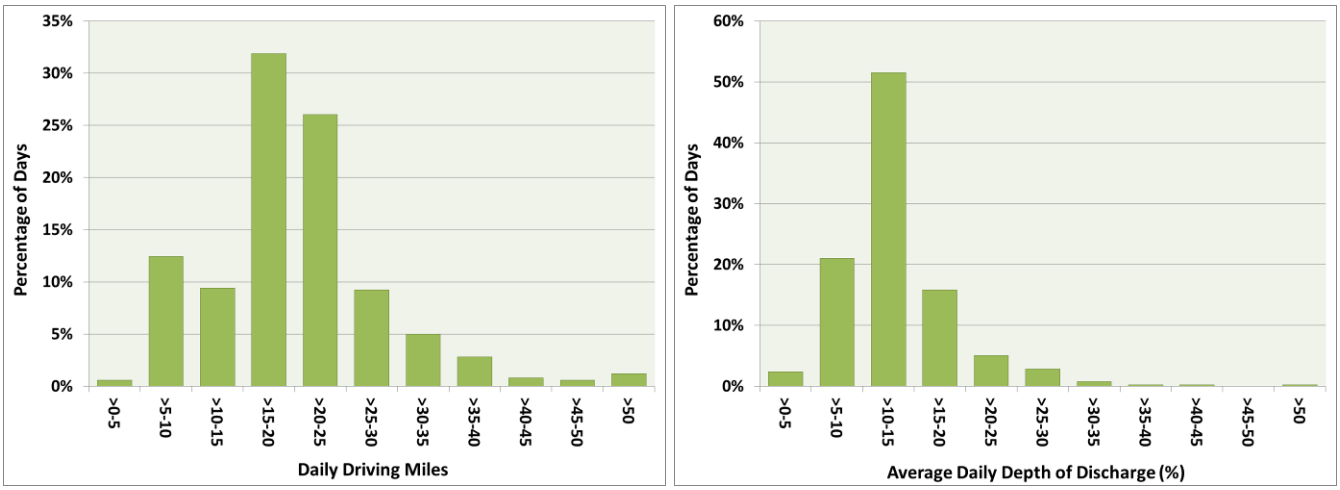
Period of 03/16/12 to 12/07/12	Unit A	Unit B	Unit C	Unit D	Total
Days in operation recorded	148	138	118	95	499
Total miles recorded (miles)	2921	2543	2613	2344	10421
Total miles driven (miles)	3004	3383	4557	3484	14428
Average daily vehicle miles travelled (miles)	20	18	22	25	21
Avg. DC energy consumption (DC kWh/mile)	0.45	0.50	0.49	0.52	0.49
Average daily depth of discharge	11.9%	11.9%	13.8%	16.7%	13.6%
Minimum battery state of charge recorded	28%	67%	46%	51%	28%
Average daily regen. braking recapture rate	22%	22%	24%	23%	23%
Number of charging events recorded	134	134	81	84	433
Average duration of charging event	1h46	1h43	2h43	2h35	2h12
Avg. energy recharged per charging event (DC kWh)	9.9	9.4	15.8	14.5	11.7

The eStars drove an average of 21 miles per day in operation with the minimum for unit B driving 18 miles/day and the maximum for unit D driving 25 miles/day on average.

The average battery depth of discharge was 13.6 percent with a maximum of 16.7 percent, stressing the fact that the eStars were used on low mileage routes, not requiring more than 13.6 percent of the total battery capacity on average. Minimum battery state of charge was measured as 28 percent, following several days when one of the vehicles was not recharged after the end of each shift.

In order to understand vehicle usage in greater details, we plotted the distribution of daily driving miles in increments of five miles and average daily depth of discharge in increments of 5 percent (Figure 4-8).

Figure 4-8: Distribution of daily driving miles (left) and average depth of discharge (right) for eStar



For about 90 percent of the recorded days when the vehicles were in operation, the eStars drove less than 30 miles per day and used less than 20 percent of the battery capacity.

The average DC energy consumption was calculated as 0.49 DC kWh/mile based on data from the data acquisition system. In comparison, from the manual data collection we calculated the average AC energy consumption as 1.05 AC kWh/mile. This large difference between AC "grid" energy[36] and DC "vehicle" energy[37] may be explained by the charger and battery efficiency and the standby current when the vehicle is plugged in to a charger but not drawing any current. This "stand-by" power is likely caused by the low-voltage system batteries and the vehicle accessories (fans, battery cooling system, vehicle display) remaining powered on.

The average daily regenerative braking recapture rate was calculated as 23 percent, indicating that 23 percent of the total energy used for operating the vehicle was energy recovered when braking. The eStar regenerative braking feature improved vehicle efficiency and extended available range by 22 percent.

The number of charging events recorded show that vehicles were not charged every day they were operating. On average the measured charging time was 2 hours and 12 minutes with the minimum for unit B as 1 hour and 43 minutes and the maximum for unit C as 2 hours and 43 minutes on average.

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[36] Energy charging the battery from the point where electricity is introduced from the electric outlet to the battery charger.

[37] Energy charging the battery from the point where electricity is introduced from the battery charger to the battery.

4.4.2 On-Road Testing

4.4.2.1 Purpose

The CalHEAT Research Center contracted with the Electric Vehicle Technical Center (EVTC) of Southern California Edison to test one E-Truck over two2 routes designed by the EVTC on local street roads, and at the safe speed of traffic in order to simulate real-world operation. The test vehicle, a MT E-Cell (see vehicle characteristics in Section 4.3.1.1), was a prototype vehicle used by FCCC for testing and demonstration, similar to the one used by the partner fleet at the downtown Los Angeles facility. The main goal of this task was to evaluate the maximum vehicle range, energy consumption from the grid in kWh per mile and total charging time following a controlled testing process.

Figure 4-9: The MT E-Cell walk-in van used for the on-road testing

Actual electric range and overall energy consumption vary widely with driving conditions such as drive cycle and vehicle accessories utilization. The numbers presented in this report are representative of specific drive cycles and driving conditions and were derived from testing done in a controlled environment. They should not be used to predict electric range and overall energy consumption in different driving conditions.

4.4.2.2 Results

We present below the main results and findings of the road testing. For further information, please see Appendix 4A.

Performance Testing

The performance tests revealed that vehicle acceleration time increases as the battery state-of-charge (SOC) decreases. For instance, the average acceleration time from 0 to 55 MPH was 38 seconds at 80 percent SOC and 51 seconds at 40 percent SOC.

Range Testing (from 100 to 0 percent SOC)

In order to evaluate the total driving range, the vehicle was driven by an experienced driver on two different routes without using auxiliary loads (such as air conditioning and cabin fan) until the vehicle could no longer operate. Then the vehicle was brought back to the EVTC where it was fully charged. Table 4-16 below presents the summary of the on-road testing data.

Table 4-16: Summary of MT E-Cell on-road testing data

	Urban Range Test **Min. Payload**	**Urban Range Test** **Max. Payload**	**Delivery Route** **Min. Payload**
Duration of Drive	2h 52min	2h 15min	3h 28min
Total Distance Travelled	67.6 miles	56.2 miles	56.5 miles
Low Indicator Range	53.6 miles	44.9 miles	45.6 miles
Power Limiting Range	66.1 miles	55.8 miles	54.5 miles
Charge Duration (bulk of the charge)	13h 15min	13h 45min	13h 20min
Total Charge Energy	66.8 AC kWh	67.5 AC kWh	67.4 AC kWh
AC Energy Consumption	0.99 AC kWh/mile	1.20 AC kWh/mile	1.19 AC kWh/mile

The total vehicle range was measured between 56 and 68 miles depending on payload and duty cycles. The total vehicle range for the urban range test was 17 percent lower for the maximum payload test than for the minimum payload test. The total vehicle range was 16 percent lower for the delivery route than for the urban range test at minimum payload. The delivery route was designed to simulate a more intensive duty cycle, with more stops per mile than the urban range test.

Once the low indicator range is active, the vehicle has about 12 miles of range available before the vehicle goes in limp-home mode where the power is limited. In normal operation, one would most likely not want to operate after the low indicator range is active. This reduces the useful vehicle range available for normal operation to between 45 and 54 miles depending on payload and duty cycles.

Vehicle efficiency was calculated between 1.0 and 1.2 AC kWh/mile, equivalent to 31.3 and 37.6 MPG[40].

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[38] Minimum payload = driver and test equipment only.

[39] Maximum payload = payload close to 4,520 lbs.

Charger Performance Test

Charging duration was measured as about 13 hours and 30 minutes to reach the bulk of the charge and can take up to 17 hours and 30 minutes to reach a full charge[41]. Total charge energy was measured as about 67 AC kWh. Given the total vehicle range determined by the road testing (between 56.2 and 67.6 miles), we estimate that 1 hour of charging represents 4.0 to 4.8 miles of range.

A continuous power draw of 260 to 300 W was recorded after the charge was completed and until the vehicle was unplugged.

4.4.2.3 Conclusions

The vehicle performance characterization performed by the Electric Vehicle Technical Center provided controlled test evaluation of a FCCC MT E-Cell all-electric delivery van. The evaluation recognized the vehicle's potential for a successful delivery vehicle and identified several issues to be addressed:

- Vehicle total range was significantly lower than advertised.

The lower than advertised range could limit the versatility of the vehicle and decrease its ability to drive enough miles to offset diesel fuel and thus payback the higher electric vehicle upfront cost in a satisfactory period of time.

- Vehicle useful range is dependent on payload and duty cycle.

When implementing a battery electric truck project, route characteristics (payload, daily miles, average speed, number of stops per mile, etc…) should be considered to select a route that will closely match the useful range of the vehicle and include a buffer to be able to comfortably cover the route and return to the depot.

- Charging time is much longer than advertised.

The higher-than-advertised charging time could limit the ability of the vehicle to be recharged overnight and be available for service the next business day.

- Calculated vehicle efficiency is lower than what we measured in the in-use data collection.

While this test calculated vehicle efficiency between 1.0 and 1.2 AC kWh/mile, in-use data collection recorded an efficiency of about 1.5 AC kWh/mile (see Section 4.4.1.2). This evaluation did not pinpoint the reasons for this difference but identified payload, duty cycle, and continuous power draw after the charge was completed as factors affecting total vehicle range and vehicle efficiency.

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[40] 1 gallon of diesel = 37.6 kWh [5]

[41] Bulk charging is defined as battery State-Of-Charge goes from 0 to 100% and total charging as battery SOC goes from 0 to 100% and battery current drops to 0.

- Vehicle charging should meet existing safety requirements and adhere to the widely adopted SAE J1772 standard.

4.4.3 Chassis Dynamometer Testing

4.4.3.1 Purpose

The CalHEAT Research Center contracted with the Center for Environmental Research and Technology (CE-CERT) of the University of California, Riverside's College of Engineering to evaluate the performance and energy use of a Class 5 (Gross Vehicle Weight Rating = 16,500 lbs.) battery electric urban delivery vehicle. The test vehicle, a Smith Electric Newton Step Van, was tested over two standardized drive cycles (the Hybrid Truck Users Forum Parcel Delivery Class 4 – HTUF4 and the Orange County Bus Cycle - OCBC) as well as a steady state range test. Testing was carried out on the University of California, Riverside Heavy-Duty Chassis Dynamometer. The main goal of this task was to evaluate maximum vehicle range, energy consumption from the grid in kWh per mile and total charging time.

Figure 4-10: The Newton Step Van on the UC Riverside Heavy-Duty Chassis Dynamometer

Actual electric range and overall energy consumption will vary widely with driving conditions such as drive cycle and vehicle accessories utilization. The numbers presented in this report are representative of specific drive cycles and driving conditions and were derived from testing done in a controlled environment. They should not be used to predict electric range and overall energy consumption in different driving conditions.

4.4.3.2 Results

We present below the main results and findings of the chassis dynamometer testing. For further information, please see Appendix 4B.

Please note that due to testing site infrastructure limitations, we were not able to use the charging current recommended by Smith Electric Vehicles to recharge the Newton Step Van (220V/63A or 208V/75A). The charging current used for this testing was 32A. Therefore, the

charging times recorded in this report are longer than what one would expect at a customer site equipped with the recommended charging infrastructure. In addition, using a different charge rate may affect the charger efficiency and thus, the overall energy consumption calculated in this report may be larger than if the vehicle had been charged at the recommended charging rate.

- Energy consumption, regenerative braking and equivalent fuel economy

Table 4-17 below summarizes the overall DC and AC energy consumption, the regenerative braking recapture rate and the equivalent fuel economy for the two drive cycles (HTUF4 and OCBC) and the steady state range test the Newton Step Van was tested on.

Table 4-17: Summary of the chassis dynamometer main results

Test Cycle	Overall DC Energy Consumption	Overall AC Energy Consumption	Regenerative Braking Recapture Rate	Equivalent MPG
HTUF4	0.67 DC kWh/mile	0.81 AC kWh/mile	32%	46.4 MPGe
OCBC	0.72 DC kWh/mile	0.88 AC kWh/mile	37%	42.7 MPGe
Steady State	0.80 DC kWh/mile	0.98 AC kWh/mile	1%	38.4 MPGe

The Newton Step Van reached the best equivalent fuel economy and the lowest energy consumption on the HTUF4 drive cycle. The OCBC drive cycle, with more accelerations and decelerations, is a more intensive drive cycle and thus, equivalent fuel economy was lower and energy consumption higher than for the HTUF4 cycle. However, the increased number of decelerations compared to the HTUF4 cycle allowed the vehicle to recapture 5 percent more energy during braking.

While the Newton Step Van was tested on the steady state range test to primarily measure the total battery capacity, we report energy consumption, regenerative braking recapture rate and equivalent fuel economy for information and comparison purposes. As expected, the Newton Step Van had the lowest equivalent fuel economy and the highest energy consumption on the steady state range test. Regenerative braking recaptured very little energy, which was expected since the drive cycle had only one acceleration event and one deceleration event.

- Total battery capacity

From the steady state range test, the total battery capacity was measured at 89.64 AC kWh.

- Total driving range

Using the overall AC energy consumption for the HTUF4 and OCBC drive cycles and the total battery capacity, the total driving range for each drive cycle was estimated using the equation below:

$$\text{Total Driving Range (mile)} = \frac{\text{Total Battery Capacity (AC kWh)}}{\text{Overall AC Energy Consumption (AC kWh/mile)}}$$

Table 4-18 below shows the estimated total driving range for the HTUF4 and OCBC drive cycles and the measured total driving range for the steady state range test.

Table 4-18: Newton Step Van total driving range on selected drive cycles

Test Cycle	Total Driving Range
HTUF4	110.7 miles (estimated)
OCBC	101.9 miles (estimated)
Steady State	91.6 miles (measured)

- Battery charging

Table 4-19 below shows the charge duration at bulk charging (battery SOC goes from 0 to 100 percent) and total charging (battery SOC goes from 0 to 100 percent and battery current drops to 0):

Table 4-19: Newton Step Van charging times at 32A charging current

At 32A Charging Current	Time (hh:mm:ss)
Bulk Charging	12:58:49
Total Charging	14:20:45

The bulk charge duration took about 13 hours and total charge duration took about 14 hours and 20 minutes.

- Charging efficiency

Dividing the overall DC energy consumption by the overall AC energy consumption, the charging efficiency from AC to DC was calculated. Table 4-20 shows the charging efficiency from the point where electricity is introduced from the electric outlet to the battery (AC to DC):

Table 4-20: Newton Step Van AC/DC charging efficiency at 32A charging current

At 32A Charging Current	AC/DC Charging Efficiency
HTUF4	82.7%
OCBC	81.8%
Steady State	81.6%
Average	82.0%

The average charging efficiency from AC to DC was calculated at 82 percent, meaning that for 1 AC kWh sent to the vehicle, the battery receives 0.82 DC kWh.

- Stand-by energy consumption

A continuous power draw of 65 to 140W was measured after the charge was completed and until the vehicle was unplugged.

4.4.3.3 Conclusions

The chassis dynamometer testing performed by the Center for Environmental Research and Technology of the University of California, Riverside provided a controlled test evaluation of the Smith Electric Newton Step Van. The testing recognized the vehicle's potential for a successful delivery vehicle and identified several important findings and areas that will need further research.

- The Newton Step Van is more efficient and cleaner than equivalent diesel vehicles

Table 4-21 compares the fuel economy and well-to-wheel greenhouse gas emissions of the Smith Electric Newton Step Van and a 2006 FCCC MT-45 tested on chassis dynamometer by NREL in 2010 [12].

Table 4-21: Fuel economy & GHG emissions comparison between MT-45 and Newton Step Van

Drive Cycles	2006 FCCC MT-45		2012 Smith Electric Newton Step Van	
	Fuel Economy	GHG Emissions	Fuel Economy	GHG Emissions
NYCC	6.1 MPG	2108 gCO2e/mile	N/A	N/A
OCBC	9.5 MPG	1354 gCO2e/mile	42.7 MPGe	160 - 471 gCO2e/mile
HTUF4	11.7 MPG	1099 gCO2e/mile	46.4 MPGe	147 - 434 gCO2e/mile

We find that the Smith Electric Newton Step Van is over three times more efficient than a 2006 FCCC MT-45. Equivalent fuel economy on the Newton Step Van was less dependent on drive cycle than the MT-45. For instance, the Newton Step Van equivalent fuel economy was 8 percent lower on the OCBC cycle compared to the HTUF4 cycle, while the MT-45 fuel economy was 19 percent lower on the OCBC cycle compared to the HTUF4 cycle.

The Newton Step Van emits much less greenhouse gases than a diesel MT-45 but E-Trucks greenhouse gas emissions depend on the power content of the electricity used to recharge the vehicle. For instance, on the OCBC cycle, greenhouse gas emissions varied between 160 gCO_2e / mile if the vehicle is recharged in PG&E territory and 471 gCO_2e / mile depending if the vehicle is recharged in LADWP territory.

- Total driving range was higher than advertised

While Smith Electric Vehicles advertises a total driving range of up to 80 miles for the Newton Step Van, the chassis dynamometer testing estimated a total driving range superior to 100 miles on the HTUF4 and OCBC cycles.

- Vehicle useful range is dependent on operating conditions

Total driving range was 8 percent lower on the OCBC cycle than on the HTUF4 cycle. As expected, actual electric range and overall energy consumption will vary widely with driving conditions such as drive cycle and vehicle accessories utilization.

We recommend that further testing be carried on to analyze all factors influencing actual electric range and overall energy consumption. In particular, temperature effects on battery

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[42] We assumed that producing and burning 1 gallon of diesel emits 12.9 kg of CO_2 equivalent on a well-to-wheel basis [4].

[43] Estimated GHG emissions factors in 2011 for the 5 largest utilities in California varied from 400 to 1180 lbs. CO_2 / MWh [13].

performance and air conditioning usage should be investigated to characterize their impact on total driving range.

- Regenerative braking extends total driving range

Regenerative braking recapture rate was calculated as 32 percent for the HTUF4 cycle and 37 percent for the OCBC cycle. The Newton Step Van regenerative braking feature extended available range by 34 miles for the HTUF4 cycle and by 38 miles for the OCBC cycle.

- Battery charging was comparable with other E-Trucks

Despite charging at a lower current than what was recommended, the Newton Step Van can be fully recharged in about 14 hours and 20 minutes, which is similar or better than the total charging times of the Navistar eStar and the FCCC MT E-Cell. Charging at the recommended current will markedly decrease the charging time to about 6 to 8 hours.

- Grid energy consumption better represents E-Truck energy consumption

While E-Trucks use DC energy from the vehicle batteries, they are generally recharged using AC energy from the grid. A small amount of energy is lost in the conversion from AC to DC. While DC kWh/mile is sometimes used to characterize the efficiency of the electric powertrain, AC kWh/mile is a better metric to represent the overall efficiency of E-Trucks and should be used when comparing efficiencies with other propulsion technologies such as diesel vehicles.

- Stand-by current draw decreases overall vehicle efficiency

The Newton Step Van stand-by current draw was lower than for the FCCC MT E-Cell but was still significant enough to impact overall vehicle efficiency.

We recommend that further testing be carried out to better understand the origin of the stand-by current draw of E-Trucks when plugged in but not charging and explore ways to reduce its impact on overall E-Truck efficiency.

4.4.4 Comparison with Conventional Vehicles

4.4.4.1 Freightliner Custom Chassis Corporation (FCCC) MT-45

Model Year	2006	
Chassis Manufacturer	FCCC	
Engine Manufacturer	Cummins	

Engine	Fuel	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
Cummins 5.9L ISB 200	Diesel	16,000 Class 4	6,300 lbs.	700 ft^3	>65 mph	No

The MT-45 is a Class 4 truck available in different configurations. It has traditionally been one of the walk-in van platforms of choice for parcel delivery fleets. Table below lists the engine characteristics of the MT-45.

Table 4-22: FCCC MT-45 engine characteristics

Engine	
Peak power	200 HP (150 kW)
Peak torque	520 lb-ft (702 Nm)

In 2010, the National Renewable Energy Laboratory and CALSTART evaluated the performance of parcel delivery trucks. Odometer and retail fueling records data were collected on three FCCC MT-45 parcel delivery trucks operating in and around Los Angeles, CA. Over a 1-year period, the three vehicles drove 35,567 miles with an average fuel economy of 7.9 MPG. Table 4-23 summarizes the data collected on these 3 vehicles [12].

Table 4-23: Summary of in-use results from previous study [12]

	Unit 1	Unit 2	Unit 2
Miles Collected	13,099 miles	11,344 miles	11,124 miles
Miles per Day	21.4 – 49.3 miles (Average 39.4 miles)		
Average Speed (>0)	16.3 – 20.9 MPH		
Lifetime Fuel Economy	7.2 MPG	8.6 MPG	8.2 MPG

In addition, a vehicle was tested on a chassis dynamometer over three different drive cycles. Table 4-24 below summarizes the fuel economy measured during the test.

Table 4-24: Summary of chassis dynamometer results from previous study [12]

Drive Cycles	Fuel Economy (mpg)
NYCC	6.1
OCBC	9.5
HTUF4	11.7

4.4.4.2 Isuzu Utilimaster Reach Van

Model Year	2011
Chassis Manufacturer	Isuzu
Powertrain Manufacturer	Isuzu

Engine	Fuel	GVWR (lbs.)	Payload	Cargo Volume	Top Speed	HVIP Eligible Vehicle
Isuzu 4JJI-TC 3.0L turbo	Diesel	12,000 Class 3	3,408 (12′) 3,267 (14′)	540 ft^3 (12′) 630 ft^3 (14′)	>65 mph	No

The Reach Van is a Class 3 truck available in two different configurations: a 12-foot or a 14-foot body. It represents a smaller option than the FCCC MT-45, with a smaller payload, cargo space, and engine. Table 4-25 below lists the engine performance of the Reach Van.

Table 4-25: Isuzu Reach Van Vehicle Characteristics [14]

Traction Motor	
Peak power	150 HP (112.5 kW)
Peak torque	282 lb-ft (381 Nm)
Dimensions	
Tires	215/52 R16E
Wheelbase	151 in.
Overall Length	260.9 in. (12') / 281.0 in. (14')
Overall Width	88 in.
Overall Height	113 in.
Cargo Area Length	150.9 in. (12') / 171.0 in. (14')
Cargo Area Width	73 ¼ in.
Cargo Area Height	82 in.
Rear Loading Floor Height	31 in.
Rear Door Opening Height	74 in.
Rear Door Opening Width	67 in.

We collected data from two Reach Vans operating from the Los Angeles facility. These two vehicles were operating on routes similar to the routes the E-Trucks were operating on. Table 4-26 below summarizes the data collected on these two vehicles.

Table 4-26: Summary of in-use data for 2 Isuzu Reach Van

	Unit 1	Unit 2
Miles Collected	249 miles	595 miles
Miles per Day	8.0 – 45.1 miles Average 17.0 miles	9.4 – 65.1 miles Average 40.0 miles
Average Speed	16.9 MPH	19.5 MPH
Lifetime Fuel Economy	10.9 MPG	11.5 MPG
Lifetime Fuel Consumption	1.4 gallons/hr	1.4 gallons/hr

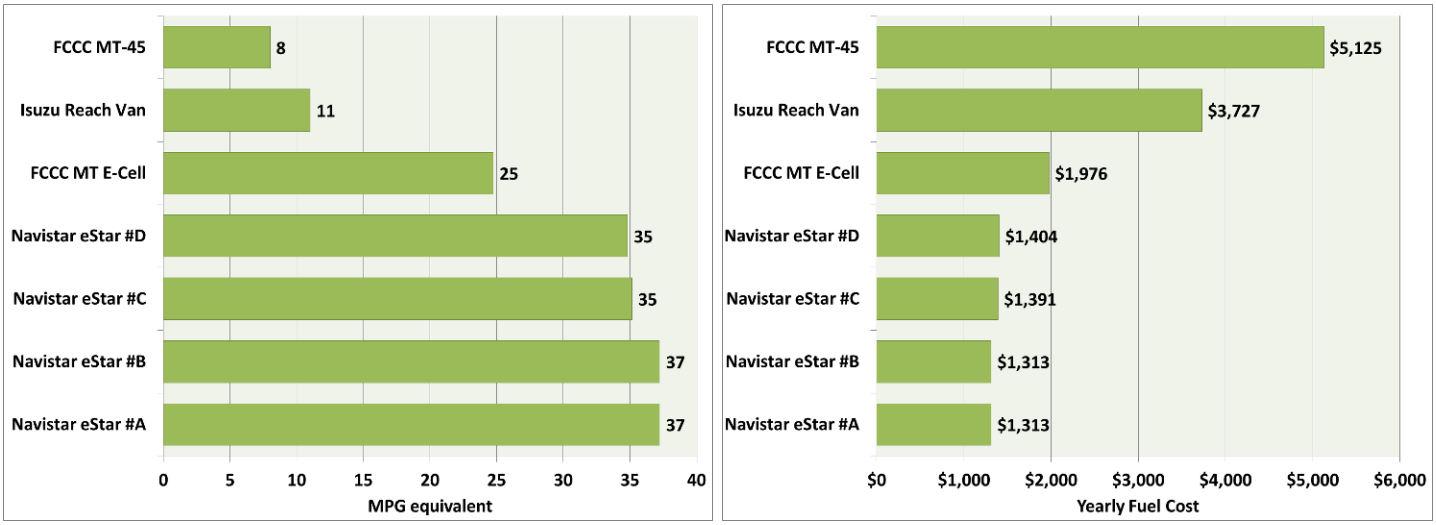
4.4.4.3 Fuel efficiency and fuel cost comparison

We assumed each vehicle was driven 10,000 miles per year and that diesel sold for $4.1 per gallon and electricity for 13¢ per kWh [15]. Fuel economy for the FCCC MT-45 was taken from the in-use data collection done by NREL in 2010 [12]. Fuel economy for the Isuzu Reach Van,

FCCC MT E-Cell and Navistar eStar was taken from the in-use data collection done for this project, assuming that 1 gallon of diesel contains 37.6 kWh [5].

Figure 4-11 below compares the miles-per-gallon equivalent and the yearly fuel cost for two diesel vehicles: FCCC MT-45 and Isuzu Reach Van and five E-Trucks: one FCCC MT E-Cell and four Navistar eStar.

Figure 4-11: In-use fuel efficiency and yearly fuel cost comparison between project E-Trucks and selected diesel vehicles.

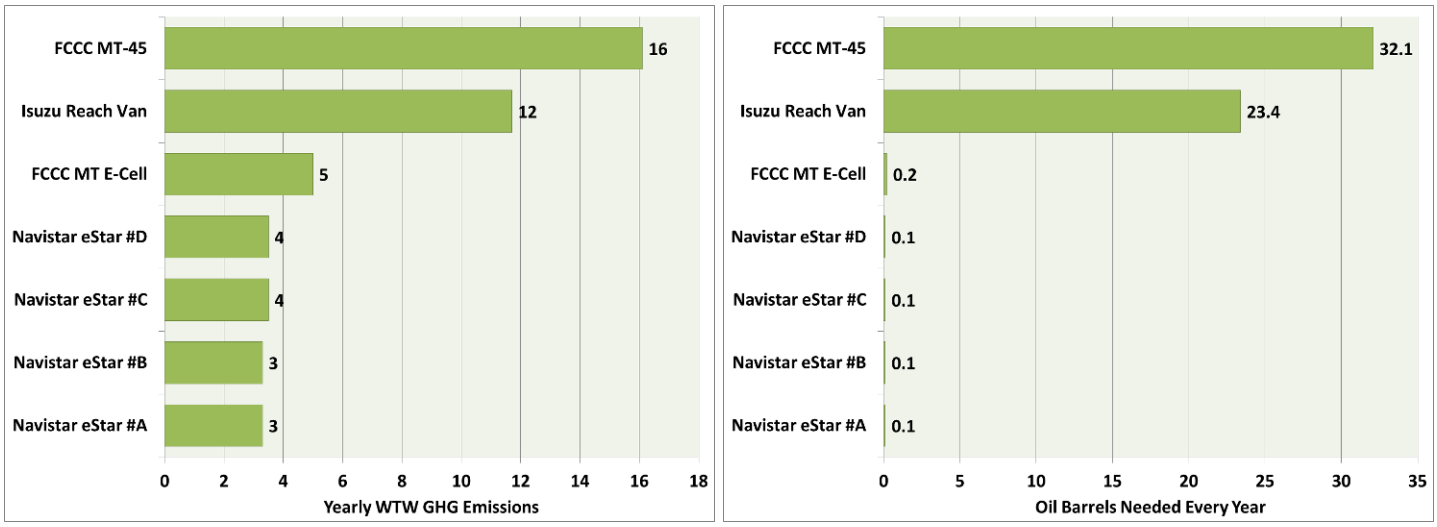


We see that E-Trucks are more efficient than conventional diesel vehicles, with E-Truck efficiency being up to 4 times better than the fuel efficiency of similar diesel vehicles. E-Trucks are also cheaper to operate since they are more efficient and are generally fueled with cheap electricity. E-Truck yearly fuel cost is up to 80 percent lower than diesel fuel cost.

4.4.4.4 GHG emissions and oil comparison

Figure 4-12 compares the yearly well-to-wheels (WTW) greenhouse gases (GHG) emissions and crude oil consumption on the same vehicles presented above using the same assumptions. In addition, we assumed that producing and burning one gallon of diesel emits 12.9 kg of CO_2 equivalent on a WTW basis, while the carbon intensity of California electricity is 0.45 kg of CO_2 equivalent per kWh. We also assumed that 1,000 gallons of diesel required 25.7 barrels of oil to be produced and transported, while 1,000 kWh of California electricity requires 0.0125 barrels of crude oil to be produced [4].

Figure 4-12: Yearly greenhouse gases emissions and oil consumption comparison between E-Trucks and selected diesel vehicles.



With no tailpipe emissions, E-Trucks are cleaner to operate than vehicles fueled with fossil fuels. On a WTW basis, E-Trucks emit up to 70 percent less greenhouse gases when recharged with California electricity. Using domestically produced electricity, E-Trucks use almost no crude oil.

4.4.5 E-Truck Performance Conclusions

The performance evaluation carried out for this project evaluated seven E-Trucks from three different vehicle models. While the in-use data collection provided valuable insights on how E-Trucks were being used in parcel delivery operation, the on-road testing and the chassis dynamometer testing provided a better understanding of E-Truck technology and evaluated in a controlled environment the performance of two different models. Among the many findings and recommendations derived from the performance evaluation, the following eight are of particular importance:

- Use E-Trucks on higher mileage routes.

The five E-Trucks deployed at the downtown Los Angeles facility were used on low mileage routes. During the performance evaluation period, the four eStars drove an average of 21 miles per day while the MT E-Cell drove an average of 27 miles per day. Such short driving range will not offset sufficient fuel to pay for the higher upfront costs of E-Trucks. We recommend that E-Trucks be deployed on longer routes. While the on-road testing of the MT E-Cell revealed a usable driving range limited to 40-60 miles, the data collected on the four Navistar eStars shows that the eStar could be driven on longer routes while keeping enough battery capacity as a safety margin. For instance, data shows that driving an average of 1.55 miles would use 1 percent of battery SOC. The Navistar eStar could drive on similar drive cycles close to 100 miles per charge and still have about 40 percent of battery capacity left.

To minimize range anxiety, E-Trucks should be deployed first on short routes to increase a fleet's positive experience with electric vehicle technology. Then E-Trucks should be gradually moved to longer routes, aiming to use the maximum battery capacity possible while keeping a certain percentage of battery capacity as a safety margin.

- Train E-Truck drivers.

Data collected on the eStars as well as on the chassis dynamometer testing showed that regenerative braking recovers a significant amount of energy while braking. Drivers should make the best use of regenerative braking features to extend total driving range. We recommend that drivers be trained and coached to learn how to adapt their driving techniques to E-Trucks.

- Operating conditions impact E-Truck performance.

The on-road and chassis dynamometer testing showed that payload and drive cycle influenced vehicle energy consumption and ultimately total driving range. While testing of the impact of vehicle accessories such as air conditioning and cabin fans was unable to be done, vehicle accessories will use energy from the batteries and impact total driving range. Lastly, lithium-ion batteries used in E-Trucks generally perform differently depending on ambient temperature. Weather conditions will also impact E-Truck performance.

We recommend that further testing be carried out to better understand the impact of operating conditions on E-Truck performance.

- "Stand-by" energy consumption impacts overall E-Truck efficiency.

A current draw was measured on both the MT E-Cell and Newton Step Van after the charge was completed and until the vehicle was unplugged. In addition, data from the eStar indicates that a similar current draw may exist on this vehicle as well.

While we were not able to precisely determine the origin of this "stand-by" current draw, it is likely caused by the low voltage system batteries and the vehicle accessories (fans, battery cooling system, vehicle display, among others) remaining powered on. We recommend that further testing be carried out to better understand the origin of the stand-by current draw of E-Trucks when plugged in but not charging and explore ways to reduce its impact on overall E-Truck efficiency.

- AC energy consumption is a better measure of overall vehicle efficiency.

AC energy represents the energy charging the battery from the point where electricity is introduced from the electric outlet to the battery charger. DC energy represents the energy charging the battery from the point where electricity is introduced from the battery charger to the battery. The conversion from AC to DC is not perfect and a certain amount of energy is lost in the process so that the AC energy consumption is always greater than the DC energy consumption.

While DC energy consumption (DC kWh/mile) is a good indicator of the efficiency of the drivetrain, AC energy consumption (AC kWh/mile) is a better indicator of the overall efficiency of the vehicle and should be used to compare the efficiency of E-Trucks with other vehicles.

- E-Trucks are more efficient and cheaper to operate.

E-Trucks are more efficient than conventional diesel vehicles, with E-Truck efficiency being up to four times better than the fuel efficiency of similar diesel vehicles. E-Trucks are also cheaper to operate since they are more efficient and are generally fueled with cheap electricity. An E-Truck yearly fuel cost is up to 80 percent lower than diesel fuel cost.

- E-Trucks are cleaner to operate on a well-to-wheels basis.

With no tailpipe emissions, E-Trucks are cleaner to operate than vehicles fueled with fossil fuels. On a well-to-wheel basis, E-Trucks emit up to 70 percent less greenhouse gases when recharged with California electricity. E-Trucks use almost no crude oil when using domestically produced electricity.

- Different data collection methods exist to evaluate E-Truck performance.

The performance evaluation carried out for this project used a wide range of data collection techniques, from manual readings of vehicle odometers and electric meters to chassis dynamometer testing. Each data collection technique presented different benefits and drawbacks:

- Manual data collection was fairly cheap to implement, requiring only revenue-grade meters to record vehicle electric consumption. Many commercial fleets currently track vehicle mileage and fuel consumed, so data collection and processing is easy to implement. However, information remains limited.
- Using data acquisition systems is more expensive to implement, but costs remain reasonable. The information will provide many details about vehicle operation and E-Truck performance. However, data can be expensive to process and analyze, especially if vehicle parameters are being collected at a high sampling rate.
- Road testing proved to be a very cost effective option, providing a lot of information about the performance of one particular E-Truck model. Testing was used to replicate closely in-use operation and did not require expensive equipment.
- Chassis dynamometer testing is the most expensive options as it requires contracting with one of the few facilities in North America able to test medium- and heavy-duty vehicles. Results may differ somewhat from in-use operation if one does not select a representative drive cycle but testing will provide the most thorough information about the performance of one particular E-Truck model.

4.5 E-Truck User Acceptance

In order to assess the user acceptance of the E-Trucks, we conducted surveys and interviewed several fleet staff. Comparisons were made between electric and conventional trucks to

determine the advantages and disadvantages during normal everyday use. Driver surveys assessed the performance of the E-Trucks and the mechanics surveys assessed their serviceability and maintainability.

Drivers were asked to complete a survey rating the E-Trucks in key vehicle performance areas compared to typical baseline trucks. Due to the subjective nature of driver impressions performance was rated on a scale from "Much worse" to "Much better" than a similar conventional truck. The driver survey covered the following areas:

- Maneuverability at low speeds.
- Acceleration / Deceleration.
- In-cab controls.
- Braking.
- Interior / exterior noise level.
- Overall vehicle rating.
- Additional driver comments.

A sample driver survey is provided in Appendix 4C.

In order to evaluate the serviceability and maintainability of the E-Trucks, mechanics were asked to provide subjective feedback on various service and maintenance aspects of electric and conventional vehicles. A sample mechanic survey is provided in Appendix 4D.

Lastly, the fleet manager was asked to rate the E-Trucks from a parcel delivery fleet management perspective compared to conventional vehicles. A sample fleet manager survey is provided in Appendix 4E.

4.5.1 Summary of User Acceptance Surveys

Four drivers completed the survey for the Navistar eStar (one full time and three part time). In addition, two fleet maintenance mechanics and one fleet manager also completed the survey. While this is a small sample size, the information captured by the surveys provides valuable input from actual E-Truck users to evaluate the performance of the Navistar eStar and identify areas of improvement. The tables below provide the summary of the survey results that were obtained from the four drivers, two mechanics and the fleet manager. All surveys were also accompanied by extended interviews.

Table 4-27: Summary results of performance surveys

Property of the Navistar eStar compared to a similar conventional truck	**Much worse**	**Somewhat worse**	**Same**	**Better**	**Much better**
Initial launch from stand still	☐	☒	☐	☐	☐
Maneuverability at slow speeds	☐	☐	☐	☒	☐
Acceleration	☐	☐	☐	☒	☐
Shift quality of the transmission	☐	☐	☒	☐	☐
Pulling power with load	☐	☐	☒	☐	☐
Coasting / Deceleration	☐	☐	☐	☒	☐
Overall braking behavior	☐	☐	☐	☒	☐
Productivity (able to cover routes quicker)	☐	☒	☐	☐	☐

Table 4-28: Summary results of operation surveys

Property of the Navistar eStar compared to a similar conventional truck	**Much worse**	**Somewhat worse**	**Same**	**Better**	**Much better**
Cold Start	Not applicable				
Reliability	☐	☐	☒	☐	☐
Inside noise level	☐	☐	☐	☐	☒
Outside noise level	☐	☐	☐	☐	☒
Issues with pedestrian traffic	No particular problem noted				
In-cab ergonomics (control, switches, access doors…)	☐	☒	☐	☐	☐

- **Did you have any issues with electric range (ran out of battery, battery running low at the end of the shift…)?**

No issues.

- **Did you have any issues with charging (vehicle not charging when plugged in, vehicle discharged in the morning, vehicle not fully charged in the morning…)?**

Before the problem was solved by Navistar, drivers had to wait for the vehicle to be completely shut off (dashboard turned off and electrical system powered down) to be able to put the vehicle in charge.

- **Please provide an overall rating of the Navistar eStar.**

Very poor	Poor	Good	Very good	Excellent
☐	☐	☒	☐	☐

The above summary results indicate that the overall ratings of the eStar were found to be good. In terms of performance, most of the ratings were better than a similar conventional truck or equally good. Initial launch and productivity of the truck in parcel delivery operations were judged "somewhat worse" than for a conventional truck. Drivers rated interior and exterior noise levels as "much better" than for a conventional diesel-powered trucks while they rated in-cab ergonomics as "somewhat worse".

With only one vehicle in service, less feedback was collected on the MT E-Cell. No particular complaints or issues were reported. The vehicle does not have the same issues as the eStar regarding initial launch from stand still, productivity and in-cab ergonomics. With same or better initial launch from stand still and better acceleration than the eStar, the MT E-Cell was considered a better option for "pick-up and go" operations, characteristic of parcel delivery. In addition, the higher maximum speed makes the vehicle more versatile.

4.5.2 Summary of Interviews

Following the surveys, drivers and mechanics were interviewed in an informal group discussion to gather feedback on some of the Navistar eStar features, investigate on low rating identified in the surveys and discuss ways the vehicle could be improved. In this section, we discuss findings on the Navistar eStar derived from the interviews.

- Driver assignment

Out of the four drivers that we interviewed, only one driver was a full-time employee, assigned to a specific route and with a designated vehicle (unit C). During the interview process, it was discovered that some full-time drivers had experienced issues with the vehicle early in the project and did not regard the eStar as the best option when one is on a very tight delivery schedule. Since driver performance is evaluated on the ability to cover routes on time, drivers have not assimilated easily and it has led to poor driver acceptance, especially with the full-time

drivers. As a result, some of the Navistar eStars were used as back up vehicles or assigned to part-time drivers who have less choice as to the vehicle they can drive and generally work on shorter routes.

It is interesting to note that unit C, which was assigned to only one full-time driver, did not report any maintenance issues throughout the evaluation period, whereas unit D for instance, which was assigned to several part-time drivers, reported several issues. During the interviews, drivers agreed that the E-Trucks should be designated to one driver who would take ownership of his vehicle and take better care of it.

- Driver training

During the discussion with drivers, we learned that not all had undergone specific E-Truck driver training. In addition, some drivers were still hesitant about specific E-Truck operations, such as putting the vehicle in charge at the end of each shift.

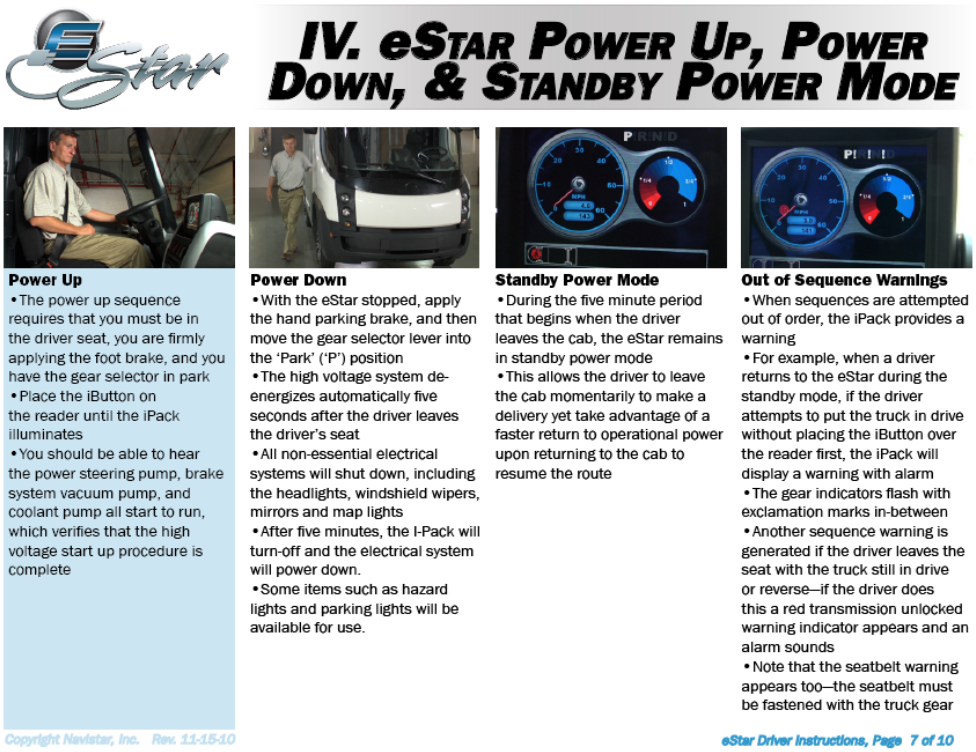
- Air conditioning

Two drivers reported having issues with the air conditioning not working.

- Initial launch from stand still and overall productivity

The initial launch from stand still and the ability to cover routes quicker were judged somewhat worse or much worse by the drivers and maintenance mechanics. After further discussion, it was determined that the power-up sequence as well as the physical configuration of the vehicle was slowing down driver operation.

Figure 4-13: Extract from the eStar Driver Instructions Manual – Page 7 [16]



IV. eStar Power Up, Power Down, & Standby Power Mode

Power Up

- The power up sequence requires that you must be in the driver seat, you are firmly applying the foot brake, and you have the gear selector in park
- Place the iButton on the reader until the iPack illuminates
- You should be able to hear the power steering pump, brake system vacuum pump, and coolant pump all start to run, which verifies that the high voltage start up procedure is complete

Power Down

- With the eStar stopped, apply the hand parking brake, and then move the gear selector lever into the 'Park' ('P') position
- The high voltage system de-energizes automatically five seconds after the driver leaves the driver's seat
- All non-essential electrical systems will shut down, including the headlights, windshield wipers, mirrors and map lights
- After five minutes, the I-Pack will turn-off and the electrical system will power down.
- Some items such as hazard lights and parking lights will be available for use.

Standby Power Mode

- During the five minute period that begins when the driver leaves the cab, the eStar remains in standby power mode
- This allows the driver to leave the cab momentarily to make a delivery yet take advantage of a faster return to operational power upon returning to the cab to resume the route

Out of Sequence Warnings

- When sequences are attempted out of order, the iPack provides a warning
- For example, when a driver returns to the eStar during the standby mode, if the driver attempts to put the truck in drive without placing the iButton over the reader first, the iPack will display a warning with alarm
- The gear indicators flash with exclamation marks in-between
- Another sequence warning is generated if the driver leaves the seat with the truck still in drive or reverse—if the driver does this a red transmission unlocked warning indicator appears and an alarm sounds
- Note that the seatbelt warning appears too—the seatbelt must be fastened with the truck gear

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eStar Driver Instructions, Page 7 of 10

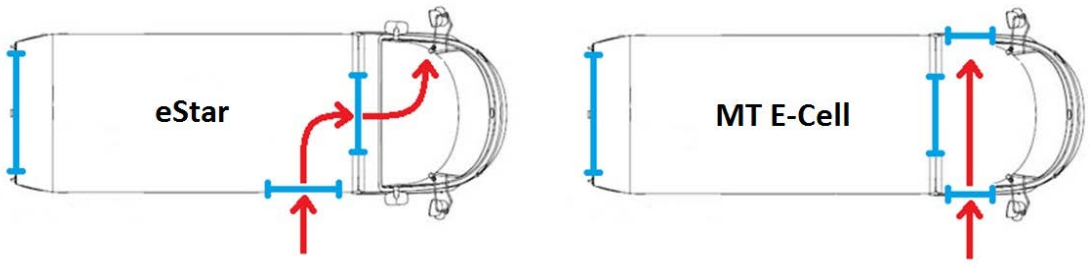
As explained in the eStar Driver Instructions manual (Figure 4-13), starting the vehicle is more complicated than turning a key in conventional walk-in vans or in most personal vehicles. In addition, the power up sequence needs to be followed in the proper order. If the driver ignores the sequence, the system will freeze and will need to be turned off completely before the driver can attempt to restart the vehicle, which can take up to 5 minutes.

Some drivers were confused by the power-down and standby power mode. There are no obvious clues to notice the difference between power-up and standby power mode (like a diesel engine shutting off). This has left some driver confused if the vehicle was still "on" and added to the general feeling that the truck was less productive.

- Access doors

Based on an existing walk-in van chassis, the MT E-Cell is equipped with both driver and passenger doors as seen on Figure 4-14 on the right. On the other hand, the eStar was built on a different design not fully adapted to parcel delivery applications. In order to exit or enter the eStar, the driver has to pass through the rear cab door and the side door (see Figure 4-14 on the left). This takes more time to get in and out of the vehicle and also increases the chance of driver hesitation with the keyless entry system.

Figure 4-14: Driver entry path (red line) for the Navistar eStar and FCCC MT E-Cell.



Some drivers noted the "claustrophobic" effect of not having a driver and/or passenger door and stressed that they felt unsafe as a result.

- Roll back in drive

Several drivers noticed and/or complained about the vehicle rolling back while in drive. As mentioned in the eStar Driving Instructions manual (Figure), there is no driveline creep to hold the vehicle from rolling back and the handbrake should be used to hold or launch the vehicle from a stop on an incline.

Figure 4-15: Extract from the eStar Driver Instructions Manual – Page 2 [16]

- Lag when starting

In addition to the long power up sequence described earlier, the eStar has a lag of a few seconds when shifting out of or into park which adds time to the initial launch from stand still (Figure 4-16).

Figure 4-16: Extract from the eStar Driver Instructions Manual – Page 2 [16]

Changing Gears

- The eStar must be stopped to change gears
- The brake pedal must be pressed
- There is no gear engagement sensation with the eStar
- Gear changes are instantaneous except when shifting out of or into park
- When engaging or disengaging park, you need to allow up to 5 seconds for the parking pawl to engage or release

- Navistar eStar Generation 2

In early 2012, Navistar launched an updated version of the Navistar eStar, improving heating, air conditioning, motor, charger and battery pack. All four vehicles monitored for this project were upgraded with new software and hardware. All the drivers and mechanics noted that the new version was sensibly improved, including better braking behavior, and improved roll back in drive.

- E-Truck charging

Several drivers experienced problems with recharging the vehicle. They had to wait for the vehicle dashboard to switch off before putting the vehicle in charge. The issue was fixed with a software upgrade.

- Additional comments

Below is a non-exhaustive list of additional driver and mechanic comments regarding the Navistar eStar collected during the interview process:

- Vehicle needs to start and shut off quicker.
- Vehicle needs driver and passenger doors for safety and productivity.
- Vehicle drives smoothly when loaded.
- Vehicle is very low and not adapted to loading docks.
- Truck rolls back in drive.
- Vehicle has weak acceleration.
- Drivers enjoyed not having to breathe diesel fumes when refueling the vehicle and not breathing exhaust fumes in the cabin.

- Electric mirrors and reading light are really handy.
- Vehicle is jerky at low speed.
- Drivers reported that people "stare" at the vehicle, want to take pictures of it and ask about it and want to know how it works.
- One vehicle operated on a university campus where delivery vehicles are not allowed to use their horn. The driver reported that the quietness of the vehicle was appreciated by university staff.

4.5.3 Conclusions

The user acceptance surveys and interviews revealed several E-Truck specific issues on the Navistar eStar. Particularly, drivers complained about the long time needed to start the vehicle caused by the long and laborious power-up and power-down sequences and the delay when shifting out or into park. However, complaints also originated from vehicle design issues, not related to E-Truck specific characteristics. For instance, all drivers complained about the lack of a driver and a passenger door on the eStar, which dramatically increased the time needed to get in and out of the vehicle.

Because of its original design (cabin and electric powertrain), the eStar was not fully adapted to parcel delivery operation and as a result, driver operations were considerably slowed down compared to a conventional vehicle. While electric powertrain design needs to be improved, we also noticed that users will often associate physical design issues, such as driver/passenger doors issues, with E-Truck specific issues. Therefore, it is important to design a new vehicle with the needs of the users in mind to improve the general acceptance of the vehicle.

The user acceptance surveys and interviews also revealed a gap in driver training. We believe driver training is essential to ensure better acceptance of E-Trucks and successful E-Truck deployments overall. With the eStar in particular, there were more than a few new operating steps that drivers needed to assimilate. Drivers are more likely to adopt and accept a vehicle if they are better trained on its operation. Similarly, driver assignment is important to ensure a successful deployment of advanced technology vehicles such as E-Trucks. Some drivers are more willing and able to deal with changes. These "early adopter" drivers should be selected first for advanced technology vehicles deployment.

4.6 Service and Maintenance

Electric vehicles will typically have lower maintenance costs than conventional fossil-fueled vehicles for the following reasons [17]:

- The battery, motor, and associated electronics require little to no regular maintenance.
- There are fewer fluids to change.
- Brake wear is significantly reduced, due to regenerative braking.
- There are far fewer moving parts relative to a conventional internal combustion engine.

In order to estimate the service and maintenance benefits of E-Trucks compared to conventional trucks, we regularly interviewed from April to December 2012 the two fleet mechanics in charge of vehicle maintenance at the downtown Los Angeles facility. While we only collected general E-Trucks maintenance information and estimates of conventional vehicles maintenance costs, we were able to develop a first look at the service and maintenance benefits of E-Trucks in parcel delivery applications. We believe a more complete and in-depth analysis is needed to further investigate and validate our findings.

4.6.1 E-Truck Availability Evaluation

Vehicle availability is defined as the percentage of time that a vehicle is potentially available for use, regardless of whether the vehicle is actually used on the particular day. Due to project constraints, vehicle availability was not tracked accurately during the performance testing period but mechanics regularly provided updates on major maintenance issues that occurred during the performance testing period. The following is a list of issues that were recorded for each individual E-Truck in operation at the downtown Los Angeles facility.

Unit A (eStar)

- On May 7th, 2012, the engine light went on and a leak was noticed coming from the driveshaft. The vehicle was sent to the dealership for repairs.
- In early December 2012, it was noticed that the coolant pump, needed during driving and charging, was working intermittently. The vehicle was sent to the dealership for repairs.

Unit B (eStar)

- In early December 2012, it was noticed that the vehicle dashboard was working sporadically and that the vehicle wouldn't shut down. The vehicle was sent to the dealership for repair.

Unit C (eStar)

No issues were reported throughout the testing period.

Unit D (eStar)

- In September 2012, one of the rear-view mirrors was damaged. Because of internal billing issues and a long lead time to get the replacement part, the vehicle was out of service for several days. While the vehicle was out of service, the 12V batteries powering the auxiliary loads ran out and had to be recharged. Upon recharge of the 12V batteries, the engine light went on and the truck wouldn't start. The truck was sent to the dealership for repair. In total, the vehicle was out of service for five weeks for a minor issue.

Unit E (E-Cell)

- One battery pack had to be replaced in November 2011.

- On September 3rd, 2012, the driver noticed a burning smell and the vehicle would not go over 15 MPH. As of May 2013, the vehicle had not been put back in service.

Navistar and FCCC engineers responded promptly to any reported issues in order to bring the vehicles back to service as soon as possible. They also provided several software upgrades to the vehicles that improved their performance or solved issues identified during the deployment.

The E-Trucks encountered several issues that made them generally less available than conventional diesel trucks. Since these vehicles were early production vehicles and had limited in-service experience (for instance only four MT E-Cells have been built and two commercialized in this configuration), maintenance issues were anticipated to arise during the project performance period. Fleet mechanics had limited experience with E-Truck maintenance procedures and thus, all major repairs were handled by the E-Truck manufacturers. In addition, E-Truck manufacturers carried a limited inventory of spare parts. These two factors added considerable delays when solving any maintenance issue. At this early stage of vehicle development, true vehicle availability comparison between E-Trucks and conventional diesel vehicles would be difficult.

4.6.2 Maintenance Cost Analysis

The research team collected general maintenance costs and maintenance intervals data for an average conventional vehicle at the downtown Los Angeles facility. The information reported in Table 4-29 refers to recurring maintenance procedures for conventional diesel vehicles that are not needed for E-Trucks. Any additional maintenance costs would be considered non-recurring. Please note that maintenance costs and intervals reported in this section will vary widely with driving conditions such as miles driven and number of stops per day. The numbers presented in Table 4-29, and in this section are representative of a specific facility and specific driving conditions. They should not be used to predict E-Truck maintenance savings under different driving conditions.

Table 4-29: Analysis of diesel maintenance costs and intervals at the downtown Los Angeles facility

Specific to downtown LA facility	Conventional Vehicle Maintenance Interval	Yearly Maintenance Costs[44]	
		Low Estimate	High Estimate
Oil Change / Oil Filter	Older models: ~4 times per year Newer models: based on mileage	$100	$250
Fuel Filter	Depends on mileage & filter conditions 1 – 2 years	$10	$20
Air Filter	Depends on mileage & filter conditions 2 years	$25	$50
Diesel Exhaust Fluid	On 2010 Certified Engines ~2% of fuel consumption[45]	$2.79 per gallon in June 2013 [19]	
Engine Coolant	Depends on mileage & engine conditions Typically 3-4 years	$50	$100
Smog Check	On older vehicles only	$20 for diesel $85-100 for gasoline	
Brakes	Depends on truck usage Typically 1-4 years	$100	$400
Tires	Depends on truck usage Typically 2-3 years	$150	$400
12V Starter Battery	Up to 10 years	Not a significant expense	
Total	Low estimate: 10,000 miles per year High estimate: 15,000 per year	$500	$1300

Maintenance savings for E-Trucks compared to conventional diesel vehicles will vary widely depending on driving conditions, vehicle usage, driver behavior, vehicle model and regenerative braking usage.

The research team estimates that for an E-Truck operating from the downtown Los Angeles facility, maintenance savings would be around $250 per year, or 2-3¢ / mile for a vehicle that drives about 10,000 miles per year without including brakes and tires savings. For a vehicle that drives about 15,000 miles per year and including some brake and tire savings, we estimate that maintenance savings would be around $1,300 per year, or equivalent to 8-10¢ / mile.

[44] Not including labor costs.

[45] Cummins estimates that DEF consumption will be approximately 2% of fuel consumption, depending on vehicle operation, duty cycle, geography, load ratings, etc… [18]

4.7 E-Truck Charging

This section discusses E-Truck charging based on the in-use data collection, on-road testing, and chassis dynamometer testing described in Section 4.4. The results provide a comprehensive overview of an important aspect of E-Truck deployment by comparing the charging infrastructure needs of different E-Truck models, providing a comprehensive analysis of E-Truck charging patterns in parcel delivery operation and evaluating the impacts of E-Trucks charging on the building where they are recharging as well as on the local and state grid.

4.7.1 Charging Infrastructure

4.7.1.1 FCCC MT E-Cell All-Electric Delivery Van

The FCCC MT E-Cell is equipped with a charging port that is not SAE J1772 compliant. In order to charge the vehicle, a simple cord is used with a twist-lock plug on one end of the cord to connect directly to the vehicle charger and a NEMA L6-30 connector on the other end of the cord to connect to a wall plug (Figure 4-17). The charge port is located on the back of the vehicle, between the left rear wheel and the rear bumper.

Figure 4-17: The MT-E Cell recharging (left) and the vehicle side of the charging cable (right)

While this set up has the advantage of working without installing expensive charging equipment, it is not compatible with commercially available electric vehicle charge stations and can present some safety challenges. For instance, the vehicle delivered to the EVTC for the road testing (see Appendix 4A) did not support Article 625 of the National Electric Code including the following safety requirements:

- Interlock that de-energizes the electric vehicle connector when disconnected from vehicle.
- Automatic de-energization of cable upon over-exposure to strain.
- Overcurrent protection.
- Personnel protection system against electric shock.

4.7.1.2 Navistar eStar

The Navistar eStar is equipped with a charge cord that meets the voluntary SAE J1772 standard, which makes the eStar compatible with commercially available Electric Vehicle Supply Equipment (EVSE) such as the Clipper Creek Model CS-60 that was installed to recharge the eStars at the downtown Los Angeles facility (Figure 4-18 / left). The charge port is located on the back of the vehicle, above the right rear wheel (Figure 4 18 / right).

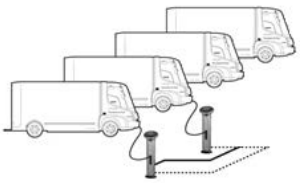
Figure 4-18: A Clipper Creek Model CS-60 (left) and a Navistar eStar recharging (right)

One EVSE was installed for each eStar in operation and each driver was requested to plug-in at the end of each shift. This allowed the vehicles to be fully recharged for the next shift the following day. However, given the low daily mileage that these vehicles covered, we identified that charging infrastructure could be better optimized to fit vehicle use patterns. Next, three different cases provide an alternative to the option of having one EVSE per E-Truck.

From the in-use data collected at the downtown Los Angeles depot (see Section 4.4.1.2), the following assumptions are made: driving 20 miles will use 15 percent of the battery SOC and will require 2 hours of charging to get the battery SOC back to 100 percent, driving 40 miles will use 30 percent of the battery SOC and will require four hours of charging to get the battery SOC back to 100 percent and driving 60 miles will use 45 percent of the battery SOC and will require 6 hours of charging to get the battery SOC back to 100 percent.

Case #1 - While the downtown Los Angeles depot installed one charger per vehicle, this case shows that only two chargers could be used to recharge all four vehicles without any vehicle ever reaching battery SOC levels lower than 70 percent or a charging duration higher than 4 consecutive hours.

Table 4-30: eStar charging infrastructure analysis – Case #1

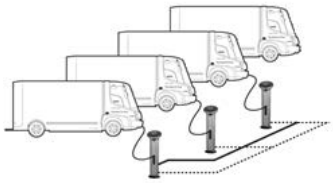


Case #1
Installed 2 charger for 4 vehicles
Each vehicle drives an average of 20 miles/day
Maximum charging duration = 4 consecutive hours
Minimum battery SOC = 70%

Charging Times	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Unit A	2h	No charging	4h	No charging	4h	No charging	No charging
Unit B	2h	No charging	4h	No charging	4h	No charging	No charging
Unit C	No charging	4h	No charging	4h	No charging	4h	No charging
Unit D	No charging	4h	No charging	4h	No charging	4h	No charging

Case #2 - On the other hand, if the vehicles drove an average of 40 miles per day, a third charger would need to be installed to recharge the four vehicles without any vehicle ever reaching battery SOC levels lower than 40 percent or a charging duration higher than 8 consecutive hours.

Table 4-31: eStar charging infrastructure analysis – Case #2

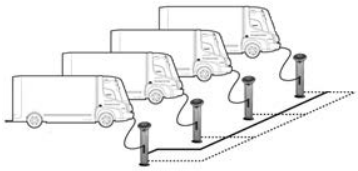


Case #2
Installed 3 charger for 4 vehicles
Each vehicle drives an average of 40 miles/day
Maximum charging duration = 8 consecutive hours
Minimum battery SOC = 40%

Charging Times	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Unit A	No charging	8h	4h	4h	No charging	8h	No charging
Unit B	4h	No charging	8h	4h	4h	No charging	No charging
Unit C	4h	4h	No charging	8h	4h	No charging	No charging
Unit D	4h	4h	4h	No charging	8h	No charging	No charging

Case #3 - If the vehicles drove an average of 60 miles per day, an additional charger (for a total of four) would need to be installed to recharge the four vehicles without any vehicle ever reaching battery SOC levels lower than 50 percent or a charging duration higher than 6 consecutive hours.

Table 4-32: eStar charging infrastructure analysis – Case #3



Case #3
Installed 4 charger for 4 vehicles
Each vehicle drives an average of 60 miles/day
Maximum charging duration = 6 consecutive hours
Minimum battery SOC = 50%

Charging Times	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Unit A	6h	6h	6h	6h	6h	No charging	No charging
Unit B	6h	6h	6h	6h	6h	No charging	No charging
Unit C	6h	6h	6h	6h	6h	No charging	No charging
Unit D	6h	6h	6h	6h	6h	No charging	No charging

This simple analysis identifies an opportunity where charging infrastructure could be better optimized to fit vehicles use patterns. This could lead to lower charging infrastructure costs, but potential capital cost savings will depend on the particular characteristics of each depot. However, it may be more cost-effective to overbuild the charging infrastructure upfront in anticipation of future E-Truck deployments, if existing vehicles are redeployed on longer routes, or if more E-Trucks are added.

Further analysis is needed to better understand the costs and benefits of optimizing charging infrastructure to fit vehicle use patterns and evaluate potential savings.

4.7.1.3 Smith Electric Newton Step Van

The Smith Electric Newton Step Van is equipped with a charge cord that meets the voluntary SAE J1772 standard, which makes the Newton Step Van compatible with commercially available EVSEs (Figure 4-19). The vehicle is fitted with an on-board charger compatible with 220V / 63A or 208V / 75A electrical circuits, which will allow for recharge times of 6 to 8 hours. The charge port is located on the back of the vehicle, between the right rear wheel and the rear bumper.

Figure 4-19: The Smith Electric Newton Step Van charge port

4.7.1.4 E-Truck Charging Infrastructure Costs

In 2012, CALSTART released a report highlighting the key findings and recommendations of the E-Truck Task Force (E-TTF) [20]. The main goal of the E-TTF is to speed and support effective E-Truck production and use. Surveying more than 125 industry leaders, the E-TTF identified infrastructure costs and planning complications as a surprise to fleets and important issues needing resolution. E-Truck charging infrastructure costs include:

- EVSE options & hardware costs

Several options exist to charge E-Trucks. The most common options have been defined by the voluntary SAE J1772 standard (Table 4-33).

Table 4-33: Summary of SAE charging configurations [21]

SAE Charging Configurations	AC Level 1[46]	AC Level 2	DC Level 3 "Fast Charging"
Voltage / Current Characteristics	120V 12 - 16A	240V Up to 80A	200-600V DC Up to 400 A
Grid Power	1.4 to 1.9 kW	Up to 19.2 kW	Up to 240 kW
Estimate of Hardware Costs	N/A	$500 to $5,000	~$15,000

- Installation cost

Charging infrastructure installation costs vary greatly depending on site conditions (including distance to existing electric utility equipment, need to add new circuits and conduits) and charging current requirement (higher current will allow faster charging but will require more expensive hardware). The E-TTF gave a first estimate of infrastructure installation costs between $100 and $5,000 per EVSE [20].

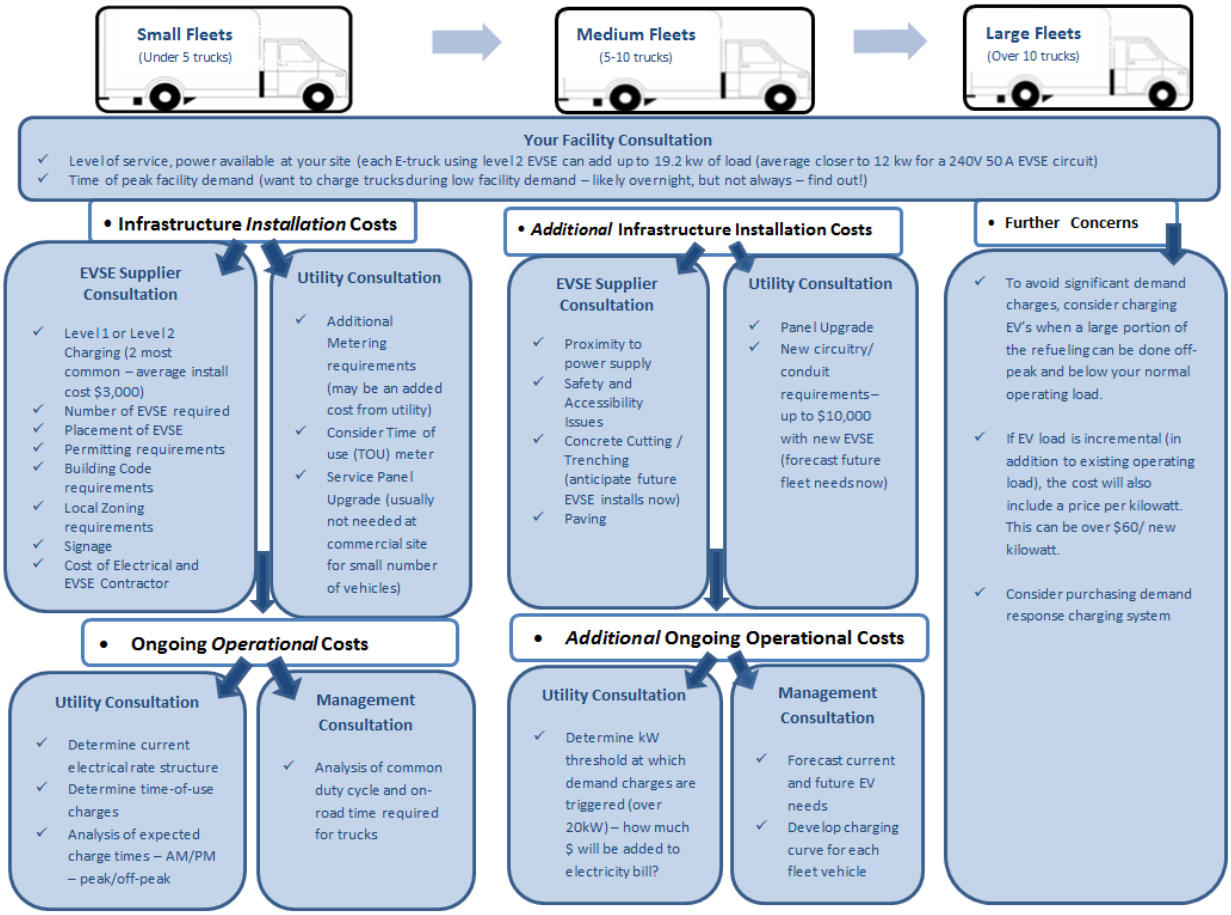
- Operating Costs

[46] Not applicable for commercial electric vehicles.

Operating costs for E-Truck charging infrastructure include electricity costs, distribution or demand charges and potential EVSE network costs.

To achieve a successful E-Truck deployment project, fleet users need to avoid unexpectedly high initial infrastructure costs and electricity demand charges through careful advance deployment planning and through securing strong service and support commitments from manufacturers [20]. The E-TTF provided planning guidelines to help fleets plan E-Trucks infrastructure projects (Figure).

Figure 4-20: E-TTF Infrastructure Planning Guidelines for E-Truck Fleets [20]

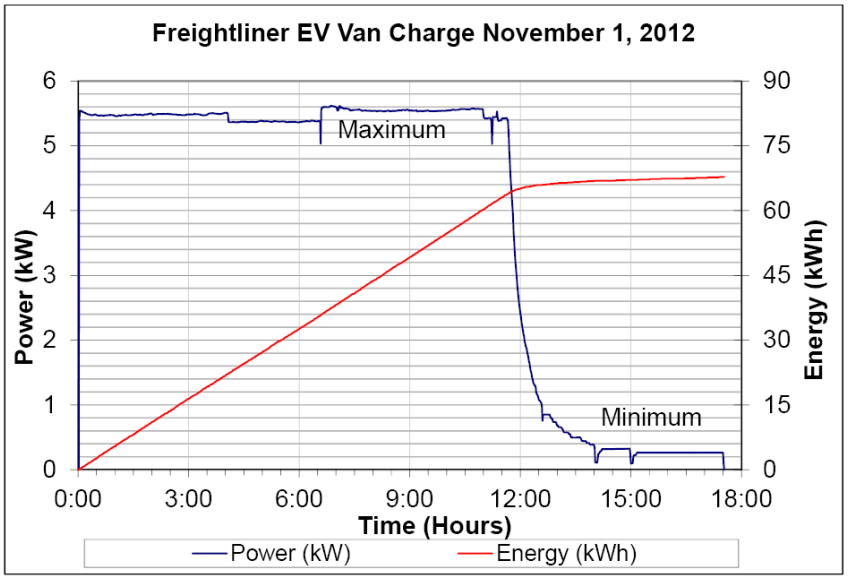


4.7.2 Frequency and Length of Charging

4.7.2.1 FCCC MT E-Cell All-Electric Delivery Van

FCCC advertises that the MT E-Cell battery system needs only 6 to 8 hours to reach a full charge if it charges through standard 220V outlet [22]. During the road testing (see Appendix 4A), a FCCC MT E-Cell was charged at a nominal voltage of 240V from 0 to 100 percent SOC. Typical charge duration was measured between 12 and 14 hours to achieve the bulk of the charge and over 17 hours to achieve a full charge (Figure 4-21).

Figure 4-21: FCCC MT E-Cell charging profile



Vehicle operating schedules vary per route, but we witnessed at the downtown Los Angeles facility that vehicles were generally in operation from 6 a.m. to 6 p.m. during weekdays. This leaves about 12 hours to recharge the vehicle at night, barely adequate to achieve the bulk of the charge. The long charge duration could conflict with vehicle availability in parcel delivery fleet use.

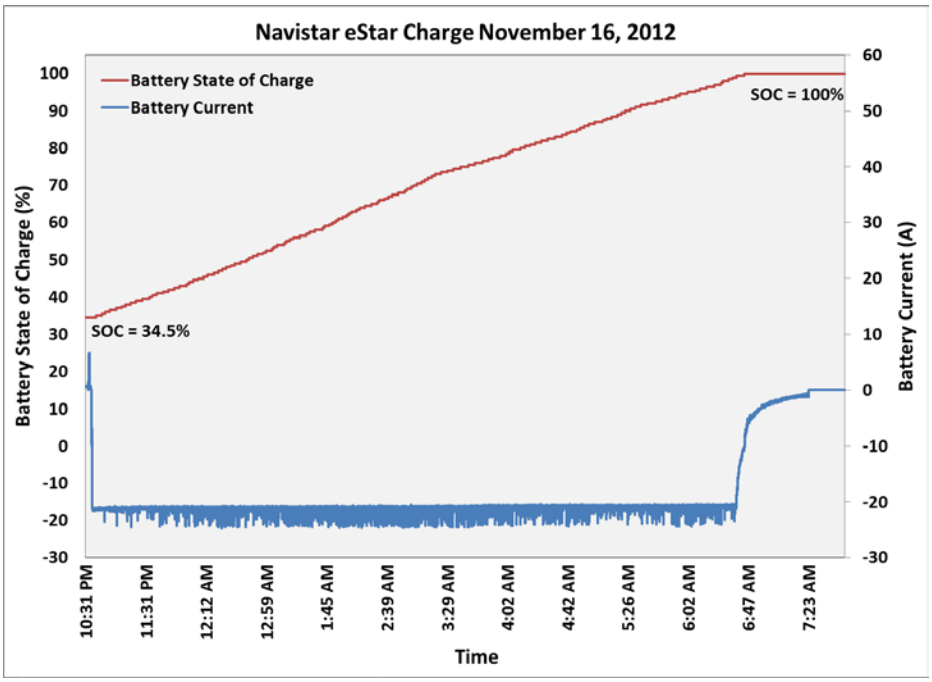
During the road testing, maximum charging current was recorded at 23.2 A (AC) and maximum grid charging power at 5.6 AC kW. A continuous power draw of 260 to 300 W was recorded after the charge was completed and until the vehicle was unplugged. This stand-by power draw can negatively impact the E-Truck overall equivalent fuel economy.

For instance, a vehicle operates for a duration of 10 hours every weekday, recharges for 10 hours each night and stays plugged in the remainder of the time (that is: 4 hours/weekday and 24 hours/weekend day), drawing 300 W of stand-by power. Calculated for a week's usage, the vehicle would have consumed 20 AC kWh of stand-by energy, adding 0.10 AC kWh/mile to the overall AC energy consumption (an equivalent loss of 3.8 MPG).

4.7.2.2 Navistar eStar

Navistar advertises that the eStar can recharge in approximately 8 hours [23]. Although we were not able to directly verify that claim, the in-use data collected on the four Navistar eStars (see Section 4.4.1.2) indicate that typical charge duration would be more than 8 hours to reach a full charge. For instance, the chart below shows a charging event from 34.5 percent to 100 percent SOC for which charge duration was measured at 7 hours and 47 minutes to achieve the bulk of the charge and 8 hours and 29 minutes to achieve a full charge (Figure 4 22). Extrapolating on this example, we estimate the total charging time from 0 to 100 percent SOC would take between 12 and 13 hours.

Figure 4-22: Navistar eStar charging profile



The long charge duration could conflict with vehicle availability in parcel delivery fleet use. However, the performance evaluation of the eStar estimated the total vehicle range was up to 100 miles (see Section 4.4.5), indicating that the eStar could operate through a wide variety of parcel delivery drive cycles without using the full range capacity, requiring a charge duration less than the 12 to 13 hours needed for a full charge from 0 to 100 percent battery SOC.

Maximum charging current was recorded at 24.3 A (DC) and maximum grid charging power was estimated at 8.8 AC kW[47]. This is higher than for the FCCC MT E-Cell (5.6 AC kW), which explains why the eStar estimated total charging time is lower than the MT E-Cell total charging time despite the fact that the eStar has a larger battery (80 kWh versus 55.5 kWh).

The team carried out an in-depth analysis of the data collected on the four Navistar eStar vehicles available, looking at a period of 6 weeks from August 14 to September 23, 2012, for which data was available for each vehicle. This represented 41 days of continuous data (29 business days and 12 weekend days). Table 4-34 summarizes vehicle and charging unit usage.

[47] We assumed a charger efficiency of 90%.

Table 4-34: Summary of eStar charging data for the period of 8/14 to 9/23/2012

Vehicle & Charging Unit Usage	Period of 08/14/12 to 09/23/12
Number of charging units	4 (Clipper Creek CS-60)
Cumulative number of days in operation	116
Cumulative number of charging events	105
Percent of time with a vehicle connected to charging unit	45%
Percent of time with a vehicle drawing power from charging unit	6%
Average length of time with vehicle drawing power per charging event	2h 08min
Average electricity consumed per charging event (DC kWh)	12.5

Out of 116 cumulative days in operation, only 105 charging events were recorded, which indicates not every vehicle was plugged in to an EVSE at the end of each shift, contrary to what was requested of each E-Truck driver. Between August 14 and September 23, vehicles were plugged in to a charging unit 45 percent of the time and drew power from a charging unit 6 percent of the time, indicating that the vehicles were plugged in to a charger much longer than what was needed to recharge the batteries. The average charging duration was 2 hours and 8 minutes and the average electricity consumed per charging event was 12.5 DC kWh, equivalent to an estimated 13.9 AC kWh[48].

Figure 4-23 show that the majority of charging events lasted between 1 and 3 hours and drew between 5 and 15 DC kWh (equivalent to an estimated 6 to 17 AC kWh).

[48] We assumed a charger efficiency of 90%.

Figure 4-23: Distribution of charging times and charging DC energy for the Navistar eStar

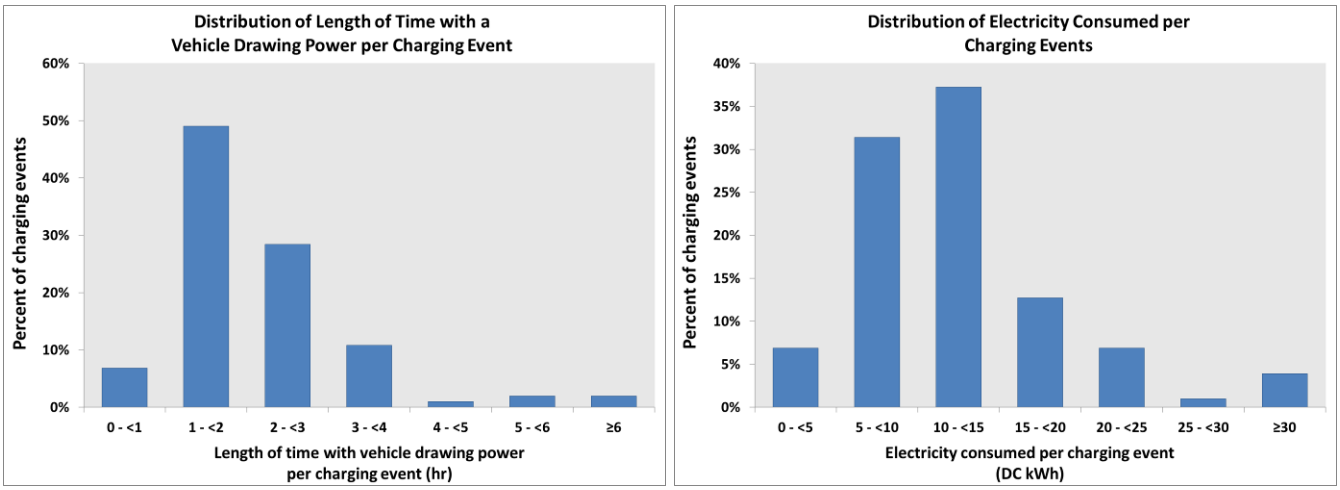


Table 4-35 below breaks down the data in further details, separating weekdays and weekends.

Table 4-35: Comparison of eStar charging data for the period of 8/14 to 9/23/2012 between weekdays and weekend

Vehicle & Charging Unit Usage	Weekday	Weekend
Cumulative number of days in operation	111	5
Cumulative Number of charging events	103	2
Percent of time with a vehicle connected to charging unit	42%	51%
Percent of time with a vehicle drawing power from charging unit	8%	1%

As expected for a parcel delivery fleet, the vehicles were operating and charged mostly on weekdays but the team recorded five days when vehicles operated on weekends. Between August 14 and September 23, vehicles were plugged in to a charging unit 42 percent of the time on weekdays and 51 percent on weekends and drew power from a charging unit 8 percent of the time on weekdays and 1 percent on weekends. Again, this indicates that the vehicles were plugged in to a charger much longer than what was needed to recharge the batteries.

Figure 4-24: Cumulative hours with eStars operating and charging versus time of day for the period of 8/14 to 9/23/2012

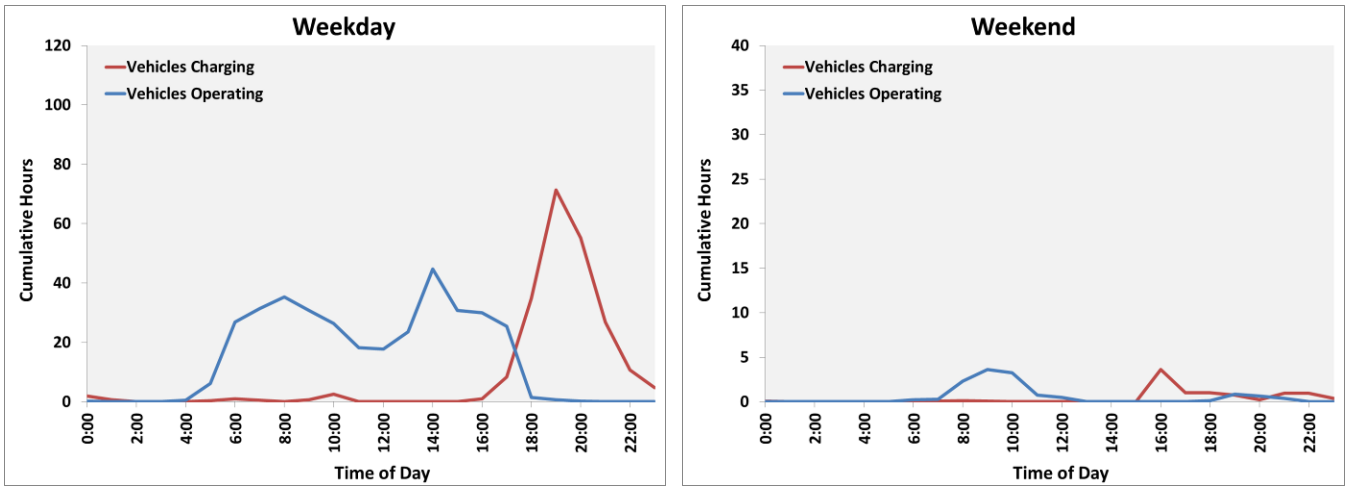


Figure 4-24 above show that the vehicles were mostly operated between 6 a.m. and 6 p.m. on weekdays. Some vehicles were occasionally operated on Saturday mornings from 8 a.m. to 12 p.m. Matching the vehicle operating profile, the wide majority of vehicle charging occurs on weekdays between 5 and 10 p.m. (at the end of the shift), with the peak happening around 7 p.m. Little to no charging occurred on weekends.

Figure 4-25: Percent of time with eStars connected to a charger versus time of day for the period of 8/14 to 9/23/2012

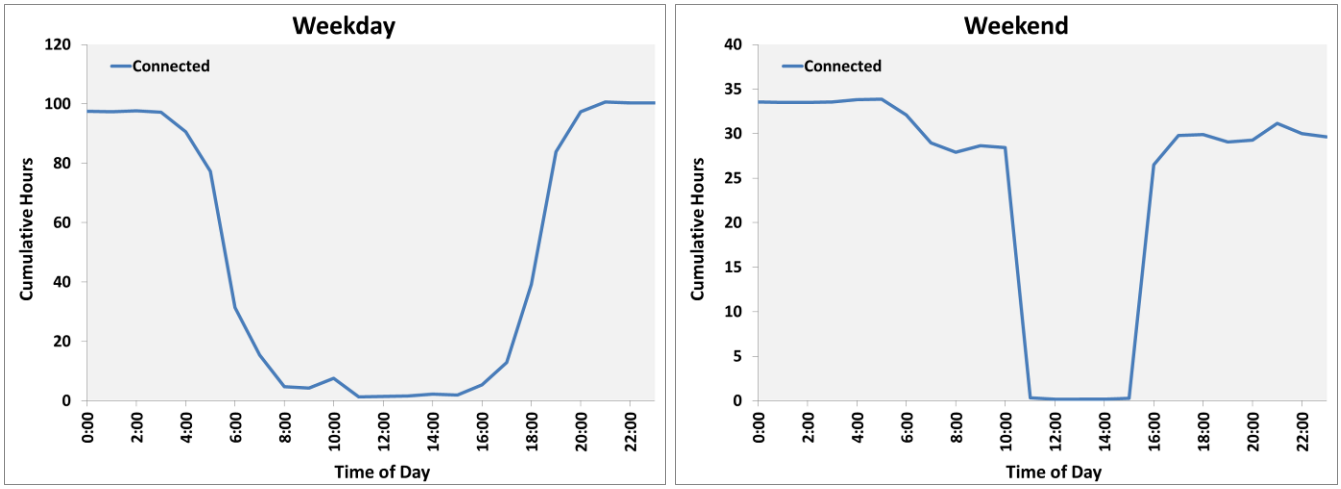
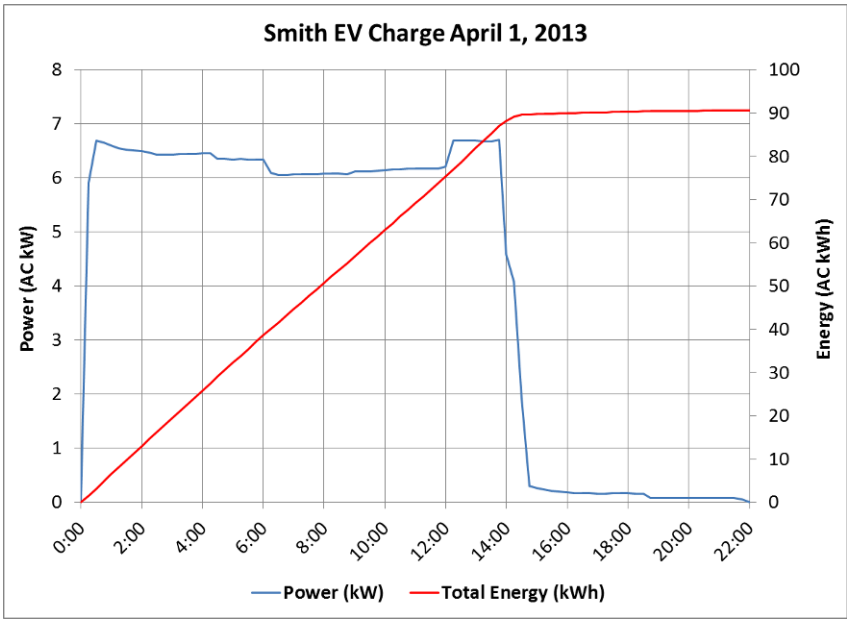


Figure 4-25, above, further explains the charger availability profile: most vehicles were plugged to a charging unit between 5 p.m. and 6 a.m. on weekdays. Vehicles were never available for charging between 11 a.m. and 4 p.m. since the downtown Los Angeles facility uses demand response strategies to decrease the peak electricity demand of the facility by switching off conveyor belts, floor lights and electric vehicles chargers from 11 a.m. to 4 p.m.

4.7.2.3 Smith Electric Newton Step Van

Smith Electric reported that the Newton Step Van needs 6 to 8 hours to reach a full charge at a continuous current of 75A [24]. For this project, a Smith Electric Newton Step Van was tested on a chassis dynamometer (see Appendix 4B). Both the facility electrical system and the EVSE used for this testing were limited in the grid current that could be used for charging. Due to these testing site infrastructure limitations, we were not able to use the charging current recommended by Smith Electric Vehicles to recharge the Newton Step Van. Therefore, the charging times recorded were longer than what one would expect at a customer site equipped with the recommended charging infrastructure. Typical charge duration from 0 to 100 percent SOC was measured at about 13 hours to achieve the bulk of the charge and 14 hours and 20 minutes to achieve a full charge (Figure 4-26).

Figure 4-26: Smith Electric Newton Step Van charging profile at 32A current



While this total charging time is long and may conflict with vehicle availability in parcel delivery fleet use, Smith Electric Vehicles has specified the Newton Step Van is to be recharged at a much higher current, which would reduce markedly the typical charge duration and guarantee vehicle availability in parcel delivery fleet use.

During the chassis dynamometer testing, maximum charging current was recorded at 17 A (DC) and maximum grid charging power at 6.7 kW. A continuous power draw of 65 to 140W was measured after the charge was completed and until the vehicle was unplugged. This stand-by power draw is lower than the one measured on the FCCC MT E-Cell but can still negatively impact the E-Truck overall equivalent fuel economy.

4.7.3 Short and Long Term Grid Impacts

4.7.3.1 California grid impacts

Today, E-Trucks represent a very small share of the truck population in California and within the next five years, this share should remain small. Therefore, their short-term impacts on the California grid will be minimal. As E-Trucks are adopted more widely in California in the next 20 years, their impact on the California electric grid will grow. However, this team estimates that long-term impacts on the California grid will remain minimal.

For instance, if 10 percent of Class 3-4 urban delivery trucks in California were E-Trucks, it would represent a total energy consumption of 70,000-100,000 MWh per year, assuming that these vehicles drive between 10,000 and 15,000 miles per year at an average of 1.0 AC kWh/mile. This would represent less than 0.10 percent of total commercial retail sales of electricity in California in 2010[49]. If these 7,000 E-Trucks were all charging at the same time, it would represent a total load of 49 MW, assuming an average charging rate of 7 kW. This would represent 0.10 percent of the California Independent System Operator peak load in 2012[50].

4.7.3.2 Local grid impacts

Similarly, E-Trucks will have minimal short- and long-term impacts on local utility grids. For instance, 1,000 E-Trucks in the Los Angeles Department of Water and Power territory would represent a total energy consumption of 10,000-15,000 MWh per year, assuming that these vehicles drive between 10,000 and 15,000 miles per year at an average of 1.0 AC kWh/mile. This would represent about 0.11 percent of total commercial retail sales of electricity in LADWP territory in FY 2010-2011[51]. If these 1,000 E-Trucks were all charging at the same time, it would represent a total load of 7 MW, assuming an average charging rate of 7 kW. This would represent about 0.11 percent of the LADWP peak load[52].

In the short and long term, E-Trucks will impact local distribution infrastructure serving facilities where E-Trucks are deployed. Utilities need to know the location(s) where electric vehicle charging will most likely occur so they can study the local distribution in advance and upgrade the infrastructure if needed. In some cases, battery electric truck charging could require a utility to make infrastructure upgrades to accommodate the added demand (distribution substation and transformers for instance). The question of who pays for electric vehicles utility infrastructure upgrades (utility ratepayers or companies deploying electric vehicles) will need to be answered as more E-Trucks are deployed in California.

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[49] Commercial retail sales of electricity for California in 2012 was 121,180,000 MWh [25].

[50] CAISO peak load in 2012 was 46,846 MW on August 31 at 15:53 [26].

[51] Commercial retail sales of electricity for LADWP in FY 2010-11 was 13,345,682 MWh [27].

[52] LADWP peak load in 2010 was 6,142 MW on September 27,2010 [27].

4.7.3.3 Building impacts

Electric rates vary considerably, depending not only on the utility itself, but also on the electrical characteristics of the specific customer purchasing the power. Rate structures for commercial / industrial customers generally include the following items [28]:

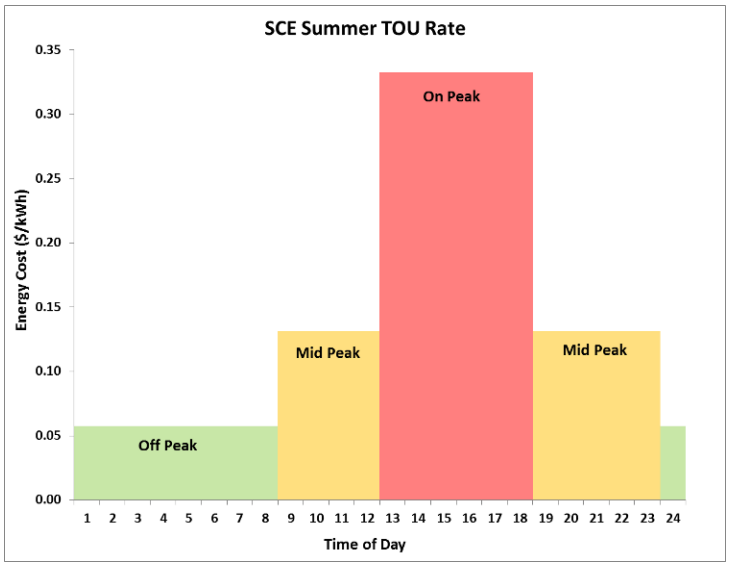
- Account charge.
- Distribution or demand charge.
- Transmission charge.
- Energy charge.
- Power factor adjustment.
- Taxes and fees.

Using battery-electric instead of gasoline or diesel powered trucks will mean an increase in the facility electricity consumption and a decrease in fuel purchases. Due to the complexity of electric rates compared to simple fuel prices, we recommend facility managers implementing E-Trucks carefully review their electric rates to minimize E-Truck charging impacts on the facility electricity bill. To illustrate potential impacts for a facility deploying E-Trucks, we take a closer look at "Time-of-Use" pricing and demand charges, two components of electric rate structures that can greatly influence the economic success of E-Trucks.

Time-of-Use Pricing

Time-of-Use or TOU pricing is implemented by utilities to encourage customers to shift their loads away from peak demand times (during hot, summer afternoons in California for instance) [28]. Customers will pay more for electricity during on-peak hours. For instance, Southern California Edison's TOU General Service rate charges almost six times more per kWh in the summer during on-peak hours than off-peak hours (Figure 4 27) [29].

Figure 4-27: Southern California Edison Summer TOU General Service rate charge



Charging on-peak can have rather dramatic impact on fuel costs savings, even cancelling the advantage E-Trucks have over diesel vehicles in certain cases (Table 4-36).

Table 4-36: E-Truck fuel cost sensitivity analysis to TOU energy pricing

10,000 mi/yr	Vehicle Efficiency	Fuel Prices	Fuel Cost	Charging Off-Peak	Charging Mid-Peak	Charging On-Peak
Diesel	11 MPG	$4.10/gallon	$0.37 / mi.	N / A		
Electric	1.05 AC kWh/mi.	Varies[53]	$0.14 / mi.[54]	$0.06 / mi.	$0.14 / mi.	$0.35 / mi.

Demand charges

Electric utilities generally charge their commercial and industrial customers a monthly demand charge based on the highest amount of power drawn by the facility [28]. A quick review of electric rate schedules for the five largest investor-owned utilities in California shows that demand charges vary between $10 and $20 per kW [29 to 33]. For some facilities, demand charges can represent a large part of the electricity bill.

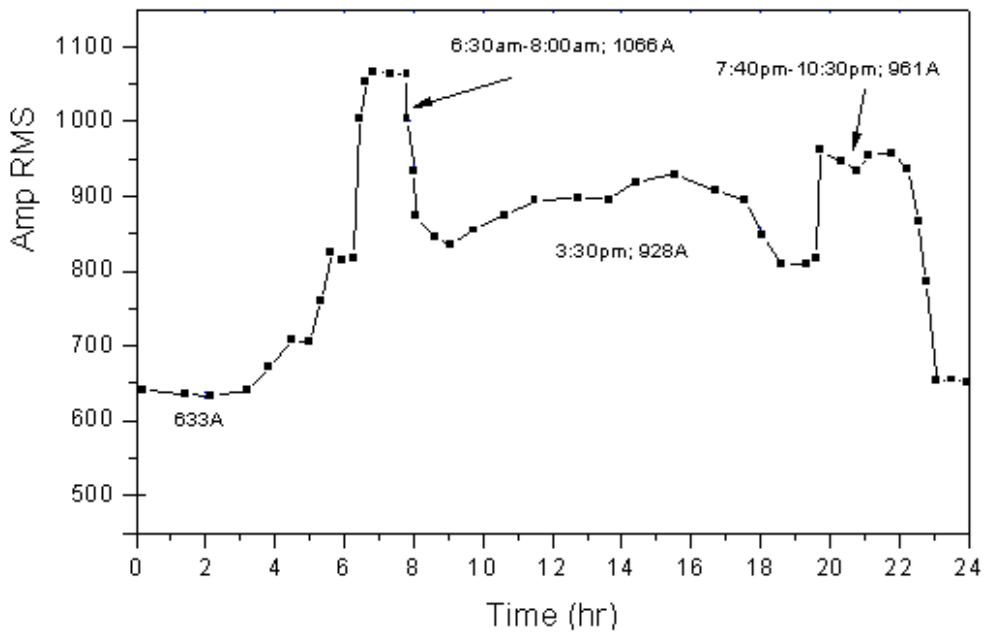
A typical parcel delivery facility, like the one in downtown Los Angeles, usually shows two main periods of activities: in the morning between 6 and 8 a.m. when packages are loaded onto

[53] SCE Summer TOU General Service: Off-Peak = $0.05745/kWh, Mid-Peak = $0.13142/kWh, On-Peak = $0.33236/kWh [29].

[54] We assume $0.13/kWh [15].

the delivery trucks and between 6 and 10 p.m. when trucks are unloaded. This increased activity translates into higher facility energy consumption during these periods (Figure 4-28).

Figure 4-28: Building load in ampere from a typical day at a 120-vehicle parcel delivery facility [8]



Charging E-Trucks right upon returning to the facility can mean adding electrical load to a facility already drawing a large amount of power from the grid. In the worst case scenario, E-Truck charging can increase the peak load of the facility and thus increase demand charges. As Table 4-37 below shows, demand charges can have a significant impact on fuel costs savings, even cancelling the advantage E-Trucks have over diesel vehicles in certain cases.

Table 4-37: E-Truck fuel cost sensitivity analysis to demand charges driving 10,000 miles/year

10,000 mi/yr	Vehicle Efficiency	Fuel Prices	Fuel Cost w/o Demand Charges	Fuel Cost w Demand Charges @ 8.8kW & $10/kW	Fuel Cost w Demand Charges @ 8.8kW & $20/kW
Diesel	11 MPG	$4.10/gallon	$0.37 / mi.	N/A	N/A
Electric	1.05 AC kWh/mi.	$0.13/kWh	$0.14 / mi.	$0.24 / mi.	$0.35 / mi.

4.7.4 Conclusions

- Charging infrastructure is an important component of any E-Truck deployment project

E-Truck charging infrastructure costs can be very high and will depend on many factors. Fleet managers should carefully plan E-Truck deployments. Resources exist to help fleets plan E-Trucks infrastructure projects such as the E-TTF Infrastructure Planning Guidelines.

- Charging time depends on charging infrastructure

From the field data, we noticed that charging time was significantly longer for the MT E-Cell and eStar than what was advertised by their respective manufacturers. The long charge duration could conflict with vehicle availability in parcel delivery fleet use.

In order to decrease charging time, higher charging current can be used, like on the Smith Electric Newton Step Van. The charging current should be specified to guarantee vehicle availability. However, using higher charging currents to charge faster will be more expensive to install. There is a trade-off between charging time and charging infrastructure costs: the lower the charging time, the more expensive the charging infrastructure will be.

- E-Truck "stand-by" power can negatively impact overall energy consumption

The team noticed that E-Trucks drew a small amount of power from the grid after battery charging was completed and until vehicles were unplugged. This "stand-by" power is likely caused by the low voltage system batteries and the vehicle accessories (fans, battery cooling system, vehicle display) remaining powered on. This stand-by power draw can negatively impact the E-Truck overall equivalent fuel economy and E-Trucks manufacturers should find ways to minimize power draw when the vehicle is plugged in to the grid but not charging.

- Impacts of E-Truck charging will be focused on building and local grid infrastructure

The largest grid impacts were identified at the building level. Deploying E-Trucks will require facility managers to understand the electrical load profile of the building where E-Trucks are deployed in order to maximize return on investment. Demand response strategies should be implemented to take advantage of low energy prices such as Time-of-Use pricing and to avoid penalties such as demand charges.

For the downtown Los Angeles facility, recommendations are that E-Truck charging be delayed after the second peak of activity between 6 and 10 p.m. Existing technologies could be used to implement this change. For instance, the Navistar eStar is equipped with a charging timer that can delay when charging starts.

The research team identified local infrastructure upgrades as another short- and long-term impact of E-Trucks. Electric utilities and companies deploying E-Trucks will need to work together to share the costs of local infrastructure upgrades in a way that is fair for ratepayers and acceptable for utility cost recovery structures but that does not deter companies from deploying E-Trucks.

4.8 Findings and Recommendations

This section discusses the business case for E-Trucks, using data presented in this report as inputs for a business case analysis of E-Trucks in parcel delivery applications. The first look is at how vehicle usage influences the business case and then assesses the role of incentives for purchase at this early stage of the E-Truck market. Next is how right-sizing E-Truck battery packs and reducing battery costs can improve the economic success of E-Trucks.

This section also explores how Vehicle-To-Grid strategies can benefit E-Trucks in certain cases and help the adoption of commercial electric vehicles.

Lastly, this section summarizes the findings and recommendations developed in this report to inform fleets and E-Truck manufacturers on the overall performance of E-Trucks, to provide insights on how the technology can be improved on the one hand and better used on the other hand and to give information to the CalHEAT roadmap to outline actionable steps on the electrification pathway identified by the roadmap.

4.8.1 Business Case for E-Trucks

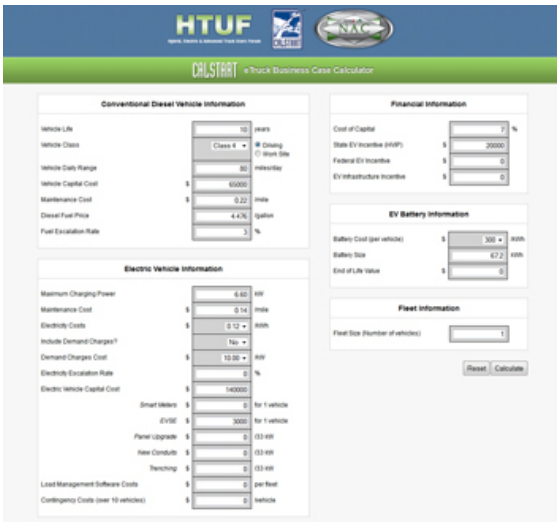
The business case for high-efficiency vehicles is important to understand in the early stages of market introduction. High-efficiency vehicles and E-Trucks in particular have much higher upfront costs than similar diesel or gasoline trucks but will have lower operation and maintenance costs. The business case for E-Trucks relies on finding the best-use profiles that will maximize operational savings and achieve low payback periods.

As part of the E-TTF (introduced in Section 4.7.1.4), a calculator was developed to evaluate the business case of commercial battery electric trucks. The calculator compares the capital and operational costs of an E-Truck to a conventional diesel truck. It includes a comprehensive list of vehicle and infrastructure inputs and is designed to compute sensitivity analyses on key inputs such as vehicle daily range, fuel prices, battery cost, and incentives [34].

- Figure 4-29 shows a screenshot of the calculator. To assess the economic value of E-Trucks, we focused on two economic analysis metrics: Simple Payback Period (SPP)
- Net Present Value (NPV)

For more information about the business case analysis methodology, please see [34].

Figure 4-29: Screenshot of the E-TTF Business Case Calculator



To better understand the business case for E-Trucks, the team compared a Class 4-5 parcel delivery E-Truck driving different distances. Then, the team compared the business case for E-Trucks with and without current incentives from the California HVIP program. Lastly the team analyzed the influence of E-Truck battery size and prices on the business case.

Table 4-38 below lists the input parameters that were used to analyze the business case of a Class 4-5 parcel delivery E-Truck replacing an equivalent conventional diesel vehicle.

Table 4-38: Input parameters for business case analysis of a Class 4-5 parcel delivery E-Truck [34]

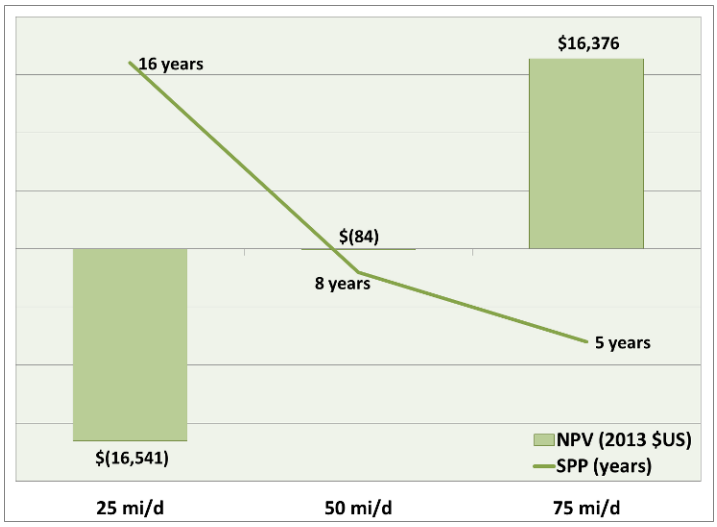
Vehicle Life	10 years
Fuel Economy	Diesel 11 MPG E-Truck 0.9 AC kWh/mile
Vehicle capital cost	Diesel $65,000 E-Truck $135,000
Maintenance cost	$0.05/mile saving for E-Truck
Fuel prices	Diesel $4.1 per gallon Electricity $0.12/kWh
Fuel escalation rate	Diesel 3% Electricity 0%
EVSE capital cost	$3,000
Cost of capital	7%
HVIP Incentive	$40,000

Diesel and E-Truck fuel economy were derived from Section 4.4 and E-Truck maintenance costs savings from Section 4.6. For more information about assumptions and references, please see [34].

4.8.1.1 Influence of E-Truck usage

Figure 4-30 below shows how daily mileage driven influences the business case for E-Trucks.

Figure 4-30: Influence of daily mileage on business case for a Class 4-5 parcel delivery E-Truck



In this example, we analyzed three different cases: a Class 4-5 parcel delivery E-Truck driving 25, 50 and 75 miles per day, 5 days a week and 50 weeks a year, replacing an equivalent conventional diesel truck.

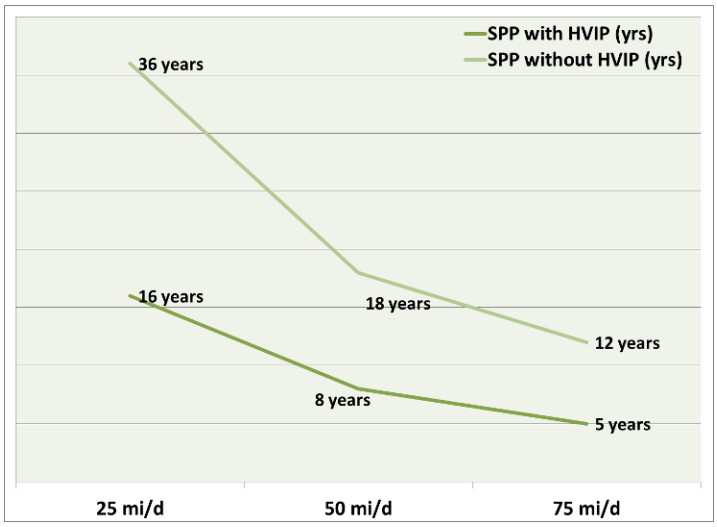
We see that E-Trucks make a good business case when driven 75 miles per day. In that case, the SPP is about 5 years - the higher upfront cost will be repaid in about 5 years. In addition, the NPV of about $16,000 indicates a benefit when using an E-Truck in that application. As the vehicle is driven fewer miles per day, the business case worsens. At an average of 50 miles driven per day, the SPP is still under the 10-year vehicle lifetime but the negative NPV indicates the investment's lack of financial worth. Lastly, at an average of 25 miles driven per day, the SPP is over the 10-year vehicle lifetime, indicating that the initial upfront investment will not be recouped by fuel and maintenance savings.

These results clearly show that a high utilization of the E-Truck is needed in order to make a compelling business case. By "high" utilization we mean a daily mileage greater than 50 miles. At these high daily utilization rates, a sufficient amount of diesel fuel is displaced by cheaper electricity to make the investment into higher upfront costs E-Trucks worthwhile. However, at lower daily utilization rates (lower than 50 miles), fuel and maintenance savings will not pay for the higher incremental cost that E-Trucks typically show.

4.8.1.2 Influence of E-Truck purchase incentive

Figure 4 31 shows how purchase incentives influence the business case for E-Trucks.

Figure 4-31: Influence of California HVIP incentive on business case for a Class 4-5 parcel delivery E-Truck



In this example, we analyzed the same three cases described in Section 4.8.1.2 with and without including the California HVIP purchase incentive.

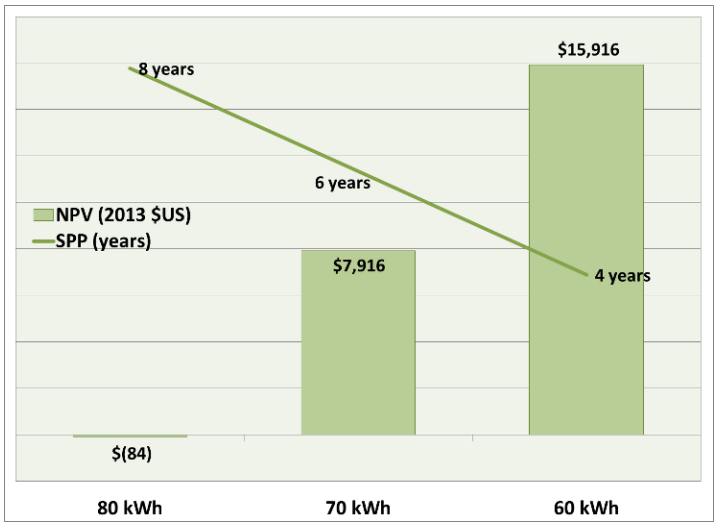
At this early stage of the E-Truck market, purchase incentives play a crucial role for the commercial viability of E-Trucks, as they greatly reduce the simple payback period and thus make E-Trucks more likely to be purchased by commercial fleets.

4.8.1.3 Influence of E-Truck battery size and prices

As the E-Truck market matures and more vehicles are sold, incentives for purchase are expected to decrease and ultimately disappear. To compensate for this decrease in incentives, E-Trucks incremental costs need to be reduced. The team has identified two ways believed to help decrease E-Truck incremental costs: (1) right-sizing E-Truck batteries, and (2) reducing battery costs.

To illustrate the first point, we compare three different cases: a Class 4-5 parcel delivery E-Truck with an 80, 70 and 60 kWh battery, driving 50 miles per day, 5 days a week and 50 weeks a year, replacing an equivalent conventional diesel truck. We assume that total driving range is equal to 100 miles with a 80 kWh battery, 85 miles with 70 kWh and 75 miles with 60 kWh. With a 60 kWh battery, the E-Truck would be able to easily cover 50 miles per day and still have a comfortable safety margin to limit range anxiety. The E-TTF estimated current E-Truck battery costs as about $800 per kWh (installed pack), which means a 60 kWh battery would be $16,000 cheaper than an 80 kWh battery [20]. Figure 4-32 shows how battery size influences the business case for E-Trucks.

Figure 4-32: Influence of battery size on business case for a Class 4-5 parcel delivery E-Truck



Right-sizing E-Truck batteries to better fit how the vehicle is used can greatly increase the business case for E-Trucks and will be an important pathway to explore as incentives for purchase are expected to decrease. Reducing the size of the battery would also reduce the weight of the vehicle and allow for more payload capacity. But because a smaller battery would require more frequent, deeper discharges, battery life could be reduced as a result [20].

Battery prices for electric vehicles are expected to drop in the next 10 years. For instance, the E-TTF identified three future average battery costs over time (installed pack) [20]:

- 2015: $500 – 600 / kWh
- 2020: $450 / kWh
- 2025: $300 / kWh

Table 4-39 below shows how battery prices influence E-Truck incremental costs. We used the same E-Truck as we described in earlier examples, with a 60 kWh battery and we assumed that only battery prices decreased and that diesel vehicle costs remained the same.

Table 4-39: Influence of battery prices on a Class 4-5 parcel delivery E-Truck incremental cost

Battery Size	60 kWh
Estimated Range	Up to 75 miles
Incremental Cost @ $800/kWh (current)	$54,000
Incremental Cost @ $600/kWh (2015)	$42,000
Incremental Cost @ $450/kWh (2020)	$33,000
Incremental Cost @ $300/kWh (2025)	$24,000

Lower battery costs, coupled with right-sized battery packs are expected to greatly reduce E-Truck incremental costs from $54,000 to $24,000 in 2025. With such incremental costs, E-Trucks will become very competitive options for conventional diesel and gasoline trucks, especially if other E-Truck component costs become cheaper and fossil fuel prices continue to rise.

4.8.2 Vehicle to Grid

In addition to driving, E-Trucks could be used as power sources providing power to the electrical grid or to a building while realizing a net profit [34]. Equipped with bidirectional chargers, E-Trucks could be used in Vehicle-To-Grid (V2G) operations to help the adoption of commercial electric vehicles.

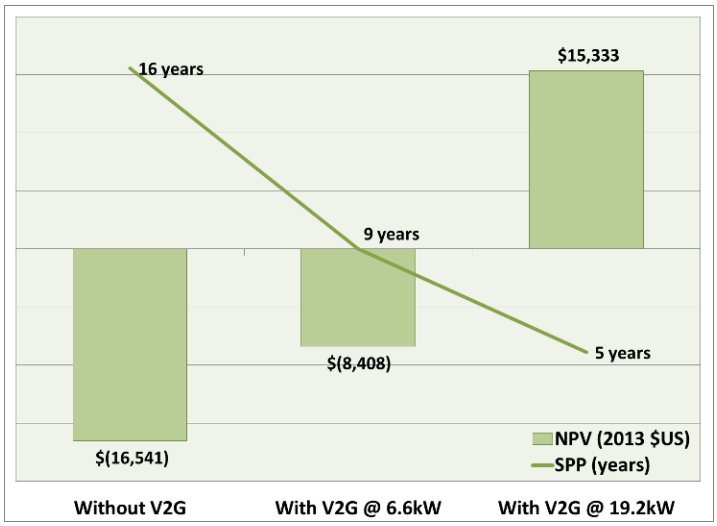
To illustrate the potential of V2G to improve the business case for E-Trucks, see the example described in Section 4.8.1. Table 4-40 below lists the input parameters used to analyze the business case of E-Trucks with additional use for V2G. For more information about assumptions and references, please see [34].

Table 4-40: Input parameters for business case analysis of a Class 4-5 parcel delivery E-Truck with additional use for V2G [34]

Daily time plugged in	55% of the day
Battery efficiency	85%
Grid efficiency	93%
Dispatch to contract ratio	10%
Regulation prices	Up $30/MW-h Down $30/MW-h
Power electronics cost	$500
Wireless connection cost	$100
Bidirectional charger cost	$1,500
On-board metering cost	$50

In this example, the team evaluates an E-Truck driving an average of 25 miles per day. As described in Section 4.8.1.1, at this low daily utilization rate, replacing a diesel vehicle by an E-Truck does not make a good business case. Therefore, look at using the E-Truck for V2G to provide frequency regulation in addition to regular daily urban driving use. The impacts of the additional use for V2G on the business case are shown in Figure 4 33.

Figure 4-33: Effect of V2G on E-Truck business case



When including additional use for V2G at a charging/discharging power level of 6.6 kW, the SPP decreases to 9 years and the NPV increases by about $8,000 (in 2013 US Dollars) but remains negative. When using a power level of 19.2 kW (the upper limit currently used for Level 2 chargers), the financial worth of the investment improves dramatically with a SPP of 5 years and a NPV of over $15,000. The V2G could offset the low utilization of the E-Truck by providing additional use of the vehicle battery when plugged-in. Although lower power levels (6.6 kW) provide some benefits, high power levels (19.2 kW) are preferred.

The example above used market regulation prices of $30 per MW-h. Table 4-41 shows that regulation prices for the California Independent System Operator (CAISO) vary widely.

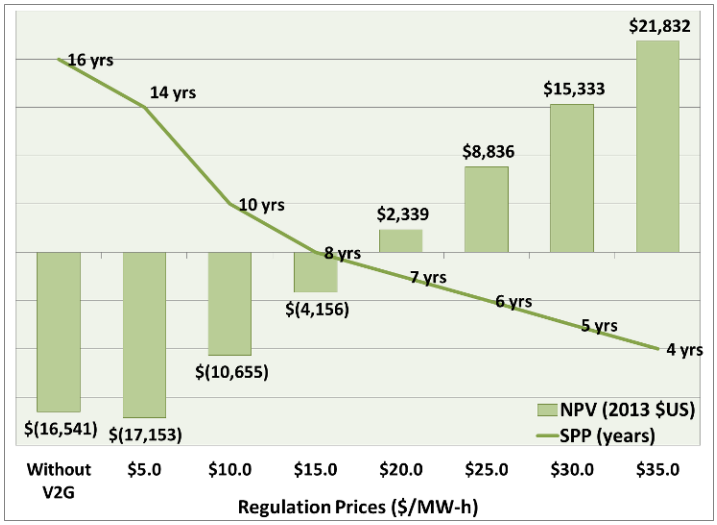
Table 4-41: Annual hourly average CAISO regulation prices [34]

CAISO	Year	Regulation Down	Regulation Up
Annual Hourly Average Price ($/MW)	1999	$20.84	$20.22
	2000	$50.15	$77.28
	2001	$42.33	$66.72
	2002	$13.76	$13.41
	2003	$18.43	$18.08
	2004	$10.95	$17.95
	2005	$16.05	$20.94
	2006	$17.01	$18.94
	2007	$9.97	$16.81
	2008	$15.67	$18.94

To assess the impact of regulation prices on the business case, we carried out a sensitivity analysis, varying regulation prices from $5 to $35 per MW-h.

Figure 4-34 presents the results for the same vehicle with additional use for V2G at a power level of 19.2 kW.

Figure 4-34: Influence of regulation prices on E-Truck business case with V2G



Regulations prices would have to be higher than $15 per MW-h in order to make a good business case for using E-Trucks in V2G.

Using E-Trucks for V2G, specifically for frequency regulation, increases the E-Truck battery usage and can dramatically improve the business case for commercial electric vehicles.

As identified in Section 4.7.3.3, demand charges can represent a large part of the electricity bill of a facility and can also have a significant impact on the business case for E-Trucks. In addition to frequency regulation, E-Trucks could be used for other V2G strategies such as demand response and peak shaving.

4.8.3 E-Trucks in Parcel Delivery Applications

This report presents a comprehensive performance evaluation of three E-Truck models using information and data from in-use data collection, on-road testing and chassis dynamometer testing. The findings of this report confirm the good fit of E-Trucks for parcel delivery applications previously identified by the CalHEAT roadmap:

- Vehicles operate in dense urban areas characterized by low speeds and stop-and-go operation.

The four Navistar eStars and the FCCC MT E-Cell were deployed by the parcel delivery fleet in the downtown Los Angeles area, a dense urban area. The routes these vehicles operated on were characterized by low average speeds and stop-and-go operation.

- Vehicles operate on a fixed route covering less than 100 miles per day.

The routes the E-Trucks operated on were fixed routes covering on average between 18 and 27 miles per day. Both the Navistar eStar and the Smith Electric Newton Step Van met total driving range expectation of about 100 miles but the total driving range of the FCCC MT E-Cell was measured below 70 miles. This report identified operating conditions, such as payload and route characteristics as impacting E-Truck performance and ultimately total driving range.

- Vehicles return to the same depot every day where they can be recharged.

The E-Trucks returned to the same depot every day where they were recharged.

- Vehicles can be recharged overnight.

The five E-Trucks were recharged overnight but the performance evaluation estimated that if the vehicles were used on much longer driving routes, long charge duration could conflict with vehicle availability. For routes close to an E-Truck total driving range, charging current may need to be increased to insure vehicle availability.

- Electric motors are able to produce maximum torque at low speeds, giving E-Trucks strong driving characteristics, particularly in stop-and-go or urban driving situation.

E-Truck performance was evaluated as comparable as or better than similar conventional diesel vehicles. While the drivers reported design issues on the Navistar eStar, the three E-Truck models showed strong driving characteristics and the performance evaluation recognized the vehicles' potential for successful delivery vehicles.

- Electric motors also offer the ability to operate with very low noise, an advantage in certain delivery applications.

On one particular route, one E-Truck operated on a university campus where very low noise proved to be an advantage over other vehicles.

This report also informs fleets and E-Truck manufacturers on the overall performance of E-Trucks, provides insights on how the technology can be improved on the one hand and better used on the other hand and gives information to the CalHEAT Roadmap to outline actionable steps on the electrification pathway identified by the Roadmap. The key findings and recommendations of this report fall into five major categories:

- Performance.
- Maintenance.
- Fleet deployment.
- Charging.
- Business case.

The next sections discuss these five categories in greater detail, listing several key findings and discussing recommendations and next steps.

4.8.3.1 E-Truck performance

Section 4-4 presented a comprehensive performance evaluation of E-Trucks in parcel delivery, including a review of information from in-use data collection, on-road testing and chassis dynamometer testing. Table 4-42 below summarizes the E-Truck performance key findings.

Table 4-42: Summary of E-Truck performance key findings

E-Truck Performance Key Findings	Report Section(s)
Operating conditions impact E-Truck performance	4.4.2 – 4.4.3
AC energy consumption is a better measure of overall vehicle efficiency	4.4.1 – 4.4.3
E-Trucks are more efficient and cheaper to operate	4.4.3 – 4.4.4
E-Trucks are cleaner to operate on a well-to-wheels basis	4.4.3 – 4.4.4
Different data collection methods exist to evaluate E-Truck performance	4.4.1 – 4.4.3

The on-road and chassis dynamometer testing showed that payload and drive cycle influenced vehicle energy consumption and ultimately total driving range. While we were not able to test the impact of vehicle accessories utilization such as air conditioning and cabin fan, vehicle accessories usage will use energy from the batteries and impact total driving range. Lastly, lithium-ion batteries used on E-Trucks generally perform differently depending on ambient temperature. Weather conditions will also impact E-Truck performance.

Recommendations are that further testing be carried out to better understand the impact of operating conditions on E-Truck performance.

AC energy represents the energy charging the battery from the point where electricity is introduced from the electric outlet to the battery charger. DC energy represents the energy charging the battery from the point where electricity is introduced from the battery charger to the battery. The conversion from AC to DC is not perfect and a certain amount of energy is lost in the process so that the AC energy consumption is always greater than the DC energy consumption.

While DC kWh/mile is a good indicator of the efficiency of the drivetrain, AC kWh/mile is a better indicator of the overall efficiency of the vehicle and should be used to compare the efficiency of E-Trucks with other vehicles.

The performance evaluation carried out for this project used a wide range of data collection techniques, from manual readings of vehicle odometers and electric meters to chassis dynamometer testing. Each data collection technique presented different benefits and drawbacks.

The recommendation is that these data collection techniques be used appropriately to provide better performance data on E-Truck deployment projects.

4.8.3.2 E-Truck maintenance

Section 4.6 presented a preliminary reliability and maintenance evaluation of E-Trucks. Table 4-43 below summarizes the E-Truck maintenance key findings.

Table 4-43: Summary of E-Truck maintenance key findings

E-Truck Maintenance Key Findings	Report Section(s)
E-Trucks need strong maintenance repair networks	0
E-Trucks have lower maintenance costs	0

Although vehicle availability was expected to be lower for these early production vehicles, maintenance issues led to long vehicle downtime because fleet mechanics had limited experience with E-Truck maintenance procedure and thus, all major repairs had to be handled by the E-Truck manufacturers maintenance repair network. In addition, E-Truck manufacturers carried a limited inventory of spare parts which added to the time it took to service E-Trucks.

Local and regional maintenance repair networks as well as spare parts inventories need to be developed in correlation with E-Truck sales. In addition, fleet mechanics need to be trained to diagnose and service E-Truck maintenance issues.

From general maintenance costs and maintenance intervals data, a first look at E-Truck maintenance savings was defined and showed a potential for lower maintenance costs. We expect E-Truck maintenance savings to vary widely with driving conditions such as miles driven and number of stops per day.

A more complete analysis is needed to further investigate and understand the potential maintenance savings of E-Trucks.

4.8.3.3 E-Truck fleet deployment

Section 4.4 presented a comprehensive performance evaluation of E-Trucks, including a review of information from in-use data collection. Section 4.5 detailed E-Truck user acceptance. Table 4-44 below summarizes the E-Truck fleet deployment key findings.

Table 4-44: Summary of E-Truck fleet deployment key findings

E-Truck Fleet Deployment Key Findings	Report Section(s)
Train E-Truck drivers	4.4.5 – 4.5.2
Assign E-Trucks to “early-adopter” drivers	4.5.2

E-Trucks can present a challenge to drivers as they have numerous new operating steps to assimilate. Drivers are more likely to adopt and accept a vehicle if they are better trained on its operation. We recommend that drivers operating E-Trucks be trained and coached to adapt

their driving techniques to E-Trucks to take advantage of regenerative braking for instance. Driver training is essential to ensure better acceptance of E-Trucks and successful E-Truck deployments overall.

User acceptance data showed that some drivers were more willing and able to deal with the changes involved in driving an E-Truck. Driver assignment is important to ensure a successful deployment of advanced technology vehicles such as E-Trucks and "early adopter" drivers should be selected first for E-Truck deployment project in order to build a positive experience.

4.8.3.4 E-Truck charging

Section 4.4 presented a comprehensive performance evaluation of E-Trucks, including a review of information from on-road testing and chassis dynamometer testing. Section 4.7 covered in detail E-Truck charging. Table 4-45 below summarizes the E-Truck charging key findings.

Table 4-45: Summary of E-Truck charging key findings

E-Truck Charging Key Findings	Report Section(s)
Charging infrastructure is an important component of any E-Truck deployment project	0
Charging time depends on charging infrastructure	0
E-Truck "stand-by" power can negatively impact overall energy consumption	4.4.2 – 4.4.3 – 0
Impacts of E-Truck charging will be focused on building and local grid infrastructure	0

E-Truck charging infrastructure costs can be very high and will depend on many factors. Fleet managers should carefully plan E-Truck deployments.

From the field data, the team noticed that charging time was significantly longer for the MT E-Cell and eStar than what was advertised by their respective manufacturers. The long charge duration could conflict with vehicle availability in parcel delivery fleet use.

In order to decrease charging time, higher charging current can be used. The charging current should be specified to guarantee vehicle availability. However, using higher charging currents to charge faster will be more expensive to install.

A current draw was measured on both the MT E-Cell and Newton Step Van after the charge was completed and until the vehicle was unplugged. In addition, data from the eStar indicates that a similar current draw may exist on this vehicle as well. This stand-by power draw can negatively impact the E-Truck overall equivalent fuel economy.

Recommendations are that further testing be carried out to better understand the origin of the stand-by current draw of E-Trucks when plugged in but not charging and explore ways to reduce its impact on overall E-Truck efficiency.

The largest grid impacts were identified at the building level. Deploying E-Trucks will require facility managers to understand the electrical load profile of the building where E-Trucks are

deployed in order to maximize return on investment. Demand response strategies should be implemented to take advantage of low energy prices such as Time-of-Use pricing and avoid penalties such as demand charges.

We identified local infrastructure upgrades as another short- and long-term impact of E-Trucks. Electric utilities and companies deploying E-Trucks will need to work together to share the costs of local infrastructure upgrades in a way that is fair for ratepayers and acceptable for utility cost recovery structures but does not deter companies from deploying E-Trucks.

4.8.3.5 E-Truck business case

Section 4.4 presented a comprehensive performance evaluation of E-Trucks, including a review of information from in-use data collection. Section 4.8 detailed a business case analysis for E-Trucks. Table 4 46 below summarizes the E-Truck business case key findings.

Table 4-46: Summary of E-Truck business case key findings

E-Truck Business Case Key Findings	Report Section(s)
Use E-Trucks on higher mileage routes	4.4.1 - 0
Incentives for purchase play a crucial role for the early E-Truck market	0
Right-sizing E-Truck battery is a viable cost reduction pathway	0
Future battery prices will make E-Trucks more cost competitive	0
Vehicle-To-Grid could improve the business case for E-Trucks	0

The E-Trucks deployed at the downtown Los Angeles facility were used on low mileage routes. At these low daily utilization rates (lower than 50 miles), fuel and maintenance savings will not pay for the higher incremental cost that E-Trucks typically show.

The recommendation is that E-Trucks be deployed on longer routes with daily mileage greater than 50 miles. At these high daily utilization rates, a sufficient amount of diesel fuel is displaced by cheaper electricity to make the investment into higher upfront costs E-Trucks worthwhile.

Incentives for purchase of E-Trucks greatly reduce the simple payback period and thus make E-Trucks more likely to be purchased by commercial fleets.

The recommendation is that incentive funding be available at this early stage of the E-Truck market.

Right-sizing E-Truck batteries to better fit how the vehicle is used can greatly increase the business case for E-Trucks and will be an important pathway to explore as incentives for purchase are expected to decrease.

The recommendation is that fleets, battery and E-Truck manufacturers work together to develop, test and demonstrate E-Trucks with scalable battery packs.

Lower battery costs are expected to greatly reduce E-Truck incremental costs. We recommend that fleets, battery and E-Truck manufacturers work together to reduce battery costs.

Using E-Trucks for V2G such as frequency regulation, demand response and peak shaving, increases battery usage and can dramatically improve the business case for commercial electric vehicles.

The recommendation is that fleets, battery and E-Truck manufacturers work together to develop, test and demonstrate V2G options for E-Trucks in delivery applications.

4.8.3.6 Summary of key recommendations

The list below summarizes the key recommendations that were developed in the previous parts:

1. Further testing should be carried out to better understand the impact of operating conditions on E-Truck performance.
2. AC kWh/mile should be used to compare the efficiency of E-Trucks with other vehicles.
3. Appropriate data collection techniques should be used to provide better performance data on E-Truck deployment projects.
4. Fleet managers should carefully plan E-Truck deployments to minimize charging infrastructure costs.
5. The charging current should be specified to guarantee vehicle availability.
6. Further testing should be carried out to better understand the origin of the stand-by current draw of E-Trucks when plugged in but not charging and explore ways to reduce its impact on overall E-Truck efficiency.
7. Demand response strategies should be implemented to take advantage of low energy prices such as Time-of-Use pricing and avoid penalties such as demand charges.
8. Electric utilities and companies deploying E-Trucks need to work together to share the costs of local infrastructure upgrades in a way that is fair for ratepayers and acceptable for utility cost recovery structures but does not deter companies from deploying E-Trucks.
9. Drivers operating E-Trucks should be trained and coached to adapt their driving techniques to E-Trucks to take advantage of regenerative braking for instance.
10. “Early adopter” drivers should be selected first for E-Truck deployment project in order to build a positive experience.
11. Local and regional maintenance repair networks as well as spare parts inventories need to be developed in correlation with E-Truck sales. In addition, fleet mechanics need to be trained to diagnose and service E-Truck maintenance issues.
12. A more complete analysis is needed to further investigate and understand the potential maintenance savings of E-Trucks.

13. E-Trucks should be deployed on longer routes with daily mileage greater than 50 miles.
14. Incentive funding needs to be available at this early stage of the E-Truck market.
15. Fleets, battery, and E-Truck manufacturers should work together to develop, test and demonstrate E-Trucks with scalable battery packs.
16. Fleets, battery, and E-Truck manufacturers should work together to reduce battery costs.
17. Fleets, battery, and E-Truck manufacturers should work together to develop, test and demonstrate V2G options for E-Trucks in delivery applications.

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CHAPTER 5: CalHEAT Market Barriers and Opportunities for Alternative Fuel-Hybrid Systems

5.1 Executive Summary

5.1.1 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.

One of the roles 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 and heavy-duty vehicles account for 9 percent of greenhouse gases in California, and approximately 20 percent of fuel used. Improvements in efficiency or reduction of petroleum use by trucks provide a substantial opportunity to reduce emissions.

This report considers one of the Roadmap's steps to reducing greenhouse gas emissions and improving efficiency in trucks: combining alternative fuels and hybrid drive propulsion in one vehicle. It examines benefits, barriers and initial pathways to merging the benefits of high-efficiency hybrid-truck technology with low carbon, alternative fuels. The benefits of the alternative fuel-hybrid combinations were compiled through extensive industry research and data collection. These provided insights into barriers, gaps, and immediate recommendations. Scenarios analyses measured the benefits of this technology path for the California truck population and the potential for greenhouse gas and emissions reductions in the future.

5.1.2 Context

Hybrid truck technology is now making its way into the marketplace. Use of alternative fuels in trucks is rising as the availability of fuels, such as natural gas, increases. Combining the two in heavy-duty vehicles can vastly increase the benefits of petroleum displacement and greenhouse gas reduction, but manufacturers have not been motivated to bring vehicles outfitted with the combination to market. In a Class 3-8 Urban Truck, as designated by CalHEAT truck classification, a switch to biodiesel-20 can displace diesel fuel and reduce greenhouse gas emissions by about 11 percent. The combined technologies can multiply the reduction, lowering greenhouse gas by as much as a factor of four, from 16 percent to more than 45 percent.

5.1.3 Purpose

The goal of this report is to explain the potential benefits and identify the barriers to combining alternative fuel and high-efficiency hybrid propulsion technologies in medium- and heavy-duty vehicles. The report also recommends actions that will surmount these barriers and accelerate the development and adoption of the combined technologies in truck fleets.

5.1.4 Recommendations

Working with the truck transportation industry, CalHEAT has pinpointed several actions and demonstrations likely to expedite, stimulate, and advance the use of combined alternative fuel-hybrid drive platforms.

- Improve natural gas on-vehicle storage tanks — Developing natural gas tanks that are lighter, higher capacity and less expensive will be crucial to adoption of alternative fuel-hybrid technology.
- Develop new natural gas engine sizes — The continuing design and development of natural gas engines in varied sizes is another important step in bringing to market trucks outfitted with the combined alternative fuel-hybrid technologies.
- Demonstrate natural gas hybrids — The frequent stop-start cycles of the vehicle types benefit from the low-speed torque that comes with hybrid propulsion.
    - Waste collection trucks — The hybrid technology low-speed torque enables faster acceleration after a stop, allowing trucks to make more stops per hour, increasing productivity and offsetting costs.
    - Transit buses — The recent development of lighter, better priced and higher capacity natural gas storage tanks makes the combination of the two technologies economically and logistically feasible.
    - Drayage trucks equipped with natural gas plug-in hybrids — The stop-start intensive operations, short hauls, and heavy loads (port container transportation, for example) benefit from the increased power and performance from hybrid propulsion's low-speed torque.
    - Regional delivery mild hybrids — Demonstrations with a mild hybrid configuration would cost less than a full hybrid but would still show emissions and CO_2 reductions, increases in fuel economy, and improved performance for a greater return on investment.

5.1.5 Potential Outcomes

Alternative fuels-hybrid technology combination in trucks presents an attractive opportunity for the California truck population. The combination maximizes the benefits of existing technology and demonstrates the potential for significant reductions in greenhouse gas. For example, the CalHEAT Class 3-8 Urban Truck category represents about 250,000 trucks in California. If only 10 percent of those trucks adopted a combination of compressed natural gas and hybrid hydraulic technology, the CO_2 emissions for the entire category would drop by 4.2 percent. With every truck that switches to the combined technologies, the CO_2 emissions decrease dramatically. The recommendations in this report will initiate the technology launch that lead to a mitigation of the barriers, a natural expansion of the market and ultimately acceptance of alt-fuel hybrids for widespread use in select medium- and heavy-duty truck fleets

5.2 Alternative Fuel Hybrid Benefits

At a time when regulators and industry are searching for effective ways to comply with mandates to reduce greenhouse gas (GHG), the alternative fuels-hybrid technology combination in trucks presents an attractive opportunity. The combination maximizes the benefits of existing technology and demonstrates the potential for significant reductions in GHG.

The potential for improving CO_2 levels overall is substantial. Take, for example, one category of trucks currently on the road, CalHEAT Class 3-8 Urban (as classified by the CalHEAT truck inventory[55] detailed in Appendix 5A,), about 250,000 trucks in all. If only 10 percent of those trucks adopted a combination of compressed natural gas (CNG) and hybrid hydraulic technology, the CO_2 emissions for the entire category would drop by 4.2 percent[56]. With every truck that switches to the combined technologies, the CO_2 emissions decrease dramatically. In fact, additional analysis shows that a very aggressive wide proliferation of the alternative fuel-hybrid combination as analyzed in Appendix 5E could reduce CO_2 levels in California 30 percent by 2030, which is 22 million metric tons below 1990 levels[57].

This section discusses the emissions-reducing properties of alternative fuels and hybrid electric vehicle technology when used alone and when combined. Separately, alternative fuels and hybrid vehicles can reduce greenhouse gas emissions in trucks. Used together, they reduce greenhouse gas emissions significantly.

5.2.1 The Alternative Fuel Advantage

Alternative fuels, when used in a conventional internal combustion engine, can reduce greenhouse gas emissions considerably. On a well-to-wheel (WTW) basis (from production, through distribution and use), renewable diesel-30 (RD30) produces 19 percent less greenhouse gas than petroleum-based fuel. CNG decreases GHG by 23 percent[58]. The alternative fuels that have the greatest impact on well-to-wheel greenhouse gas emissions are those that require the least energy to create, such as renewable natural gas (RNG). In fact, RNG captured from landfill gas actually *eliminates* greenhouse gas emissions in the capture process.

Table 5-1 lists the reductions in petroleum use and GHG for alternative fuels discussed in this study: biodiesel-20 (B20), renewable diesel-30 (RD30), CNG, RNG, with ultra-low sulfur diesel (ULSD) as the baseline fuel.

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[55] See Appendix 5A – CalHEAT Truck Inventory by Class and Application

[56] Appendix 5B Combined Benefits of Alternative Fuel and Hybrid Propulsion

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Table 5-1: Alternative Fuels GHG Reduction

Fuel Type	Petroleum Reduction %	GHG Reduction - %		
		WTT	TTW	WTW
Baseline diesel ULSD	Base	0%	0%	0%
B20	16%	65%	-1%	11%
RD30	29%	104%	1%	19%
CNG	99%	33%	21%	23%
RNG	99%	475%	21%	97%

Alternative fuels used in this study and the percentage reduction in petroleum use and GHG wheel-to-tank (WTT), tank-to-wheel (TTW), and wheel-to-wheel (WTW).

Source: California Hybrid, Efficient and Advanced Truck Research Center

5.2.2 The Benefits of Hybrid Systems

Hybrid drivetrain technology is also a powerful tool to fight greenhouse gas. Switching trucks from conventional drive trains to hybrid propulsion systems can decrease greenhouse gas by as much as 40 percent in CalHEAT Class 3 – 8 urban trucks. The three basic types of hybrid technologies – hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and hybrid hydraulic vehicle (HHV) – all greatly reduce GHG. The impact on greenhouse gas varies widely depending on how the vehicles are used, the type of vehicle and differences in hybrid and truck technology. For example, if a vehicle is operated in a stop-start cycle with little or no high speed or constant speed driving, switching to a hybrid will result in up to 70 percent less fuel consumed and consequently a considerable reduction in GHG.

Table 5-2 shows WTW reductions in GHG and petroleum use for different CalHEAT truck categories with different hybrid systems. (See Appendix 5A for more detailed definitions of each category.) The truck categories are loosely ranked by percentage GHG reduction potential but the top four categories are very closely ranked.

Table 5-2: GHG Reductions for Hybrids by CalHEAT truck category

Rank by % Reduction Potential

CalHEAT Truck Classification	Fuel Use and WTW GHG Reduction - %		
	HEV	PHEV	HHV
C3-8 Urban	10 -30	25 - 40	5 - 40
C2b-3 Van/Truck	5 - 30	15 - 40	5 - 30
C3-8 Rural	5 - 20	15 - 25	5 - 20
C7-8 Urban	5 - 20	15 - 25	5 - 20
C3-8 Worksite	5 - 10	10 - 20	2 - 10
C8 OTR	5 - 10	5 - 10	0 - 10

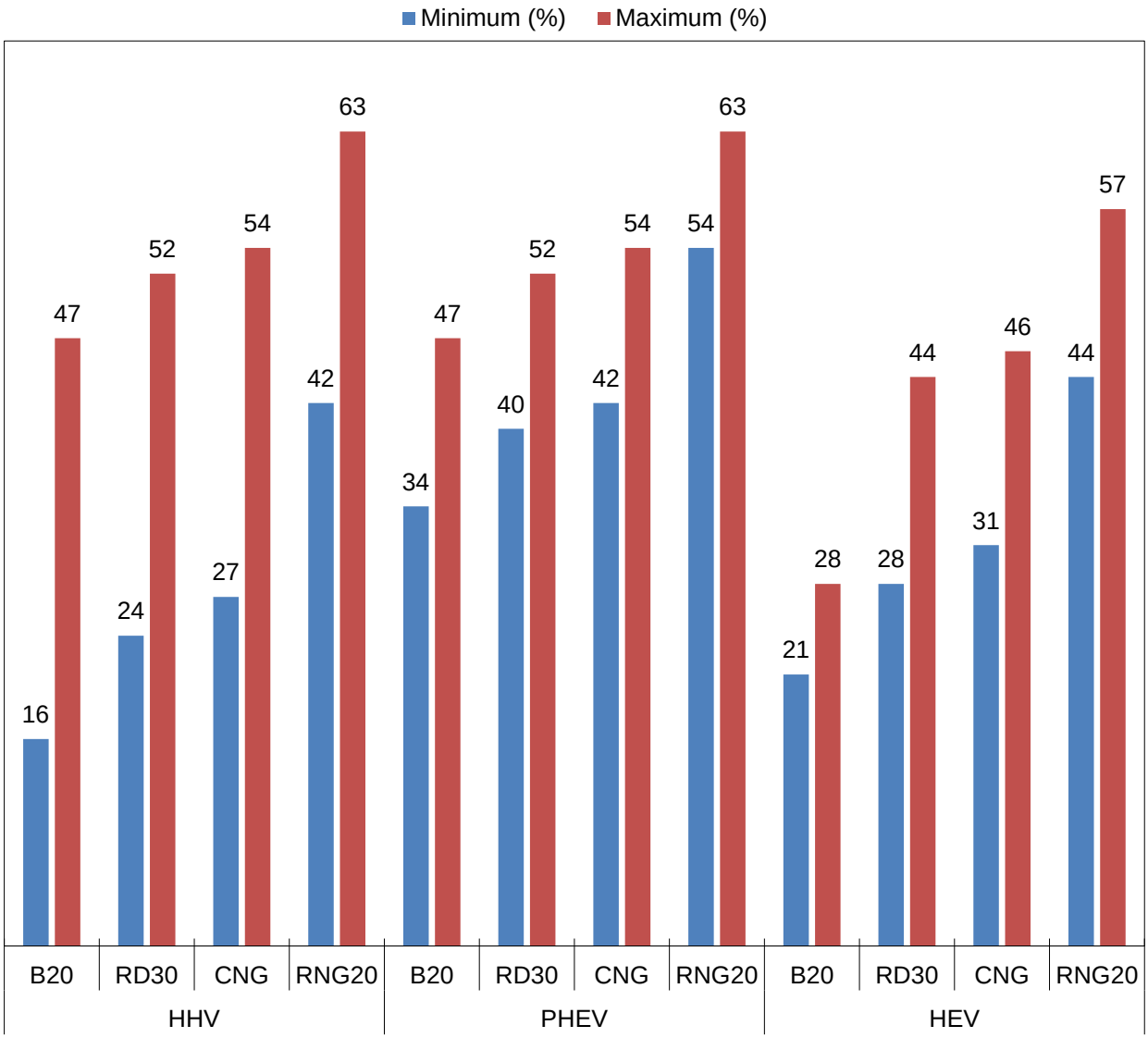
Source: "Support of CalHEAT Technology Assessment", Ricardo, November 10, 2011.

5.2.3 The Multiplier Effect: Alternative Fuels and Hybrid Technology Together

Alternative fuels and hybrid technology together significantly enhance their respective benefits. Using renewable diesel in a truck that is outfitted with hybrid electric technology, the emissions are 28 percent to 44 percent less than a petroleum-fueled conventional vehicle. This is more than two times greater than the reduction associated with solely using renewable diesel in a conventional internal combustion drivetrain vehicle as seen below in Figure 5 1. Other combinations offer even more impressive results. Renewable diesel with a plug-in hybrid electric vehicle reduces GHG 40 percent to 52 percent, a multiplier of three compared to the sole use of renewable diesel, which shows a GHG improvement of 19 percent when used alone. (See Table 5 1) Compressed natural gas combined with a hybrid electric vehicle reduces GHG 32 percent to 46 percent, a multiplier of two. Compressed natural gas used in conjunction with a plug-in hybrid vehicle lowers GHG 42 percent to 54 percent, a multiplier of three.

Figure 5 1 shows the minimum and maximum GHG reduction for each combination of fuel and hybrid type under discussion. Appendix 5C has a description of the model as well as data sources used for these calculations.

Figure 5-1: Best Near-Term GHG/ Petroleum Reduction Benefit Combines B20 or CNG



Source: California Hybrid, Efficient and Advanced Truck Research

On its own, hybrid vehicle technology as shown in Table 5-1 shows significant GHG reductions but when combined with alternative fuels the reductions are much more impressive. Hybrid electric vehicles lower GHG emissions 5 percent to 30 percent. For plug-in hybrid electric vehicles, the range of reduction in GHG is 5 percent to 40 percent.

Used alone, alternative fuels may also have less of an impact on GHG emissions than when used in conjunction with a hybrid system. RD-20 in a vehicle with a conventional engine and drivetrain decreases GHG emissions 19 percent. Compressed natural gas by itself lessens GHG by 23 percent. Renewable natural gas, however, is a special case. Used by itself in a traditional engine, it lowers GHG emissions a remarkable 97 percent, making it seem that pairing it with hybrid technology is unnecessary. But it is important to note that this environmentally friendly

fuel is an extremely limited resource. As a result, combining RNG and hybrid technology is of particular value because it can help conserve such a beneficial resource.

As stated earlier in this section the combination of alternative fuels and hybrid technology can have an impressive multiplier effect of up to 3 times.

5.3 Alternative Fuel Hybrids – Market Barriers

This section examines the obstacles to truck fleets adopting alternative fuels and hybrid propulsion technology together. It is based on extensive discussion with industry representatives from original equipment manufacturers (OEM), suppliers, utilities, and fleet companies, as well as relevant policy-making entities. Appendix 5D contains the specific questions used in the survey discussion, the data collected, and barriers reported by participants.

Table 5-3 below gives a brief description of the barriers to development and adoption of alternative fuel-hybrid systems together, from the point of view of truck industry representatives. These items will be discussed in greater detail through the rest of the section.

Table 5-3: Industry Feedback on Barriers to Adoption of Alternative Fuel-Hybrid Combination[59]

Incremental Costs	**Incremental capital**
Tech Readiness/Production Volume	Quality, reliability and performance improvement needed. Slow market demand and low volumes; need for more, varied sizes of NG engines
Increased Space and Weight	Packaging volume and weight for the two additional systems is too great
Infrastructure	Capital necessary for installation of alternative fuel infrastructure

Source: California Hybrid, Efficient and Advanced Truck Research Center Interviews with Industry

5.3.1 Business Barrier: Incremental Costs

The 'payback' or return on investment for combining the technologies is not sufficient. We could say the initial capital cost of alternatively fueled vehicles can be expensive but due to the significant cost advantage of natural gas as compared with diesel some payback on the incremental cost can be achieved within three years (an industry benchmark for the minimum acceptable payback period), especially in applications that accrue many vehicle miles per year. The initial incremental capital cost for hybrids can also be expensive. Hybrids have significantly longer payback periods, although new milder hybrids as well as hybrids in multi-

[59] Survey and extensive discussion with industry representatives from original equipment manufacturers (OEM), suppliers, utilities, fleet companies, as well as relevant policy-making entities. See Alt-Fuel Hybrid Advisory Sub-Committee listing p. ii.

speed applications, such as refuse collection, may be able to achieve three-year payback in the next few years.

When alternative fuel and hybrid technologies are combined, the incremental costs are much greater, as much as an additional $50,000 per vehicle over alternative fuel or hybrid technologies alone. While there are additional savings in fuel expenses, they do not recoup the greater investment quickly enough to make business sense.

Another cost issue is the lack of research and development funding in combining the technologies for commercial trucks. Manufacturers say the funding landscape even pits alternative fuels against hybrid technology. To surmount these economic obstacles, additional incentives are needed in the form of government policy, mandates or programs.

5.3.2 Development Barrier: Technological Readiness and Production Volume

Technologically the systems are not ready to be combined in trucks. Hybrid technology for trucks has not progressed to the point of reliability and performance necessary for wide-scale use with alternative fuels. According to the CalHEAT Roadmap for Hybrid Electric Technology, industry may be in a better position to support this technology around the middle of this decade. Additionally natural gas engines fitted for hybrid technology are difficult to find. Currently, most natural gas truck engines are adaptations of a diesel engine block, crankshaft and other parts, which are expensive, overly heavy and not properly sized. Retrofit systems pose problems with reliability and performance.

In large part, technological improvements have been stymied by low production volume. Many more units need to be produced to amortize the investment required to improve the engine and parts technology, at least 10,000 units per year, according to industry representatives. (See Appendix 5D).

5.3.3 Design Barrier: Increased Space and Weight

Trucks lack the space for both of these systems to be installed. As we know, natural gas vehicles can add additional weight related to the fuel storage system. Hybrid systems add weight due to their energy storage systems. The increase in weight that comes with adding two systems to a vehicle also concerns the industry. The extent of the problem with space and weight depends on the specific alternative fuel, hybrid system and type of truck with which they are matched. For example, the combination of CNG and hydraulic hybrids may avoid the space/weight problems because of advances in compact packaging of hydraulic accumulators. In fact, that combination works well with the stop-start cycle of a refuse truck, and even enhances performance with increased low-end torque.

5.3.4 Market Barrier: Infrastructure

The infrastructure required for natural gas is expensive. New natural gas fueling stations cost from $750,000 to $3 million to construct. (In Southern California, and other locations where natural gas is already being used or mandated as the cleanest available fuel, this might not be as significant an issue. Southern California refuse truck fleets are currently operating with natural gas with the accompanying infrastructure.) Natural gas storage is also expensive. The cost of compressed natural gas storage tanks is prohibitively high. In addition, the costs for

distributing the most environmentally friendly form of natural gas – renewable natural gas based on agricultural or landfill waste – are higher than the costs for distribution of pipeline gas. Yet renewable natural gas can produce 97 percent less GHG.

Increased market volume for alternative fuels will help lower these infrastructure costs. In addition, some natural gas utilities are offering low- or no-cost fueling station and storage in return for a quantity natural gas purchase agreement. Government policy and incentives would help overcome the costs of renewable gas distribution.

5.4 Advancing Alternative Fuel-Hybrid Deployment

This section discusses the influences, trends and actions that could stimulate the adoption of the combined alternative fuel-hybrid technologies in truck and bus fleets. These include global trends in energy production, infrastructure and component costs, and the actions that might most effectively expedite introduction of the dual technologies into truck fleets.

5.4.1 Global and Market Trends in Alternative Fuels

The rising costs, both economic and political, of petroleum consumption continue to act as powerful motivators in development of alternative fuel and hybrid propulsion technologies. At the same time, the availability of alternative fuels has improved. New technology has dramatically increased the supply of domestic natural gas, making it less expensive and much more readily available.

This exponential growth in natural gas production has prompted manufacturers to see new business opportunities and develop natural gas engines and equipment that resolves barriers discussed in Section 5.3. High-pressure direct-injection (HPDI) is one approach that has been developed to enable NG-burning engines to approach diesel efficiency and torque.

The lack of NG engines that are properly sized for use with hybrid drive trains is currently being addressed by several manufacturers. Cummins Westport Inc. is developing an 11.9-liter natural gas engine specifically for refuse and other heavy-duty trucks. Another natural gas engine program is integrating the Doosan 11 liter natural gas engine into an Autocar-made waste hauler truck for Waste Management Inc., the waste collection giant. The Gas Technology Institute and Cummins Westport are demonstrating a low-emission, high-efficiency natural gas engine for regional hauling and heavy-duty uses, which is expected to reduce GHG by 20 percent to 25 percent and fuel consumption 20 percent. All these projects are partially funded and initiated by federal and state grants, and partnerships between government and businesses.

Other manufacturers are developing new natural gas storage tanks. Chesapeake Energy Corporation and 3M Company are currently partnering to produce lower-priced, lighter-weight and higher-capacity natural gas storage tanks. Likewise, Quantum Technologies is touting newer, more compact and economical systems.

5.4.2 Industry Perspective

From the viewpoint of the truck industry[60], the best way to encourage adoption of the alternative fuel-hybrid combination is to advance development of less expensive and more effective technology. If government funds went to original equipment manufacturers for development of less expensive component parts, technologies that use fewer parts, and more integrated, cost-effective products overall, then adopting the dual technologies would make business sense for fleets. Fleet companies could recover their investment within the 3-year window considered good business practice and be assured of smooth, reliable operations. As more fleets adopt the technologies, free-market competition would bring about additional technological and economic improvements. Table 5-4 below shows the barriers that will be eased or partially overcome by current industry developments.

Table 5-4: Forces Affecting Barriers

Barriers	Industry Developments Supporting Enablers											
	Growth in NG & Bio-diesel Use	New Tank Technology	New NG Engine	Refuse Demo of NG-HHV	NG Adsorber Development	NG Turbine Development	Next Gen HEV &HHV	PHEV &EV Dev	PHEV & EV Demos	Renewable Alt Fuels	Improved Engine Performance	Infrastructure Developments
Cap $/ROI	X						X	X	X	X		X
Space/ Weight		X			X	X	X		X		X	
Technology Readiness Level	X			X			X	X	X	X		X
Product Volume	X		X		X		X	X	X		X	
Infra-Structure	X	X								X		X
Available Engines			X			X				X	X	

Source: California Hybrid, Efficient and Advanced Truck Research Center Interviews with Industry

[60] Survey and extensive discussion with industry representatives from original equipment manufacturers (OEM), suppliers, utilities, fleet companies, as well as relevant policy-making entities. See Alt-Fuel Hybrid Advisory Sub-Committee listing p. ii.

In addition, some specific truck and technology combinations could provide more immediate stimulus, say industry representatives. The drayage truck in the Class 7-8 urban truck category is expected to be an important NG Hybrid opportunity. Liquid alternative fuel, such as bio-diesel, combined with a hybrid system in beverage delivery trucks would circumvent the space and weight limitations discussed in Section 5.3. Demonstration of such an application would show the reduced greenhouse gas emissions and increased fuel economy. It would also provide important data on the return on investment.

Outfitting waste collection trucks with natural gas-hybrid technology is another opportunity to demonstrate advantages and obtain data. Because hybrid technology provides refuse trucks with increased low-end torque, the results would show not just fuel and maintenance cost savings but also productivity gains from the improved performance. As a result, a fleet could support more customers with fewer trucks.

Another action suggested by industry representatives is to perform additional testing on combining a range-extender turbine with a battery-powered electric drive system. Early testing has already shown promising results in reduced emissions. A full hybrid-turbine configuration is also in initial development, which will lower emissions and improve fuel economy for drayage-type truck applications operating in ports. In fact, the Port of Los Angeles and the Southern Coast Air Quality Management District (SCAQMD) are considering a plan to create an innovate zero-emissions truck corridor by either mandating or providing significant incentives for use of clean fuels with electric drivetrains for operating vehicles on a specific 20-mile stretch of Interstate 710. This would allow the community to approve expansion of the highway system and still comply with air quality regulations.

Use of mild hybrids or a mildly electrified CNG drivetrain is an additional option that would surmount the weight challenges of having two such heavy systems on one vehicle. This approach would minimize the additional weight and reduce the additional cost, offering an easier pathway to deployment.

5.4.3 Early Demonstrations

Testing and demonstration of the alternative fuel-hybrid combination by some public fleets and private manufacturers are laying the groundwork for the systems' eventual implementation. The New York City Department of Sanitation has tested a refuse truck that combines compressed natural gas and a hydraulic hybrid system as part of an effort to evaluate its capability and fuel efficiency.

Autocar LLC was planning to introduce a version of their Xpeditor truck in 2011 with the hydraulic hybrid RunWise system from Parker-Hannifin Corp. that is powered by a CNG engine[1]. This would be a truck that not only burns clean compressed natural gas fuel, but far less of it through use of the "RunWise" hydraulic hybrid drivetrain. Since that announcement, a Proof of Concept vehicle has been completed in the CNG-HHV configuration and demonstration tests are planned for the near future. The concept vehicle was on static display at the 2013 Waste Expo in New Orleans in May.

CNG fuel emits 20 percent less greenhouse gas than diesel fuel. Tests of the RunWise hybrid over five years show an additional 45 percent fuel savings. Brake life was extended 800 percent to 900 percent. Instead of requiring a brake job every 90 days, the interval has been extended to every two and a half years, according to test data. Likewise, in Europe, demonstrations of alternative fuel hybrids have suggested similar findings. In tests there, natural gas refuse trucks saved 15 percent to 30 percent in fuel costs when combined with a hybrid electric drive system.

Figure 5-2: Hybrid Refuse Truck at Work

A LET 2 Crane Carrier with Bosch Rexroth HRB Parallel Hybrid fueled by CNG.

Source: HTUF 2010- Hybrid Truck Users Forum, News Articles

5.5 Action Plan and Conclusions

This section describes recommended next steps and the truck applications that are currently using alternative fuels or have plans to do so. These actions and activities are in the best position to push alternative fuel-hybrid systems to the next stage of wider introduction into the truck industry. Appendix 5B provides details at a modest implementation level for NG Hybrids, but Appendix 5E reflects on the Assessment Model of much more aggressive scenarios for market penetration. The Assessment Model results suggest the possibility of significant GHG reduction in 2050 if this combination can proliferate in the market place.

5.5.1 Natural Evolution of Alternative Fuel Use in Trucks

California is already a leader in trucks using alternative fuels, thanks in part to South Coast Air Quality Management District's clean fleet rules that require fleets of transit buses, school buses, refuse trucks, street sweepers, city-owned utility trucks, airport shuttles and taxi fleets to purchase a clean-fueled vehicle when they replace or add a vehicle to their fleet. Currently Los Angeles County operates the largest CNG fleet in the United States with 2,200 CNG vehicles.

Omnitrans, the public transit agency serving the San Bernardino Valley, started to purchase CNG buses in 1997 and now has an all-CNG fleet. The agency's buses passed the 100-million mile mark in in April, 2013.

5.5.2 Natural Gas Storage

Developing natural gas tanks that are lighter, higher capacity and less expensive will be crucial to adoption of alternative fuel-hybrid technology. Continuing current projects, such as the one to produce improved tanks being undertaken by Chesapeake Energy and 3M, and encouraging new ones will remove one economic barrier to production and adoption of alternative fuel-hybrid trucks.

5.5.3 Develop New Natural Gas Engine Sizes

The continuing design and development of natural gas engines in varied sizes is another important step in bringing to market trucks outfitted with the combined alternative fuel-hybrid technologies. This includes expanding optimized NG engines, such as HPDIs, to more sizes and with improved efficiencies and performance. Smaller and lighter natural gas engines, such as the 11.9-liter natural gas engine, being developed by Cummins Westport Inc., will require less space and add less weight, overcoming another barrier to combining alternative fuels and hybrid propulsion.

As more natural gas engines are adopted, marketplace competition will lower prices of the new technology, creating more favorable economics for introducing the dual system in trucks.

5.5.4 Demonstrate Natural Gas Hybrids

The demonstrations below are recommended because each makes a particularly compelling case for adopting alternative fuel-hybrid systems. The frequent stop-start cycles of the vehicle types benefit from the low-speed torque that comes with hybrid propulsion. The faster acceleration out of a stop results in a truck being able to make more stops, increasing productivity. In addition, the hybrid's regenerative brake mechanism saves brake wear reducing maintenance costs. These factors may more than offset the additional cost of the dual technologies.

Natural gas is selected because it capitalizes on the recent surge in availability of the fuel, its resulting low cost, its impressive impact on greenhouse gas emissions, and the fact that several of the truck types discussed are currently burning natural gas (specifically Southern California refuse trucks and transit buses). Consequently, they have the infrastructure for natural gas in place.

5.5.4.1 Waste Collection Trucks

Refuse trucks' stop-start operations make them good candidates for natural gas hybrid platforms. The hybrid technology low-speed torque enables faster acceleration after a stop, allowing trucks to make more stops per hour, increasing productivity and offsetting costs. These trucks also realize maintenance savings from a reduction in brake replacement. Natural gas reduces GHG emissions and fuel expense. Clearly, waste collection trucks outfitted with

natural gas hybrid technology make a powerful case for adoption of the technology by showing increased productivity, fuel economy, GHG emissions reductions and low maintenance costs.

5.5.4.2 Transit Buses

Transit buses are another good application for combining natural gas hybrid systems. Separately both technologies are already in use within the transit industry. The recent development of lighter, better priced and higher capacity natural gas storage tanks makes the combination of the two technologies economically and logistically feasible. Hybrid propulsion improves performance in the stop-start cycle of transit. In Southern California, transit buses already burn natural gas so they have the natural gas infrastructure in place. In addition, there is a considerable amount of federal grant funding available for clean fuel technology in transit fleets, further offsetting the added cost of the combined technologies. Southern California transit buses, because they already use natural gas, would also work well for demonstrating mild hybridization, a potentially easier and quicker path to deployment. The auxiliary system for these buses could be electrified which would allow regenerative breaking for a mild hybrid system. Like the regional delivery trucks discussed below, mild hybrid NG buses would be less costly to deploy but could demonstrate benefits to a large audience.

5.5.4.3 Natural Gas Plug-In Hybrid Drayage Trucks

Drayage trucks offer an excellent opportunity to demonstrate the combined alternative fuel-hybrid systems. The stop-start intensive operations, short hauls, and heavy loads (port container transportation, for example) benefit from the increased power and performance from hybrid propulsion's low-speed torque. In fact, the torque will allow more stops and increase productivity and save maintenance costs from wear on brakes. A plug-in hybrid offers the best GHG reductions of all hybrid systems (see Table 5-2). In fact, a project is currently underway to convert a Class 8 heavy-duty truck to a natural gas burning plug-in hybrid for drayage operations in the Port of Los Angeles. The demonstration will show that natural gas hybrid technology will provide more power and better mileage in this application than natural gas alone. Testing of NG range-extender turbines for use in ports will demonstrate limited zero-emission mileage while using the cleanest available fuel for the region. These demonstrations will add impetus to the development of a planned zero-emission truck corridor on a 20-mile stretch of Interstate 710 providing entry and departure from the Port of Los Angeles-Port of Long Beach complex.

5.5.4.4 Regional Delivery Mild Hybrids

Regional delivery trucks are another good application for demonstrating the dual technologies now that lighter, less expensive and higher capacity natural gas storage tanks are available. Demonstrations with a mild hybrid configuration would cost less than a full hybrid but would still show emissions and CO2 reductions, increases in fuel economy, and improved performance for a greater return on investment. Because delivery is such a common truck activity, demonstrating the benefits of the dual technologies in commercial delivery trucks would provide useful data and encourage consideration of the dual technologies for more widespread adoption.

CHAPTER 6:
Outreach and Industry Support
CalHEAT Annual Forums

6.1 Introduction

CalHEAT held three annual forums during the first three years CalHEAT became active. These were designed to reach out to truck industry stakeholders to test research ideas in the real world, share information, receive feedback, and discover what might speed transformation of the medium- and heavy-duty truck population and what could be barriers. These sessions proved invaluable in helping to focus CalHEAT's efforts for the greatest benefit. The forums also improved the visibility of CalHEAT's work and by introducing high-efficiency, low-emissions trucks into the conversation, ultimately encouraging wider adoption of the new truck technologies.

6.2 Forum One: Getting to Zero/Near-Zero Emissions

Feb. 17, 2011, Banning's Landing Community Center, the Port of Los Angeles

The forum, "Getting to Zero: Meeting the Air Quality Needs of Southern California," attracted 148 participants. Attendees included representatives from Freightliner Custom Chassis Corp., US Hybrid, NGK Automotive Ceramics, Intertek Automotive Research, Artisan Vehicle Systems, EVI, Ford-Eaton, Kenworth, Navistar, and Vision Motors.

6.2.1 The Agenda

CalHEAT staff answered questions and presented information on CalHEAT's purpose, goals, and projects. Forum participants and CalHEAT staff discussed technology roadmap for clean, efficient advanced technologies and systems.

A roundtable including prominent industry representatives from Eaton, Cummins Westport, Capstone Turbine and Navistar discussed how and why they and their companies decided to aim for zero-emission truck fleets and technology.

Additional roundtables addressed the technology pathways to achieving zero or near zero emissions, and whether a zero- or near zero-emission corridor is feasible in Southern California.

6.2.2 Conclusions and Recommendations

6.2.2.1 Forces and Considerations in Transforming the Medium- and Heavy-Duty Truck Population

Participants' comments and concerns encompassed diverse viewpoints. A sampling is listed below:

- Extreme nonattainment areas (SCAQMD and SJVAPCD) are pushing a greater need and urgency for significantly lower, if not zero, mobile source NOx emissions.
- The San Pedro area ports indicated a need for a longer-term plan.

- There is a need to build a robust supply chain.
- Need to build market volumes in emerging technologies.
- Need to focus across technologies, across developmental stages.
- Build flexibility into future corridor designs to handle and enable future technologies
- Get broad uses out of vehicles—niche vehicles would be hard to commercialize.
- Find sufficient solutions outside of the I-710 corridor and California to ensure market is big enough to attract interest and investment.

Make sure OEMs are part of the discussion, not just driveline and component manufacturers.

6.2.2.2 Barriers to Transformation

Forum attendees seemed to think there were not a lot of external drivers for development and adoption of zero emission vehicles but most agreed that the technology exists. The real obstacle is economic, achieving reasonable payback for new technology costs. A few of their comments on the topic are below:

- No clear demand and call for zero emission vehicles now from regulators.
- Not much customer pull for ZEVs.
- There is demand from the community for ZEVs.
- Technology is not holding us back, but economics are.

6.3 Forum Two: Policies and Investments for Speeding Clean Truck Technologies

Feb. 22, 2012, Stockton Hilton Hotel, Stockton

6.3.1 Introduction

CalHEAT's second annual forum, which drew about 100 participants, focused on speeding the commercialization and deployment of clean truck technologies to help the state achieve its air quality and greenhouse gas goals. The forum opened with a presentation and discussion of the findings in the CalHEAT technology Roadmap.

6.3.2 Agenda

6.3.2.1 Policy Initiatives Speeding Clean Truck Technologies

Key staff from U.S. EPA and the California Air Resources Board discussed planned and existing regulations and policies that are driving the development and deployment of clean truck technologies. They discussed how these policies contribute to the petroleum and emission reduction goals at the heart of the CalHEAT roadmap.

6.3.2.2 Incentives and Investments Needed to Speed Clean Truck Technologies

A varied group of experts, from the California Energy Commission, Natural Gas Vehicle Coalition, the Bay Area Air Quality Management District, Wells Fargo Bank's Cleantech Group, Natural Gas Vehicle Coalition and other organizations, discussed the investments, incentives,

and additional programs needed to achieve CalHEAT's petroleum and emissions reduction goals for medium- and heavy-duty trucks.

6.3.2.3 Fleet Perspectives on Clean Truck Technologies

CalHEAT's second forum also included discussion of the challenges to widespread adoption of clean truck technologies by the people who use trucks the most, truck fleets. Participants from companies and associations including UPS and the American Trucking Association explained what they would like to see happen, including a viable business case for adopting different truck technologies, incentives and supportive government policy initiatives.

6.4 Forum Three: California's Route 66 to Clean and Efficient Trucks

March 26, 2013, Marriott Courtyard, Sacramento

6.4.1 Introduction

The purpose of CalHEAT's third annual forum was to unveil the CalHEAT Research and Market Transformation Roadmap, review its actions and hold a day long dialogue among the industry, funding providers and regulators on the best next steps to reduce petroleum use and GHG emissions in medium and heavy-duty vehicles and help meet California's environmental goals. The event drew 119 industry stakeholders, including clean and efficient vehicle and component suppliers, fuel providers, truck manufacturers, such as U.S. Hybrid, BAE Systems, Eaton Corp, Volvo Trucks, also members of the California Air Resources Board, the California Energy Commission, California Department of Transportation (CalTrans), and several air quality management districts.

6.4.2 Forum Discussions and Conclusions

Several of the panels focused on deeper consideration of specific pathways recommended in the Roadmap featuring experts on the respective topics. Below are brief summaries on the panel discussions.

6.4.2.1 Next Steps for Greater Electrification of Trucks

- Standardization, particularly in energy storage (especially batteries), is key in order to drive down costs, reduce supply chain risk and reach sustainable market volumes.
- The industry continues to need significant help in navigating California on-board diagnostics requirements.
- Accessory loads are significant on electric vehicles and electric or more-efficient accessories are an extremely important enabling technology for all electric vehicles, allowing greater efficiencies (engine-off) in hybrid trucks. There may be a need to build upon larger volumes and designs that are scalable for different applications.

6.4.2.2 Next Steps for Nearer to Zero Emission Trucks, "How Low Can We Go and Which Technologies and Fuels Provide the Best Benefits"

- Natural gas can be an enabling fuel for meeting near term lower NOx standards; however renewable natural gas and new advanced optimized or fuel-neutral engine technologies can provide even more benefits.

- There is a need for tougher standards combined with very strong incentives to support the rollout of low NOx technologies. An optional standard is a good next step.
- To fully drive the long-term production volumes needed to keep engine prices affordable, there is a strong need to expand any California low NOx standards to the national level

6.4.2.3 The Next Steps for Clean and Efficient Over-the-Road Trucks: "Which Technology and Fuels Can be Further Developed for California to Integrate a 50 State Solution?"

- There are new engine and drivetrain solutions that can get us to a 50 percent increase in fuel economy in the near- to medium-term timeframe.
- A liquefied natural Gas corridor (the 150 Station Natural Gas Highway) will be in place by the end 2013. New fuel options need to be on the table in addition to diesel.

6.4.2.4 Creating Markets for Clean Trucks: "What are the Key Mechanisms that Can Create and Expand the Market?"

- Collaboration amongst all partners to create a complete and interconnected strategy can expedite the adoption of new truck technologies; this can include affected locations (such as ports), industry, regulators, funding agencies, users, CalHEAT and others. A prime example cited was the Clean Truck Program at the Long Beach/LA ports, which required the Ports' Clean Air Action Plan, regional and state regulatory backstopping, significant state and regional funding, and the use of contract mechanisms.
- We need to find ways for the market to drive commercialization and create a business case for the fleets.
- Funding providers need to be flexible and try new ideas and approaches to incentivizing that offset risk; should encourage NOx and carbon reductions together; long-term predictability is critical.

6.4.2.5 Investments for Clean Truck Technologies: "What are the Prospects for Investment?"

- There was unanimous agreement from all attendees that there is a need for additional investments.
- Incentive vouchers are excellent as tax credits rely on fleets that might or might not have sufficient ability to tap the tax credit.
- Good incentives can be adoption accelerators.
- In addition to incentives, there is a need for R&D funding
- Fleets need help in building a business case that reduces the risks such as residual vehicle values, the need for fueling stations and repair facilities, and financing that guarantees uptime.
- Consider non-monetary incentives as well such as green curb parking, reduced tolls, and reduced registration fees.

CHAPTER 7: Conclusions and Recommendations

With the foresight of the California Energy Commission, the California Hybrid and Efficient Advanced Truck Research Center was established in 2010 for the purpose of performing research into planning, commercializing and demonstrating truck technologies that will meet California's environmental policies through 2050. A major role of the center has been to coordinate the development of the overall research and market transformation. The center has established a strong process of collaboration by working with the State's Air Resources Board, Energy Commission, Air Quality Management Districts, and MPO's; U.S. DOE and EPA; and nationally recognized medium and heavy duty truck associations and experts.

These stakeholders have worked with CalHEAT Staff side by side to participate in the development of a market and transformation roadmap, *CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks*, found in Chapter 2 of this report. Analysis of the CalHEAT Action Plan shows that implementation of the 66 action items would result in a 73 percent reduction in CO_2e by 2050, and 75 percent reduction in petroleum use, compared to projected "Business as Usual" levels without these changes.

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 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.

7.1 Recommendations

The CalHEAT Advisory Council has recommended additional research and actions as the best strategies to further the center's goals with funding from the state program created by AB-118, "Centers for Alternative Fuels and Advanced Vehicle Technology." These 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 more electrified Over-the-Road Truck
- Advanced and highly-efficient combustion technologies and fuel cell solutions
- Three hundred percent greater vehicle efficiencies leveraging driveline improvements, engine efficiencies, and improved vehicle aerodynamics and rolling resistance
- 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 percent reduction of NO_x 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 adoption 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 Chapter 2. 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 percent 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:

- Biofuel Availability and Adoption 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.

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 emissions 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.

GLOSSARY

Term	Definition
AB	Assembly Bill
AQMD	Air Quality Management District
ARB	Air Resources Board
B20	Biodiesel-20
BTE	Brake Thermal Efficiency
CalEPA	California Environmental Protection Agency
CalHEAT	California Hybrid, Efficient and Advanced Truck Research Center
CEC	California Energy Commission
CE-CERT	University of California Riverside College of Engineering Center for Environmental Research & Technology
CNG	Compressed natural gas
CO_2e	Carbon dioxide equivalents
DME	Dimethyl ether
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DPF	Diesel particulate filter
DTNA	Daimler Trucks North America LLC
ECM	Engine control module
EMFAC	EMissions FACtor, a computer model for quantification of pollutants from on-road sources
EPA	Environmental Protection Agency
EPTO	Electrified Power Take-off
g/bhp-h	Grams/brake horse power per hour
GHG	Greenhouse gas
GPH	Gallons per hour
HD	Heavy duty

HDV	Heavy-duty vehicle
HEV	Hybrid EA Electric Vehicle
HHV	Hybrid hydraulic vehicle
HPDI	High-pressure direct injection
LNC	Lean NOx Catalysts
MDV	Medium-duty vehicle
MMT	Million Metric Tons
MMT	Million metric tons
$MMTCO_2e$	Million Metric Tons of CO_2 Equivalent Emissions
MPG	Miles per gallon
MT	Metric tons
NACFE	North American Council for Freight Efficiency
NG	Natural gas
NHTSA	National Highway Traffic Safety Administration
NMHC	Non-methane hydrocarbons
NOx	Oxides of Nitrogen
OBD	On-board Diagnostics
OEM	Original Equipment Manufacturer
PHET	Plug-in Hybrid Electric Truck
PHEV	Plug-in hybrid electric vehicle
PIER	Public Interest Energy Research
PM	Particulate matter
PTO	Power Take-off
RD30	Renewable diesel-30
RFG	Reformulated gasoline
RNG	Renewable natural gas
ROI	Return on Investment

RPM	Revolutions per Minute
SCAQMD	Southern Coast Air Quality Management District
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 percent or greater vehicle freight efficiency and brake thermal efficiency.
TH	Total hydrocarbons
TTW	Tank-to-wheel
UCR	University of California, Riverside
ULSD	Ultra-low sulfur diesel
WTT	Wheel-to-tank
WTW	Well-to wheel from production through distribution and use
WVU	West Virginia University
xEV	Fully Electric Vehicle
ZEV Corridor	Zero-emission Corridor

APPENDIX 2A:
Methodology and Sources

Resources

The CalHEAT Advisory Council and Steering Committee, listed on page ii of this document, assisted and reviewed materials developed in the Roadmap and action plan. The CalHEAT Technical Advisory Group, listed on page iii, 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 CO2 benefits and adoption rates for technologies. ZMassociates Environmental Consultants (www.zmassociates.com) calculated petroleum, CO2e, 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[61] 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.

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

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

populations derived in the truck population inventory to develop baseline fuel consumption, CO_2e and NOx levels as shown in Figure 2-3: Truck CO_2e, Average Vehicle Miles Traveled and Population by Truck Category, and Figure 2-4: Relative NOx by Truck Category.

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 2-5: Promising Technology Pathways by Truck Category, 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 percent 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 Introduction and Summary section of Chapter 2, under Truck Fuel Use, through the Fuel-Related Reductions section.

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 of Chapter 2 and shown in Figure 2-12: Projected NOx Reductions 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

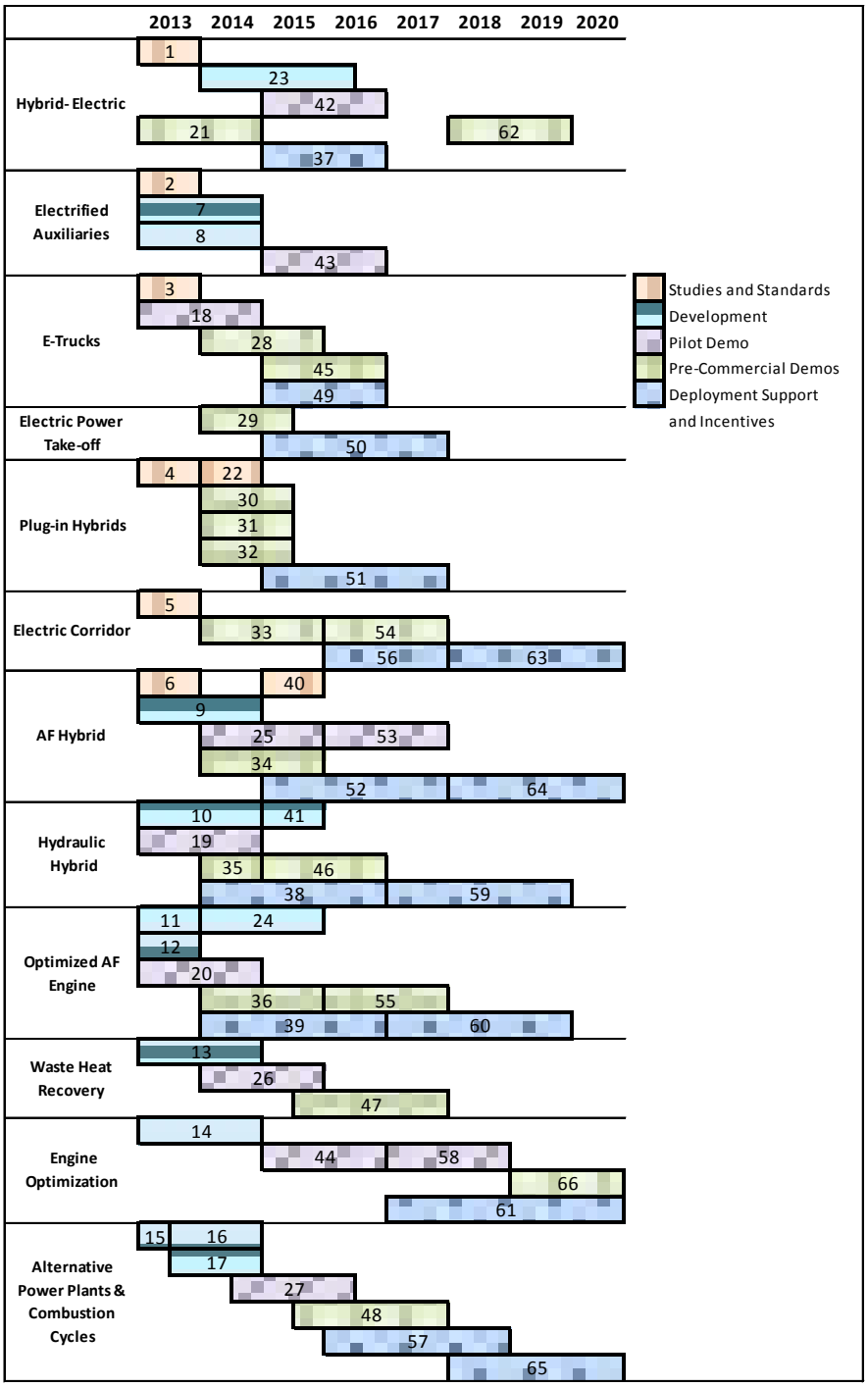
The CalHEAT staff, with the assistance of Ricardo, developed a model which used the CalHEAT categories developed for the emissions reduction model, added unique vehicle technology adoption rates for each truck technology and category, and then rolled up the result of the CO_2 reduction over time to obtain 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 Figure 2-13: Technology Adoption by Truck Category, and Figure 2-14: Technology Adoption all Truck Categories.

APPENDIX 2B:
Sixty-six Actions by Technology Strategy

In this Appendix, the 66 Roadmap actions to reduce petroleum, CO2e, and NOx, or improve truck efficiency are grouped by technology strategy and identified by action category, such as studies and standards through deployment, in, page 2B-2. A numerical list with descriptions of each action follows in, page 2B-3.

Figure 1: Sixty-Six Actions by Technology Strategy



The 66 actions to reduce petroleum, CO2e, and NOx, or improve truck efficiency are grouped by technology strategy and identified by action category, from studies and standards through deployment. Refer to, below, for a numerical list, timeline and description.

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 1: 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.
3	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.
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/supplier 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 acculumator.
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 a lower cost HHD NG solution (Heavy - Heavy 1.5 liter engine).
13	Waste Heat Recovery	Development	2013-14	Develop/apply a thermoelectric design to M-HD applications.
14	Engine Optimization	Development	2013-14	Develop an engine and system 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 demo of smart charging systems.
19	Hydraulic Hybrid	Pilot Demonstrations	2013-14	Pilot demos of enhanced parallel of dual-mode 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	Demo 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 1: 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 demo 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 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	Demo of preferred on-road connection device for electric or PHET yard hostlers.
34	AF Hybrid	Pre-Commercial Demonstrations	2014-15	Demo of two new platforms of NG/hybrid drayage truck meeting ZEV Corridor requirements.
35	Hydraulic Hybrid	Pre-Commercial Demonstrations	2014	Demo 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 1.5 liter engine 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 demo of optimized and downsized engine/s to be used in hybrid systems.
43	Electrified Auxiliaries	Pilot Demonstrations	2015-16	Pilot demo validation of electrified auxilliaries 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 1: 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	Demo 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	Demo of waste heat recovery in a vocational and line-haul truck.
48	Alt Power Plants and Combustion Cycles	Pre-Commercial Demonstrations	2015-2017	Demos of camless, opposed Piston, or HCCI engines in trucks.
49	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).
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	Demo 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	Demo 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	Stage 3 tech support of 100 drayage truck buy-downs and 200 OTR 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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

APPENDIX 2C:
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 1: 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 overcome California OBD issues		
Electrified Accessories	2. Formulate and expedite adoption of standards such as voltage variants and J1939 signal controls		
E-Trucks	3. Develop energy storage standards (pack level interfaces) to encourage greater selection and competition through SAE or IEEE, or regulation		
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.

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 2: 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 a power distribution box/supplier 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 accumulator		41. Free Piston Engine Development	
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 a lower cost HHD NG solutions (Heavy – Heavy 15 liter engines)			
Waste Heat Recovery	13. Develop/apply a thermoelectric design to M-HD applications			
Engine Optimization	14. Develop an engine and system 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 one or two new advanced engine designs such as camless, Opposed Piston and HCCI Engine		
		17. Develop a purposely-devised turbine for vehicles		

Table 3: 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 demo of optimized and downsized engine/s to be used in hybrid systems			
Electrified Auxiliaries			43. Pilot demo validation of electrified auxiliaries in Class 7-8 (non-hybrid) tractors, line haul trucks and other trucks			
E-Trucks	18. Pilot demo 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 enhanced parallel or dual-mode 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 demo of waste heat recovery in a vocational and line-haul truck				
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 or HCCI engines in trucks			

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

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 4: 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. Demo of next Stage 2 hybrid drivelines with improved design and integration, and ARB OBD compliance and electrified accessories					62. Demo 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. Demo of two new platforms of NG/hybrid drayage truck meeting ZEV Corridor requirements						
Hydraulic Hybrid		35. Demo of Series, Enhanced Parallel and/or Dual Mode (Power Split) Stage 2 Hybrids in refuse trucks	46. Demo of ultra-high efficiency Stage 3 technology using digital hydraulic components into a Class 2b and one other larger truck platform					
Optimized AF Engine		36.Demos of lower engine sizes and new lower cost 1.5 liter engine to broaden number of platforms		55. Demo of 80% decreased NOx (NZEV)				
Waste Heat Recovery				47. Demo of waste heat recovery in a vocational and line-haul truck				
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, HCCI engines in trucks				

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

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 5: 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 1000 Stage 2 hybrids starting when they become commercially available						
E-Trucks			49.Support for 1000 Stage 2 trucks to reduce ROI to 5 years (assuming daily driving of 80% of energy storage capacity					
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. Stage 3 tech support of 100 drayage truck buy-downs and 200 OTR trucks using performance-based incentives		

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

Source: California Hybrid, Efficient and Advanced Truck Research Center

APPENDIX 3A:
Hybrid Truck Driver Survey

Dates of Operation: _____

Equipment ID: _____

Please check the boxes below

Please compare the hybrid truck to the conventional non-hybrid truck

Rate the hybrid truck performance compared to typical diesel trucks	*Better*	*Same*	*Worse*	Comments
1. Maneuverability at slow speeds				
2. Pulling power with Load				
3. Acceleration				
4. Coasting/Deceleration				
5. Braking (stops load quickly and smoothly)				
6. Smoothness of shifting under acceleration				
7. In-cab controls (convenience and functioning of switches, controls, etc.)				
8. Interior noise level				
9. Exterior noise level				
10. Overall vehicle rating				

11. Any problems with the hybrid drive system (e.g. faults, shutdowns)? Yes No
    If yes, explain. _____

12. Are you interested in additional training on how to drive the hybrids more efficiently? Yes No

<u>Comments:</u> _____

_____

APPENDIX 3B:
Hybrid Truck Mechanic Survey

Mechanic: _____

Date: _____

Purpose: To solicit maintenance and service personnel feedback on the hybrid trucks to conventional diesel trucks.

1. Describe any hybrid truck problems observed during the early part of the demonstration period that were subsequently corrected by the manufacturer:

   _____
   _____
   _____
   _____

Please rate the following issues related to hybrid truck maintenance and service on a scale of 1 to 5 where 1 means unacceptable and 5 means excellent (circle the appropriate number):

	Unacceptable				*Excellent*
2. Hybrid Systems and Component Training:	1	2	3	4	5
3. Design for Maintainability:	1	2	3	4	5
4. Design for Serviceability:	1	2	3	4	5
5. Vehicle Manufacturer Support:	1	2	3	4	5
6. Hybrid System Manufacturer Support:	1	2	3	4	5

7. Describe any trends observed regarding non-routine service actions associated with the hybrid trucks including the long-term effectiveness of corrective actions:

_____
_____
_____

8. Additional Comments

   _____
   _____
   _____
   _____

APPENDIX 3C:
Development of Heavy-Duty Driving Schedules

Submitted to:

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Edited by Patrick Chen- CALSTART

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Overview

Medium- and heavy-duty vehicles are critical to the economy, yet remain a real and growing challenge to increased fuel use and carbon emissions that has been insufficiently addressed. This segment accounts for a significant portion of petroleum use state and nationwide, particularly on a per platform basis, due to high per-vehicle fuel use. Medium- and heavy-duty on-road truck traffic serving urban and goods movement needs combined with heavy-duty off-road vehicle use at distribution centers and ports, contribute significantly to fuel use, poor regional air quality, and are a sizable source of greenhouse gas emissions. One way to reduce the problems associated with medium- and heavy-duty trucks is the implementation of advanced technologies.

The California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center is a California-based resource center for research, development, demonstration and commercialization of advanced, efficient truck technologies and systems. CalHEAT is currently evaluating the performance of Class 8 urban delivery advanced trucks in a limited demonstration program in Southern California and a need for an appropriate duty cycle was determined to be important. In addition the activity under the CALSTART Hybrid Truck Users Forum determined a similar need. The primary goal of the CalHEAT project is to evaluate the benefits of heavy duty hybrid vehicle technology compared to conventional vehicles, when used in a "Beverage Delivery" application. A significant number of these vehicles are being introduced under the California HVIP (Hybrid Vehicle incentive Vouchers Program).

One key aspect of the project is performing evaluations of the vehicles on a chassis dynamometer. In order to perform such tests, a duty cycle is critical to provide results that are representative of normal operations for the vehicles. In order to develop the duty cycle, the CalHEAT project leveraged funding from the Hybrid Truck Users Forum (HTUF), a program operated by CALSTART in partnership with the U.S. Army's National Automotive Center (NAC), to gather and supply data on trucks from a Southern California Beverage Delivery Company. The collected data was provided to HTUF and its partner, West Virginia University (WVU), for analysis and development of characteristic duty cycles for hybrid truck evaluation.

Executive Summary

Two speed-time driving schedules were developed using on-road activity data from Class 8 beverage delivery tractors operating in Los Angeles. The driving schedules represented "heavy" and "light" vehicle load and were developed such that vehicle emissions and fuel economy could be evaluated while the vehicle was operated over the speed-time schedules developed using a chassis dynamometer. Activity data collected from in-use vehicles were broken down into short speed-time segments called microtrips which were classified by loading ("heavy" or "light"). A computer algorithm was then used to randomly combine similarly classified microtrips to form a large group of candidate driving schedules and the candidate driving schedule which compared most favorably to that of its parent dataset was selected for use in the evaluation.

Objectives

The objective of the project was to develop speed-time driving schedules for use in evaluating emissions and fuel economy from Class 8 tractors used for beverage delivery service in the Los Angeles metropolitan area. On-road activity data were logged from two Class 8 tractors used in beverage delivery service. Data collected by CALSTART included global positioning system (GPS) latitude, longitude and speed while the vehicles were operated over their typical delivery routes. One of the vehicles was a conventional diesel-powered tractor while the other was powered by a hybrid-electric drivetrain. Data were collected between December 11, 2010 and March 4, 2011 and represented over 900 miles of operation.

Vehicle Weights

Scant information was available for vehicle loading during the time when data were gathered. The unladen weight for the conventional tractor and trailer combination was 26,440 lbs and the hybrid tractor/trailer combination was slightly heavier as a result of hybrid components at 27,090 lbs. Actual product load data, presented in Table 1, was available from manifest sheets for five days of operation

Table 1: Vehicle Loading Data

Vehicle	Cases	Cubes	Pallets	Weight (lb)
Conventional	512	1138	18	16,776
Conventional	683	1241	17	19,234
Conventional	1027	1730	18	27,472
Conventional	433	912	20	13,747
Hybrid	433	872	17	13,075

The amount of product load data did not lend to statistical analysis but, lacking complete data, average load based on the five available data points was 18,061 lbs while the median load was 16,776 lbs. One day of load data (10b661690: 1027 cases, 1730 cubes) was considered to be an outlier as it was 52 percent heavier than the average and, excluding it from the data set resulted in an average starting product load of 15,708 lbs. Since instantaneous load data were not available an assumption that the vehicle left on its route with a full load based on its unladen weight plus the weight of product and, delivered one-half of the product load by the half-way point in its route, and returned to the distribution center unloaded. For the conventional tractor/trailer, this assumption would result in the vehicle weighing 42,148 lbs (26,440 lbs tractor/trailer weight + 15,708 lbs product weight) at the beginning of its route and 34,294 lbs at the half-way point (26,440 lbs tractor/trailer weight + 15,708 / 2 lbs product weight).

The initial plan for analysis had been to base the reduction in product loading through each delivery route on the length of each delivery stop as a percentage of the total time stopped for delivery. However, this approach proved problematic as it was observed that many vehicle stops (ignition off) were not deliveries but stops related to non-delivery activity. More specifically, many stops took place at locations where a delivery was obviously not taking place (restaurant, etc.). Given the amount of data gathered during the program it was unrealistic to classify each stop for each vehicle to determine loading.

Lacking detailed load data, the simplest assumption would be that, on each operating day, the vehicle left with a total weight of 43,050 lbs (26,750 lbs vehicle weight plus 16,300 lbs load), dropped the load, and returned weighing 26,750 lbs. This assumption would result in the vehicle weighing, on average, 38,975 lb on the outbound and 30,825 on the inbound. For purposes of driving schedule creation, data collected during outbound activity data were used to develop the "heavy" driving schedule while data collected during inbound activity data were used to develop the "light" driving schedule.

Data Collection

Data collection for the conventional and hybrid tractors was accomplished through Telogis GPS fleet tracking. The Telogis system continuously monitored each vehicle between December 11, 2010 and March 4, 2011 and recorded continuous vehicle position and speed information. The data were then downloaded as "Fleet Reports" which consisted of time-stamped data points including the vehicle location (address), latitude, longitude and speed. Table-2 shows detailed data collected from the conventional tractor on January 4, 2011 as it left the distribution facility on a delivery run.

Table 2: Telogis Fleet Report for Conventional Tractor from January 4, 2011.

Time	Location	Lat	Lon	Speed - Heading
9:02:45 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03001	-118.24526	0 mph - SW
9:02:46 AM, 04-Jan-2011	1212 S Central Ave Los Angeles, California 90021	34.03001	-118.24527	2 mph - SW
9:02:47 AM, 04-Jan-2011	1212 S Central Ave Los Angeles, California 90021	34.03	-118.24528	3 mph - SW
9:02:48 AM, 04-Jan-2011	1212 S Central Ave Los Angeles, California 90021	34.03	-118.24528	1 mph - SW
9:02:49 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03001	-118.24526	2 mph - W
9:02:50 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03002	-118.24527	3 mph - W
9:02:51 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03002	-118.24529	3 mph - NW
9:02:52 AM, 04-Jan-2011	1208 S Central Ave Los Angeles, California 90021	34.03005	-118.24527	5 mph - N
9:02:53 AM, 04-Jan-2011	1302 E 12th St Los Angeles, California 90021	34.0301	-118.24525	6 mph - N
9:02:54 AM, 04-Jan-2011	1196 S Central Ave Los Angeles, California 90021	34.03017	-118.24521	6 mph - N
9:02:55 AM, 04-Jan-2011	1194 S Central Ave Los Angeles, California 90021	34.03019	-118.24522	6 mph - N
9:02:56 AM, 04-Jan-2011	1196 S Central Ave Los Angeles, California 90021	34.0302	-118.24525	5 mph - NW
9:02:57 AM, 04-Jan-2011	1299 E 12th St Los Angeles, California 90021	34.03019	-118.24528	2 mph - W
9:02:58 AM, 04-Jan-2011	1296 E 12th St Los Angeles, California 90021	34.03017	-118.24531	5 mph - SW
9:02:59 AM, 04-Jan-2011	1207 S Central Ave Los Angeles, California 90021	34.03014	-118.24536	7 mph - SW
9:03:00 AM, 04-Jan-2011	1211 S Central Ave Los Angeles, California 90021	34.03012	-118.24541	8 mph - SW
9:03:01 AM, 04-Jan-2011	1213 S Central Ave Los Angeles, California 90021	34.03011	-118.24544	7 mph - SW
9:03:02 AM, 04-Jan-2011	1215 S Central Ave Los Angeles, California 90021	34.03009	-118.24547	6 mph - SW
9:03:03 AM, 04-Jan-2011	1219 S Central Ave Los Angeles, California 90021	34.03007	-118.24549	7 mph - SW
9:03:04 AM, 04-Jan-2011	1225 S Central Ave Los Angeles, California 90021	34.03	-118.2455	9 mph - S
9:03:05 AM, 04-Jan-2011	1228 S Central Ave Los Angeles, California 90021	34.02996	-118.24551	9 mph - SW
9:03:06 AM, 04-Jan-2011	1232 S Central Ave Los Angeles, California 90021	34.02992	-118.24555	10 mph - SW
9:03:07 AM, 04-Jan-2011	1241 S Central Ave Los Angeles, California 90021	34.02988	-118.24561	14 mph - SW
9:03:08 AM, 04-Jan-2011	1246 S Central Ave Los Angeles, California 90021	34.02983	-118.24565	15 mph - SW
9:03:09 AM, 04-Jan-2011	1250 S Central Ave Los Angeles, California 90021	34.02979	-118.24569	15 mph - SW
9:03:10 AM, 04-Jan-2011	1258 S Central Ave Los Angeles, California 90021	34.02973	-118.24574	16 mph - SW

The fleet reports also contained data points indicating locations and durations when the vehicles were stopped. It must be noted that an idle event and a stop event were differentiated in that during stop events the vehicle ignition was turned off. The amount of data suitable for processing covered over 182 hours of operation.

Data Processing

Data collected using GPS is notoriously problematic. For example, when insufficient satellites are visible to the GPS receiver as a result of tunnels, bridges, and nearby buildings, the receiver might record data points with the last known latitude and longitude and a speed of zero. In addition to data points with suspect speed data, there were frequent data dropouts where the data, normally recorded at a frequency of 1Hz, would be missing portions of data. Another issue with the GPS data was resolution of speed to 1 mph increments that, without processing, would result in extremely discontinuous data. Data processing consisted of four distinct operations and included (1) identifying data segments with anomalous data; (2) determining if the segment was repairable; (3) removing anomalous segments that were not repairable and repairing those that were and; (4) applying a data smoothing algorithm to reduce effects of low resolution speed data.

The issues presented by GPS data can be seen in Figure 1which clearly shows points where the speed recorded experienced sudden changes from high speed (~40 mph) down to 0 mph and back to the high speed.

Table 3: Telogis Fleet Report for Conventional Tractor from January 4, 2011.

Time	Location	Lat	Lon	Speed - Heading
9:02:45 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03001	-118.24526	0 mph - SW
9:02:46 AM, 04-Jan-2011	1212 S Central Ave Los Angeles, California 90021	34.03001	-118.24527	2 mph - SW
9:02:47 AM, 04-Jan-2011	1212 S Central Ave Los Angeles, California 90021	34.03	-118.24528	3 mph - SW
9:02:48 AM, 04-Jan-2011	1212 S Central Ave Los Angeles, California 90021	34.03	-118.24528	1 mph - SW
9:02:49 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03001	-118.24526	2 mph - W
9:02:50 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03002	-118.24527	3 mph - W
9:02:51 AM, 04-Jan-2011	1210 S Central Ave Los Angeles, California 90021	34.03002	-118.24529	3 mph - NW
9:02:52 AM, 04-Jan-2011	1208 S Central Ave Los Angeles, California 90021	34.03005	-118.24527	5 mph - N
9:02:53 AM, 04-Jan-2011	1302 E 12th St Los Angeles, California 90021	34.0301	-118.24525	6 mph - N
9:02:54 AM, 04-Jan-2011	1196 S Central Ave Los Angeles, California 90021	34.03017	-118.24521	6 mph - N
9:02:55 AM, 04-Jan-2011	1194 S Central Ave Los Angeles, California 90021	34.03019	-118.24522	6 mph - N
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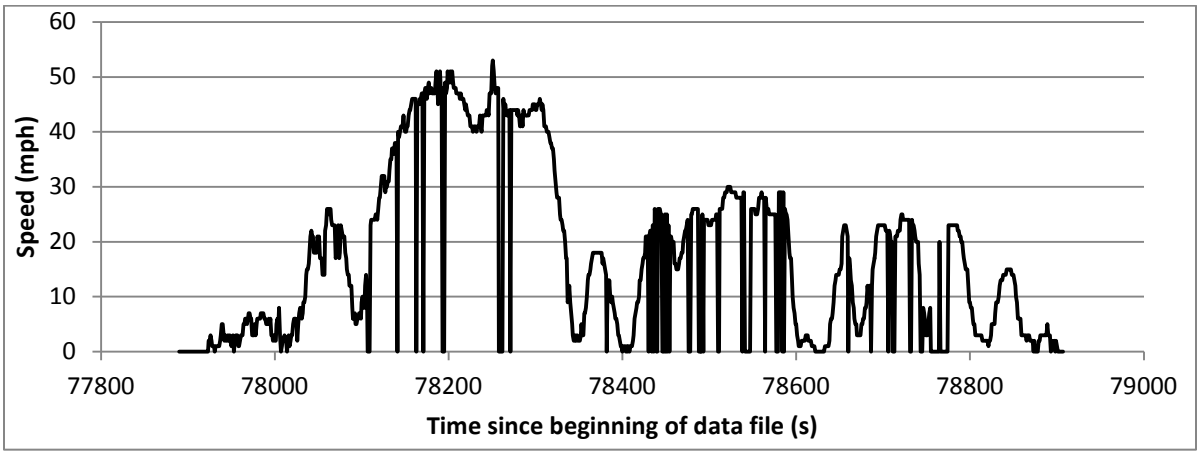
9:02:59 AM, 04-Jan-2011	1207 S Central Ave Los Angeles, California 90021	34.03014	-118.24536	7 mph - SW
9:03:00 AM, 04-Jan-2011	1211 S Central Ave Los Angeles, California 90021	34.03012	-118.24541	8 mph - SW
9:03:01 AM, 04-Jan-2011	1213 S Central Ave Los Angeles, California 90021	34.03011	-118.24544	7 mph - SW
9:03:02 AM, 04-Jan-2011	1215 S Central Ave Los Angeles, California 90021	34.03009	-118.24547	6 mph - SW
9:03:03 AM, 04-Jan-2011	1219 S Central Ave Los Angeles, California 90021	34.03007	-118.24549	7 mph - SW
9:03:04 AM, 04-Jan-2011	1225 S Central Ave Los Angeles, California 90021	34.03	-118.2455	9 mph - S
9:03:05 AM, 04-Jan-2011	1228 S Central Ave Los Angeles, California 90021	34.02996	-118.24551	9 mph - SW
9:03:06 AM, 04-Jan-2011	1232 S Central Ave Los Angeles, California 90021	34.02992	-118.24555	10 mph - SW
9:03:07 AM, 04-Jan-2011	1241 S Central Ave Los Angeles, California 90021	34.02988	-118.24561	14 mph - SW
9:03:08 AM, 04-Jan-2011	1246 S Central Ave Los Angeles, California 90021	34.02983	-118.24565	15 mph - SW
9:03:09 AM, 04-Jan-2011	1250 S Central Ave Los Angeles, California 90021	34.02979	-118.24569	15 mph - SW
9:03:10 AM, 04-Jan-2011	1258 S Central Ave Los Angeles, California 90021	34.02973	-118.24574	16 mph - SW

Figure 1: Raw GPS speed data from conventional tractor (3 Jan 2011)



Processing algorithms were developed to address data anomalies such as dropouts since they occurred frequently in each data set. The most straightforward processing algorithm utilized was the synthesis of short data segments (1-3 seconds) where the recorded speed was zero and, based on leading and trailing data, the vehicle was traveling at speed during the missing data segment. Data segments were synthesized by interpolating between the last speed data point before the missing segment and the first speed data point following the missing segment.

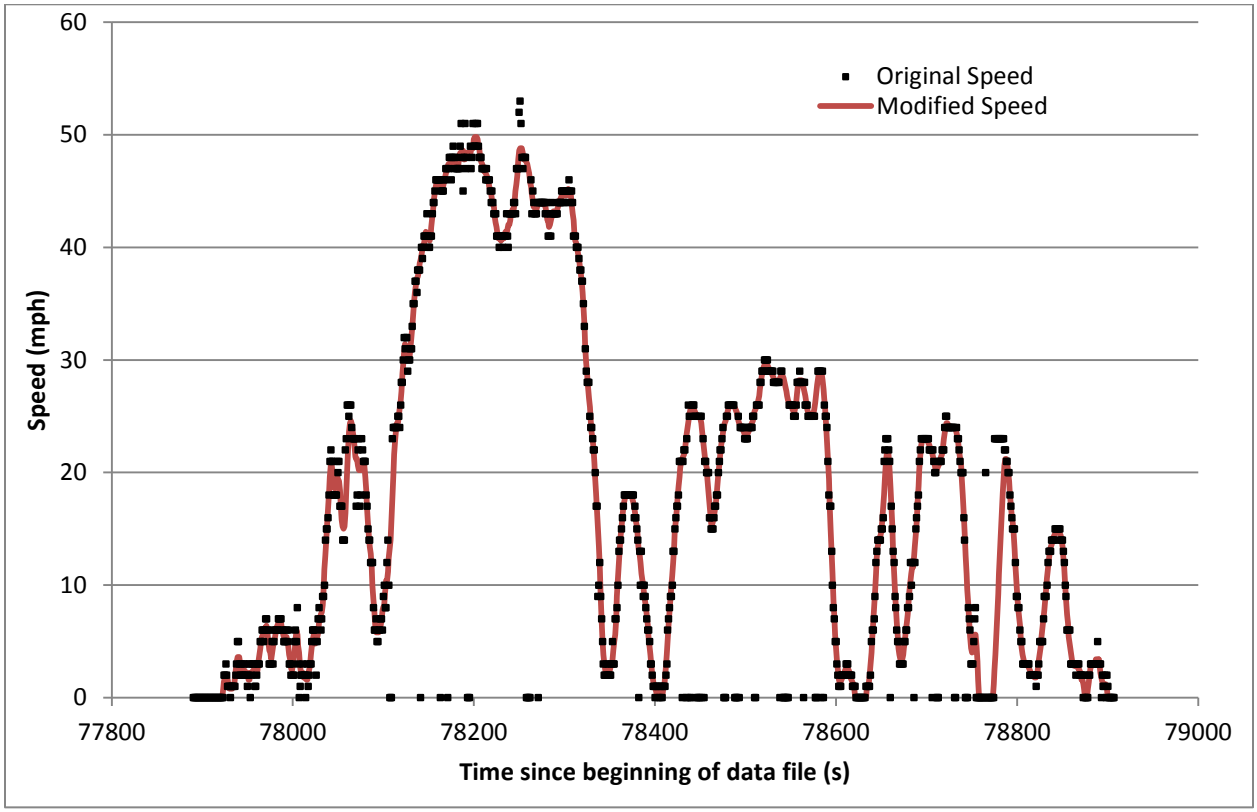
Table 4 shows a segment of data from the conventional tractor data shown in Figure 1. These data clearly show that anomalous recorded GPS speed recordings of 0 mph between data points at time 78192 and 78196. The first processing step was to replace the anomalous data points with reasonable speeds by interpolating between the last known speed before the anomalous data (48 mph @ 78192 seconds) and the first known speed after the anomalous data (49 mph @ 78196 seconds). Subsequent to substituting interpolated data for the anomalous speed points, the data were smoothed using a five-point moving average such that data continuity was achieved.

Table 4: Example of data processing steps applied to data from Figure 1

Time (s)	Recorded GPS Speed	GPS Speed (with segment substitution)	GPS Speed (with data smoothing)
78191	47	47	48.4
78192	48	48	48.4
78193	0	48	48
78194	0	48	48.4
78195	0	49	48.2
78196	49	49	48.2
78197	47	47	48.8
78198	48	48	48.8

Figure 2 shows raw and processed GPS data from the conventional tractor collected on 3 January 2011 and shows that the processing operation was reasonably successful both in replacing anomalous zero speed data points and removing discontinuities resulting from the low (1 mph) resolution of the data.

Figure 2: Raw and processed GPS speed from conventional tractor (3 Jan 2011)



Road Grade

Road grade is an important factor in evaluating on-road vehicle activity. However, obtaining accurate road grade information is difficult. In analyzing data collected during this program, the GPS latitude and longitude were cross-referenced with digital elevation data in an attempt to determine road grade. Unfortunately, the elevation data returned from the cross-referencing operation was relative to ground elevation rather than road surface elevation. As an example, when the vehicle travelled on an elevated roadway, the vehicle elevation reported was lower than its actual elevation by an amount equal to the elevation of the roadway. In addition, inaccuracies in GPS data where the surrounding topography was hilly resulted in the return of anomalous elevation data. An observed example was elevation data on a flat/level road in the vicinity of a road cut. If the GPS data were slightly off the roadway the elevation of the adjacent terrain was reported rather than that of the roadway. Lacking more accurate methodology such as atmospheric pressure sensors or roadway surface maps elevation data were not included in the analysis.

Comparison with Typical Vehicle Behavior

In order to provide a sanity-check of the processed GPS data the resulting speeds were used in a road-load analysis with metrics (weight, drag coefficient, frontal area, etc.) from the conventional tractor. The road-load analysis resulted in power levels at the vehicle wheels corresponding to individual speed data points based on the inertial load as a function of vehicle mass, speed, and acceleration, the aerodynamic drag tire rolling resistance loads as a function of vehicle speed. The power levels calculated using the processed speed and road load equation were comparable to the power levels expected from the conventional vehicle engine with peak power being approximately 250 horsepower.

Fuel Consumption Modeling

The speed-time data collected from the vehicles was used as input to a rudimentary fuel consumption model to verify that the data were representative of typical vehicle operation. The fuel consumption model consisted of a road-load analysis that included inertial, aerodynamic and tire rolling resistance vehicle loading. Since elevation data obtained by cross referencing latitude and longitude data with digital elevation maps were not reliable, loads resulting from climbing and descending hills were not modeled.

$$\text{Power}=MV\frac{dV}{dt}+\frac{1}{2}\varrho AC_dV^3+\mu MgV$$

The road load power obtained was then translated to engine power by assuming a driveline efficiency of 85 percent. By integrating the power required to propel the vehicle at the speed and accelerations collected during the program, the net energy produced by the engine was obtained. Road power was translated to fuel consumption using an assumed engine/drivetrain efficiency of 35 percent and a fuel energy content of 42 MJ/kg and the resulting net fuel economy was calculated as approximately 5.5 miles per gallon. Fuel economy for the conventional tractor, as reported by the fleet manager, ranged from 4.5 to 5.0 mpg. While the in-use fuel economy reported by the vehicle operators was lower than that obtained using modeling, the modeled fuel economy did not include fuel use at idle. If the fuel use at idle were included in the model the simulated fuel economy would be comparable to that reported by the fleet manager. Based on fuel consumption modeling, the in-use activity data used in generating the driving schedules were representative of typical on-road activity.

Microtrips

Upon completion of the data processing operations, the speed-time data were split into segments known as microtrips, each consisting of a period of idle followed by the vehicle traveling some distance before coming to a stop. Each of the individual microtrips were classified according to vehicle loading and the following statistics for each microtrip were calculated:

- Total Duration
- Idle Duration
- Average Speed (excluding idle)

- Standard Deviation of non-idle Speed

The microtrips were further classified based on their maximum speed such that microtrips where the vehicle did not exceed 4 miles per hour were considered separately from other microtrips. Operation below 4 mph implies that, while the vehicle did move forward as a result of releasing the brakes, the vehicle accelerator was not engaged. This activity is commonly known as "creep" operation and is differentiated from "normal" operation as it has less significant effect on fuel economy and emissions.

Candidate Driving Schedule Generation

The following metrics from the entire collection of "heavy" and "light" speed-time data and from the candidate cycles were calculated.

- Mean Microtrip Average Speed ($\bar{v}_{ave}$): The average of the average microtrip speed (V_{ave}) for the microtrips in the group.
- Mean Microtrip Standard Deviation of Microtrip Speed ($\bar{\sigma}_{ave}$): The average of the standard deviation of speed for the microtrips in the group.
- Percent Idle (*%idle*): Percentage of time spent idling in relation to the group duration.
- Percent Creep (*%creep*): Percentage of time spent operating in creep mode in relation to the group duration.

The weighted minimization function was calculated using the following equations

$$m_v = \left[\frac{(v_{ave})_{Cycle} - (v_{ave})_{Dataset}}{(v_{ave})_{Dataset}} \right] \qquad \text{Equation 1}$$

$$m_\sigma = \left[\frac{(\sigma_{ave})_{Cycle} - (\sigma_{ave})_{Dataset}}{(\sigma_{ave})_{Dataset}} \right] \qquad \text{Equation 2}$$

$$m_{\%idle} = \left[\frac{(\%_{idle})_{Cycle} - (\%_{idle})_{Dataset}}{(\%_{idle})_{Dataset}} \right] \qquad \text{Equation 3}$$

$$m_{\%creep} = \left[\frac{(\%_{creep})_{Cycle} - (\%_{creep})_{Dataset}}{(\%_{creep})_{Dataset}} \right] \qquad \text{Equation 4}$$

The differences calculated using Equations 1-4 were then combined using Equation 5 which provided an overall comparative metric MF. When comparing how well a group of candidate cycles compared to their parent activity group, that candidate cycle with a value of MF closest to zero was deemed the "best" representation of the activity group.

$$MF = \sqrt{0.3m_V^{\ 2} + 0.3m_\sigma^{\ 2} + 0.25m_{\%idle}^{\ 2} + 0.15m_{\%creep}^{\ 2}} \quad \text{Equation 5}$$

Table 5 and Table 6 show results of the statistical analysis of the activity data sets and of the five candidate cycles from each activity which most closely compared to their parent data sets.

Table 5: "Light" Candidate Schedules

ID	$\bar{V}_{ave}$ (mph)	$\bar{\sigma}_{ave}$ (mph)	%Creep	%Idle	MF
All Activity	10.66	5.36	20.8	33.5	-
256	10.61	5.18	19.9	34.2	0.0191
376	10.30	5.52	18.7	33.2	0.0323
106	10.48	5.41	17.7	35.3	0.0351
9	10.89	5.61	21.8	36	0.0476
313	11.07	5.16	21.3	36.2	0.0510

Table 6: "Heavy" Candidate Schedules

ID	$\bar{V}_{ave}$ (mph)	$\bar{\sigma}_{ave}$ (mph)	%Creep	%Idle	MF
All Activity	11.97	5.97	21.1	32.3	-
342	12.11	5.98	20.8	32.4	0.0109
36	11.47	6.15	23.3	33.7	0.0416
302	11.62	6.03	21.7	29.9	0.0430
34	12.19	5.65	22.9	34.5	0.0444
204	11.41	6.19	24.5	33.2	0.0516

The candidate driving schedule #256 was selected to represent light activity while the candidate driving schedule #342 was selected to represent heavy activity. Idle redistribution was required for each driving schedule since the schedules were developed for use during chassis dynamometer emissions and fuel economy testing. Driving schedules typically contain an approximately 30 second long idle period at their beginning to accommodate the driver and an approximately 30 second long idle period at their end to allow for exhaust measurement delay. Redistribution of idle does not affect the statistical properties of the driving schedules. Figure 3 and Figure 4 show, respectively, the synthesized “Heavy” and “Light” driving schedules.

Acceleration Rates

Acceleration rates of the candidate driving schedules were examined by the Center for Environmental Research and Technology at the University of California: Riverside and found to be acceptable for use on their chassis dynamometer.

Figure 3: Driving schedule composed of microtrips from activity classified as "Heavy".

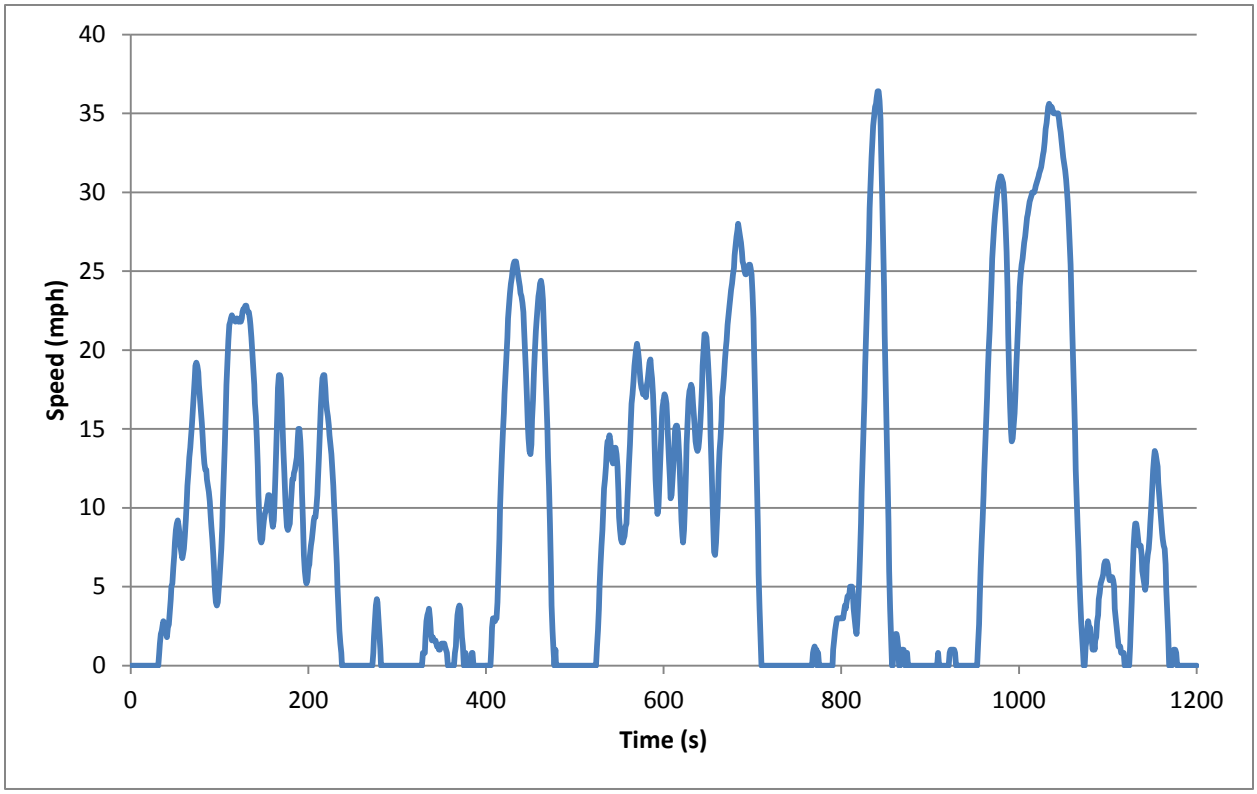
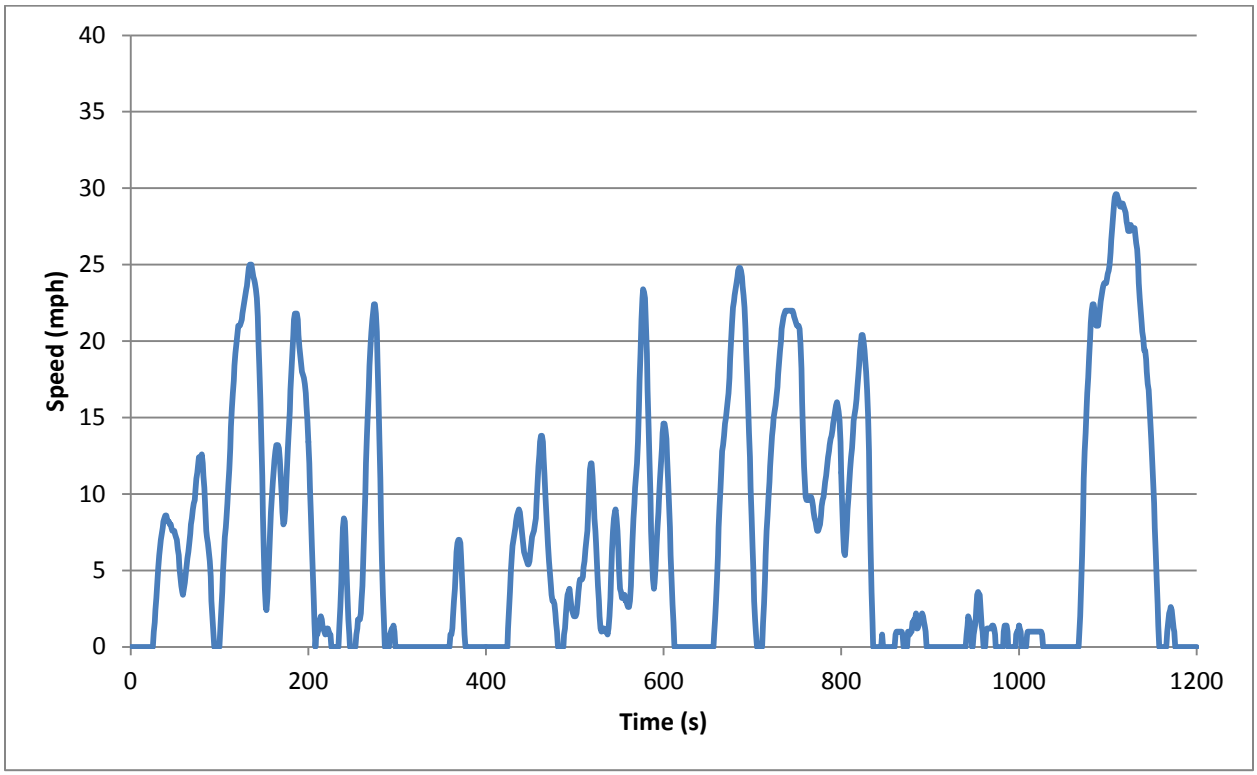


Figure 4: Driving schedule composed of microtrips from activity classified as "Light".



Summary

Two driving speed-time driving schedules for use in evaluating emissions and fuel economy from beverage delivery tractors were developed with each driving schedule being composed of segments of in-use speed-time activity data collected from conventional and hybrid beverage delivery tractors while operating in the Los Angeles area. Each driving schedule was selected from a group of speed-time driving schedules developed from parent (heavy and light) data based on how well its average speed, standard deviation of speed, percent idle and percent creep compared to its parent data set. The "Heavy" driving schedule was developed using activity data when the vehicle was engaged in outbound activity and in the first half of its daily delivery schedule while the "Light" driving schedule was developed using inbound activity from the second half of its daily delivery schedule. The assumed loading for the heavy driving schedule was 38,975 lb and, for the light driving schedule, 30,825lb. The driving schedules have been forwarded to UC Riverside CE-CERT for review for use on their chassis dynamometer. CE-CERT's initial review found both driving schedules to deceleration and acceleration rates which were acceptable for use on their chassis dynamometer.

APPENDIX 3D:
Assessment of the Emissions and Fuel Economy of a Class 8 Conventional and Class 8 Hybrid Truck

Chassis Dynamometer Testing

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Executive Summary

Background:

The goal of this study was to evaluate the performance of a conventional truck and two hybrid class 8 trucks for emissions and acceleration rate from 0 to 20 mph. The conventional truck and one of the hybrids are used by a Southern California Beverage Delivery Company (BDC) to deliver product in the Los Angeles, California area. The second hybrid is a newer, slightly higher horsepower model used by Freightliner to demo their latest hybrid technology. The emissions and fuel economy measurements were made on CE-CERT's Heavy-Duty Chassis Dynamometer (HDCD) using two specially developed cycles based upon data obtained for the actual operation of these trucks in Los Angeles.

All of the trucks were manufactured by Freightliner and all of them used Diesel Particulate Filters (DPF) and Selective Catalytic Reduction (SCR) for emissions control. The conventional truck has a Cummins ISC 300 hp, 8.3L engine and an Allison Transmission. The BDC hybrid has a Cummins ISB 280 hp, 6.7L engine, an Eaton transmission, and a 40 kW electric motor. The newer Freightliner hybrid has a Cummins ISB 325 hp, 6.7L engine, an Eaton transmission, and a 40 kW electric motor. The newer Freightliner was tested with its existing battery as well as an older battery designed to be more similar to that used in the BDC hybrids.

Results:

The average emissions in g/mile and g/gal fuel and fuel use in mpg are shown in Table 1. No Battery State of Charge (SOC) correction was applied to the emissions or fuel economy of the hybrids. The measured emissions of carbon dioxide (CO2) on a g/mile basis are considerably lower for the hybrid vehicles relative to the conventional vehicle (37.5 percent and 30.9 percent lower for the light and heavy cycles, respectively). The hybrids have significantly better fuel economy on a mpg basis than the conventional vehicle (59.8 percent and 44.3 percent higher

mpg for the light and heavy cycles, respectively, based on carbon balance). These results are consistent with previous studies that have shown fuel economy reductions for similar hybrid configurations and indicate that the in-use fuel economy improvements and CO2 reductions with the hybrid technology are significant.

The measured emissions of Total Hydrocarbons (THC) and Non-Methane Hydrocarbons (NMHC) are negative after subtraction of the ambient background concentrations. The particulate matter (PM) emissions were less than 0.004 g/mile for both BDC vehicles. The PM emissions were not measured for the Freightliner Hybrid. Interestingly, the emissions of carbon monoxide (CO) for the hybrid vehicles were higher than those for the corresponding conventional vehicle. Examination of real-time and exhaust and catalyst temperature data showed that the higher CO emissions were due to emissions during operation when the catalyst was at a lower operating temperature than for the conventional vehicle. These CO emissions were eliminated when the key off time between tests was reduced from 20 minutes to 1 minute. The NOx emissions for the BDC hybrid were lower for the light cycle and higher for the heavy cycle than the conventional vehicle. The NOx emissions from the Freightliner hybrid were approximately the same as those from the conventional vehicle for the 20 minute key-off soak with the new battery, and lower than the conventional vehicle for the 20 minute key-of soak with the old battery and lower for both batteries for the 1 minute key-off soak.

The BDC conventional truck had average acceleration rates of 1.1 and 1.5 mph/sec for the light and heavy cycles respectively. The BDC hybrid truck had average acceleration rates of 0.1 and 1.1 mph/sec for the light and heavy cycles respectively. The acceleration rate of the Freightliner hybrid was not measured.

Table 1: Emissions and Fuel Economy for a Conventional and a Hybrid BDC Truck

		Emissions (g/mile)						Emissions (g/gal fuel)					Carbon Balance Fuel	
	THC	CH_4	NMHC	CO	NO_x	CO_2	THC	CH_4	NMHC	CO	NO_x	CO_2	ECM	Emis-sions
	BDC Conventional, Light Cycle													
Average	-0.105	0.033	-0.139	0.113	2.897	2469	-0.423	0.134	-0.563	0.461	11.750	9955.7	4.72	4.03
Std. Dev.	0.003	0.006	0.008	0.073	1.470	50	0.018	0.025	0.037	0.306	6.234	0.6	0.12	0.08
	BDC Hybrid, Light Cycle													
Average	-0.093	0.036	-0.131	1.787	2.752	1543	-0.601	0.232	-0.842	11.493	17.709	9938.7	6.40	6.44
Std. Dev.	0.004	0.005	0.005	0.575	0.479	15	0.021	0.032	0.029	3.621	2.911	5.6	0.04	0.07
	BDC Conventional, Heavy Cycle													
Average	-0.078	0.026	-0.106	0.138	3.009	2380	-0.327	0.111	-0.443	0.476	12.551	9955.2	4.68	4.18
Std. Dev.	0.005	0.007	0.008	0.076	0.902	36	0.024	0.031	0.040	0.376	3.640	0.6	0.12	0.06
	BDC Hybrid, Heavy Cycle													
Average	-0.064	0.033	-0.098	2.882	3.939	1645	-0.386	0.201	-0.593	17.369	23.761	9928.8	6.19	6.03
Std. Dev.	0.002	0.002	0.002	0.521	0.365	22	0.005	0.011	0.009	2.945	1.906	4.6	0.05	0.09
	Freightliner Hybrid, New Battery, 20 minutes between Heavy Cycles													
Average	-0.144	-0.001	-0.144	0.163	3.016	1526	-0.964	-0.018	-0.956	1.060	19.606	9956.2	6.27	6.53
Std. Dev.	0.096	0.041	0.057	0.030	0.493	81	0.696	0.274	0.429	0.066	2.295	2.3	0.21	0.35
	Freightliner Hybrid, New Battery, 1 minute between Heavy Cycles													
Average	-0.268	-0.051	-0.219	-0.075	1.757	1336	-1.994	-0.380	-1.630	-0.557	13.120	9961.8	6.50	7.45
Std. Dev.	0.004	0.010	0.006	0.032	0.319	24	0.007	0.065	0.073	0.232	2.610	0.3	0.23	0.13
	Freightliner Hybrid, Old Battery, 20 minutes between Heavy Cycles													
Average	-0.153	-0.002	-0.153	0.311	2.390	1519	-1.020	-0.021	-1.009	2.042	15.728	9954.8	6.08	6.56
Std. Dev.	0.108	0.055	0.054	0.011	0.448	48	0.754	0.369	0.395	0.098	3.385	2.1	0.06	0.21
	Freightliner Hybrid, Old Battery, 1 minute between Heavy Cycles													
Average	-0.288	-0.069	-0.221	-0.175	2.049	1404	-2.043	-0.487	-1.572	-1.241	14.533	9963.0	6.27	7.10
Std. Dev.	0.003	0.008	0.005	0.003	0.146	29	0.020	0.047	0.068	0.005	0.733	0.1	0.07	0.15

Introduction

Hybrid technologies are becoming more commonplace for light-duty vehicles, and they are starting to develop a wider range of applications for heavy-duty vehicles as well. By combining batteries and electrical vehicle technology with an internal combustion engine, hybrids offer the potential of improved fuel economy and emissions. The objective of this project was to evaluate the emissions and fuel economy for operation of the Southern California Beverage Delivery Company (BDC) trucks as they follow cycles representative of their in-use driving patterns, and to compare the results between the conventional and the hybrid engine. An additional Freightliner truck was also tested to further examine some of the emissions trends observed for the BDC trucks.

Experimental Work Plan

This section provides information on the plan outlined in the contracted scope of work and changes that occurred as the plan was carried out.

Test Trucks and Fuel

Two vehicles from the BDC fleet were tested, one conventional truck and one hybrid truck. Approximately 5 months later a Freightliner Hybrid truck was tested. Table 2 provides a summary of the specifications for the trucks used during the chassis dynamometer testing. The technologies were all designed to meet 2010 emissions standards, and included both selective catalytic reduction (SCR) and diesel particulate filter (DPF) aftertreatment systems. The hybrid vehicles were selected to have power levels similar to those of the conventional vehicle to provide the most comparable test conditions as possible. The second Freightliner hybrid truck

was not pulled from the BDC fleet, but was a newer version of the hybrid vehicle designed for similar applications. It had a slightly higher horsepower engine, a higher voltage battery, and a revised control algorithm compared to the BDC hybrid. The fuel for all of the trucks was commercial ultra low sulfur diesel (ULSD) fuel.

Table 2: Truck Test Fleet and Fuel

Vehicle Make and Model	Engine Make and Model	Transmission Manufacturer	Electric Motor Power	Engine HP and Torque	Fuel	Odon-meter	Exhaust After treatment
BDC Trucks							
Freightliner M-2 2010 (Conventional)	Cummins ISC-300 8.3L	Allison	NA	300 HP 860 LB/FT	ULSD	13,848	DPF & SCR
Freightliner M-2 2010 Hybrid*	Cummins ISB 6.7L-280	Eaton	40 kW	280 HP 660 LB/FT	ULSD	12,788	DPF & SCR
Freightliner Truck							
Freightliner M-2 2010 Hybrid‡	Cummins ISB 6.7L-325	Eaton	40 kW	325 HP 750 LB/FT	ULSD	1,467	DPF & SCR

DPF = diesel particulate filter; SCR – selective catalytic reduction
* Tested with 350.4 nominal voltage battery
‡ Tested with 370 and 350.4 nominal voltage battery

Heavy-duty Diesel Chassis Dynamometer Test Facility

Testing was carried out on UCR's Heavy-Duty Chassis Dynamometer (HDCD) (see Figure 36, page 3D-44 for details). The dynamometer is designed to handle a range of vehicles and vehicle loads at on-road driving conditions. It includes a 48" Electric AC Chassis Dynamometer with dual, direct connected, 300 horsepower motors attached to each roll set (See Figure 1). The dynamometer applies appropriate loads to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving. A driver accelerates and decelerates following a driving trace while the vehicle is chained to the dynamometer. Emissions are collected and measured with CE-CERT's Mobile Emissions Laboratory (MEL), as described later in this report.

Figure 1: Selected Data for UCR HDD Chassis Dyno

- Performance
  - 5,000 lb 0-15 mph
  - 600 hp 45-80 mph
  - 200 hp 15 mph
- Acceleration 6 mph/sec
- Inertia Simulation
  - 10 lb increments
  - 10,000 lb – 80,000 lb range
  - 45,000 lb base inertia
- Speed accuracy +/- 0.01 mph
- Acceleration accuracy +/- 0.02 mph/sec
- Response time 44 to 100 ms

Coast down tests, for the BDC trucks, were carried out in which the vehicle is accelerated up to a set speed and then allowed to "coast down" to a lower speed. The coast downs were conducted with a fully loaded and an empty trailer. A coastdown was conducted in Los Angeles with a conventional engine cab plus trailer weighing 59,200 lbs. A coastdown was also conducted in Los Angeles using a conventional engine cab plus trailer weighing 26,320 lbs. The weights were determined on a certified scale prior to the coast down test. A BDC driver conducted the coast downs while a rider from CE-CERT recorded the data. The time it takes to coast down from the higher to lower speed while the vehicle is coasting in neutral is used to determine the vehicle's drag coefficient Cd and coefficient of rolling resistance Crr. These values are then used to determine the appropriate coefficients for the dyno to simulate on-road conditions. The average field coast down data is shown in Table 3. CE-CERT interpolated to determine the dynamometer coefficients shown in Table 4 for the weights corresponding to a trailer being three quarters full and one quarter full, respectively, that were used for this testing.

Table 3: Field Coast Down Data

Vehicle Weight (lbs)	Seconds to coast down for mph range				
	65 - 55	55 – 45	45 – 35	35 – 25	25 - 15
59,200	NA[a]	38.4	45.2	61.0	78.1
26,320	NA	21.4	27.2	35.8	55.5

Governed to 55 mph

Table 4: Dyno Coefficients for the Tests

Test Cycle	Load	A	B:	C:	Hp @ 50
	Lbs	lbs/mph	lbs/mph	lbs/mph	
Heavy	38,975	38.117	11.772	0.0043	85.00
Light	30,858	39.860	9.827	0.0231	78.53

For the Freightliner hybrid truck, emission measurements were only made for the 38,975 lb. load using the coefficients in Table 4.

Test Operating Schedule

The testing procedure begins by first securing the truck with chains to tie-downs that are part of the HDCD equipment such that the rear (drive) wheels are on the dyno's 48-inch rollers. Next, the vehicle is driven on the rollers for 30 minutes or more until the coolant and oil temperature stabilize. The vehicle operates at the engine power required to maintain the speed at 18 mph with the higher load assigned to the dyno wheels. This approach allows the engine and the mechanical equipment associated with the dyno to reach steady-state.

For the BDC testing, emission testing included the measurement of the primary and dilution exhaust flow rates and the concentrations of total hydrocarbons (THC), Methane (CH4), non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO2), and particulate matter mass with a mean diameter of 2.5 micrometers or less (PM2.5). In addition to measuring mass emissions for these pollutants, a number of engine parameters were recorded during the testing, including exhaust temperature, both dyno and engine RPM, horsepower, engine exhaust pressure, electronic fuel delivery and electronic load. Other measurements included: elevation, cycle duration, ambient temperature and pressure, humidity and ambient gas concentrations.

For the later Freightliner testing the same measurements were made, except that there was no measurement of particulate matter. In addition, for this testing temperature measurements were made before and after the DPF.

Testing for the BDC project was done over two cycles designed to represent in-use conditions for the BDC fleet. These cycles are shown in Figure 2 and Figure 3. The test cycles were developed based on microtrips from activity classified according to "heavy" and "light" loads. Calstart also requested that we determine the time to accelerate from 0 to 20 mph. Triplicate runs were carried out for each of the test cycles. The operating schedule for these tests was as follows:

1. Preliminary runs

   a. Mount cab on dyno rollers and tie it down.

   b. 15-20 minute warm up of dyno and vehicle engine. Engine on, transmission in neutral, dyno running at 45 mph. Engine coolant temperature and engine oil temperature are checked to verify the engine is warmed up. If the temperatures indicate the engine isn't completely warmed up then a short warm up trace can be run.

   c. Run coastdown testing to determine dyno coefficients that match road coefficients.

2. Daily runs

   a. Hot start test following the Calstart BDC Heavy (38,975 lbs.) cycle to warm up vehicle. Emissions not measured.

   b. 20 minute key off soak.

   c. Hot start test, with emissions testing, following the Calstart BDC Light (30,858 lbs.) cycle.

   d. Immediately following, the time to accelerate from 0 to 20 mph was determined without emission measurements.

   e. 20 minute key off soak.

   f. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

   g. Immediately following, the time to accelerate from 0 to 20 mph was determined without emissions measurement.

   h. 20 minute key off soak.

   i. Hot start test, with emissions measurements, following the Calstart BDC Light cycle.

   j. Immediately following, the time to accelerate from 0 to 20 mph was determined without emissions measurements.

   k. 20 minute key off soak.

   l. Hot start test, with emissions measurements, following the Calstart BDC Heavy cycle.

   m. Immediately following, the time to accelerate from 0 to 20 mph was determined without emissions measurement.

   n. 20 minute key off soak

   o. Hot start test, with emissions measurements, following the Calstart BDC Light cycle.

   p. Immediately following, the time to accelerate from 0 to 20 mph was determined without emissions measurements.

   q. 20 minute key off soak.

r. Hot start test, without emissions measurements, following the Calstart BDC Heavy cycle.

s. Immediately following, the time to accelerate from 0 to 20 mph was determined without emissions measurements.

t. End of engine testing.

The test schedule for the hybrid cab was identical, except that item 1.c was not necessary, as the dyno coefficients determined for the conventional engine were used for the hybrid engine.

Figure 2: Driving schedule composed of micro trips from activity classified as "Heavy"

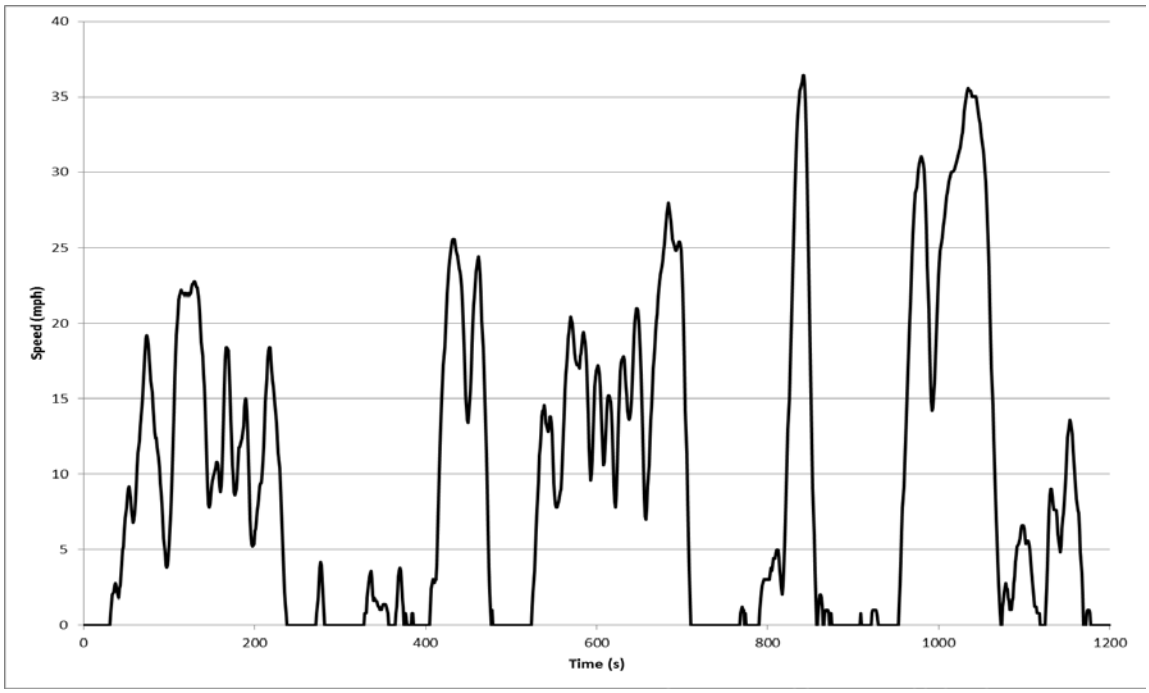
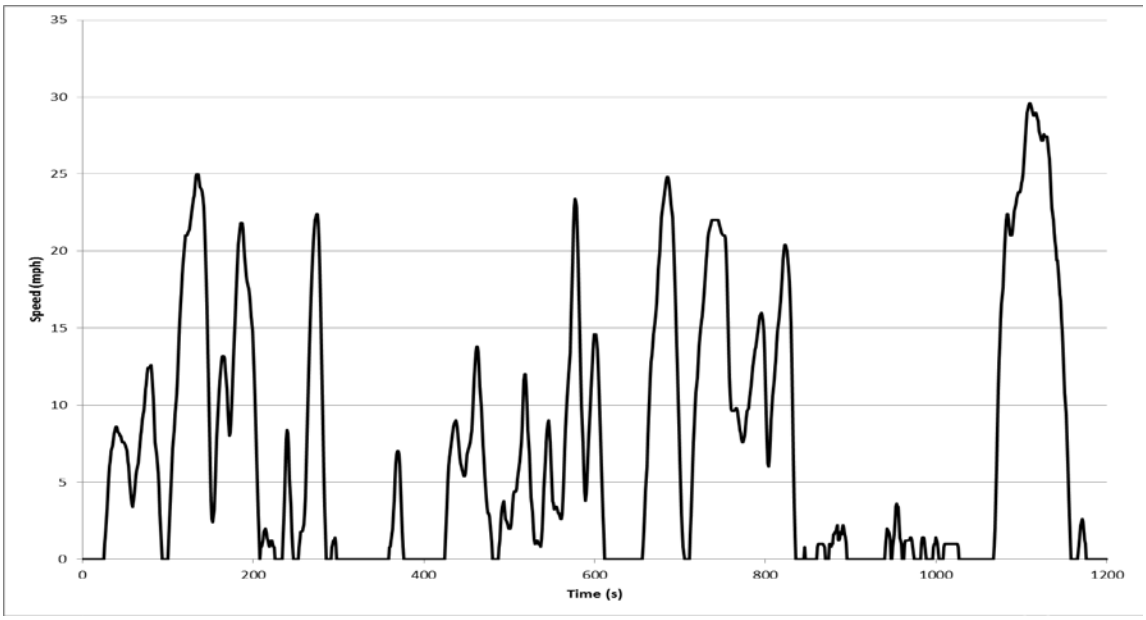


Figure 3: Driving schedule composed of micro trips from activity classified as "Light"



For the later Freightliner project, the vehicle was tested over the transient cycle shown in Figure 2 to determine emissions and fuel economy for driving operations of the truck. This vehicle was only tested with the "heavy" cycle since it was expected that stronger effects for fuel economy and emissions would be seen for this vehicle. This vehicle was also tested with two battery configurations (370 volt and 350.4 volt) to provide a comparison with the battery configuration used in the initial round of testing. The 350.4 volt battery is more comparable to that used in the original BDC hybrid, whereas the 370 volt battery is the one being used in the currently newer version of the technology. To provide a more direct comparison with the BDC hybrid, the ECM was also reflashed to older algorithm when the switch to the older battery was made.

For the newer Freightliner hybrid, it was also decided to run some additional tests with a 1 minute engine off soak, as opposed to a 20 minutes engine off soak. This was to investigate some observed trends in the emissions that it was postulated could be due to cooler catalyst temperatures for the hybrids, particularly when the electric motor is powering the vehicle.

Five test runs were made with the 370 volt battery with a 20 minute soak between the first three runs and a 1 minute soak between runs 3 and 4 and 4 and 5. The 370 volt battery was then disconnected and the 350.4 volt battery connected and the electronic control module reflashed to the same algorithm used for the BDC trucks. This process took less than 20 minutes so test run #6 began after a 20 minute engine off soak. Tests 7 and 8 also had a 20 minute engine off soak while tests 9 and 10 were run after a 1 minute engine off soak.

The operating schedule for the Freightliner was as follows:

Preliminary run (vehicle has 370 volt battery in place)

a. Mount cab on dyno rollers and tie it down.

b. 15-20 minute warm up of dyno and vehicle engine. Engine on, transmission in neutral, dyno running at 45 mph. Engine coolant temperature and engine oil temperature are checked to verify the engine is warmed up. If the temperatures indicate the engine isn't completely warmed up then a short warm up trace can be run.

c. Run coastdown testing to determine dyno coefficients that match road coefficients.

d. Hot start test following the Calstart BDC Heavy (38,975 lbs.) cycle to warm up vehicle. Emissions not measured.

e. 20 minute key off soak.

f. Hot start test, with emissions testing, following the Calstart BDC Heavy cycle.

g. 20 minute key off soak.

h. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

i. 20 minute key off soak.

j. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

k. 1 minute key off soak.

l. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

m. 1 minute key off soak.

n. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

o. Replace 370 volt battery with 350.4 volt battery and reflash electronic control module to settings used for BDC hybrid. (~15 minutes to complete). Total key off time of 20 minutes.

p. Hot start test, with emissions testing, following the Calstart BDC Heavy cycle.

q. 20 minute key off soak.

r. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

s. 20 minute key off soak.

t. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

u. 1 minute key off soak.

v. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

w. 1 minute key off soak.

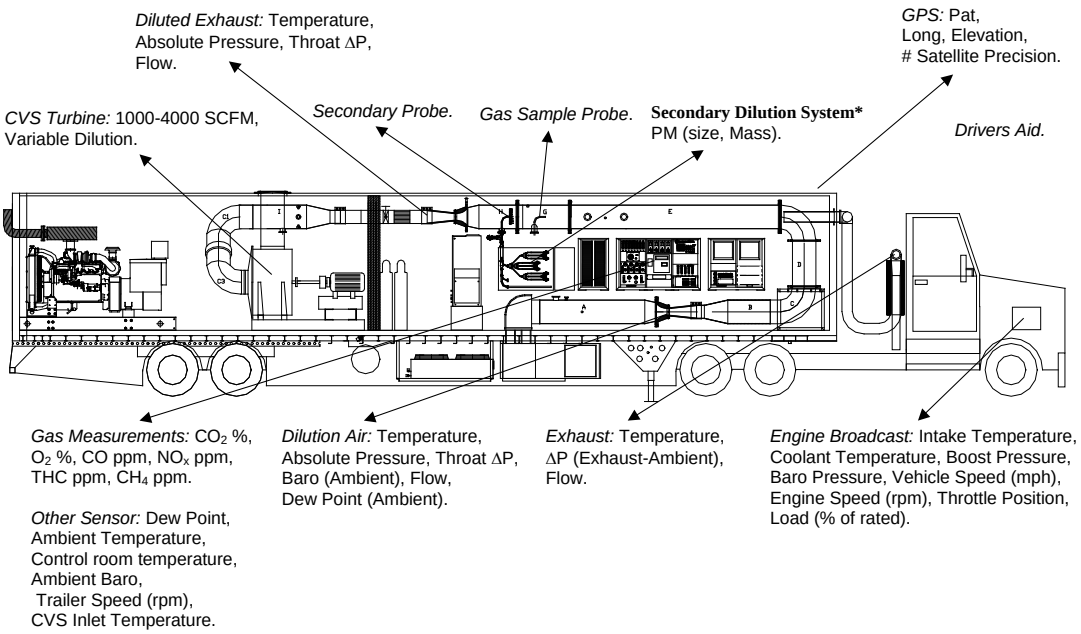
x. Hot start test, with emissions measurement, following the Calstart BDC Heavy cycle.

y. Testing completed

Measurement of Gas Concentration and Flow Rates

The sampling and measurement methods of mass emission rates from heavy-duty diesel engines are specified in detail in Title 40 of the Code of Federal Regulations (CFR), *Protection of the Environment*, Part 1065. UCR's unique mobile, heavy-duty diesel laboratory (MEL), Figure 4, is designed and operated to meet those specifications. MEL is a complex laboratory that was verified against the California Air Resources Board's (CARB's) heavy-duty diesel lab, the Department of Energy (DOE) lab in Denver, and a laboratory at the Southwest Research Institute (SwRI) in San Antonio. MEL routinely measures a wide range of gaseous species and particulate emissions from diesel engines. The capabilities and details of the MEL design and specifications are described in Cocker[62,63].

Figure 4: Major Systems within UCR's Mobile Emission Lab (MEL)



The total exhaust gases from the vehicle enter the primary tunnel in the mobile emission lab where they are diluted with filtered ambient air. The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) Venturi and dynamic flow controller. The SAO Venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system

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[62] http://eprints.cert.ucr.edu/510/

[63] http://eprints.cert.ucr.edu/511/

with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from 1,000 to 4,000 standard cubic feet per minute (scfm) with accuracy of 0.5 percent of full scale. It is capable of total exhaust capture for engines up to 600 kilowatts (kW). Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs used in the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NOx, methane (CH4), THC, CO, and CO2 at a frequency of 1 hertz (Hz) and were selected based on optimum response time and on road stability. Two hundred (200) liter (L) Tedlar bags are used to collect dilution air samples over a complete test cycle to correct for background concentrations of pollutants. In the design, eight bags are suspended in the MEL allowing eight test cycles to be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). As originally designed, four bags were used to collect tunnel samples over a complete test cycle and four were used to collect dilution air samples over a complete test cycle. Currently, tunnel concentrations are measured on a second by second basis over the test cycle and the concentrations summed and then the background concentrations from the dilution air bag subtracted. A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in Table 5 below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Table 5: Summary of Gas-Phase Instrumentation in MEL

Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH4	30/100/300/1000 (ppmC)	FID

During the Calstart truck testing exhaust flow and concentrations of CO, CO_2, NO_x, CH_4, THC and NMHC were measured. Gas phase samples were extracted and the diluted samples are analyzed second-by-second (modal data). The modal data is summed over the complete cycle to produce the integrated data for the report.

The particulate matter (PM) is passed through a secondary dilution tunnel and collected on pre-weighed Teflon filter paper. Following the conclusion of a test cycle the Teflon filters are removed, placed in the bottom half of a filter cassette, covered with the top half of the filter cassette, taken to the weighing room, and placed in a humidity and temperature controlled glove box to equilibrate before being reweighed to determine the total PM collected.

Measurement of Battery State of Charge

There are several methods for estimating the State of Charge (SOC) of a battery, including methods which depend upon voltage measurements or current measurements. We employed a

Hioki 3390 power meter to measure both voltage and current on a second by second basis over the full cycle of each test.

Quality Assurance and Quality Control Requirements

From an overview perspective, there are numerous quality control (QC) and quality assurance (QA) procedures built into the operation of MEL, mainly due to the requirements of the Code of Federal Regulations (CFR). Title 40 of the CFR specifies a number of quality control and quality assurance requirements in order to meet the Environmental Protection Agency (EPA) protocols for measurement of emissions from heavy-duty diesel engines. CE-CERT meets all the quality control and quality assurance requirements specified in Title 40 CFR.

The MEL uses precision gas blending to obtain required calibration gas concentrations. Calibration gas cylinders, certified to 1 percent, are obtained from Scott-Marin Inc. (Riverside, CA). By using precision blending, the number of calibration gas cylinders in the lab is reduced and cylinders need to be replaced less frequently. The gas divider contains a series of mass flow controllers that are calibrated regularly with a Bios Flow Calibrator (Butler, New Jersey) that produces the required calibration gas concentrations within the required ±1.5 percent accuracy.

Computer Data Files

Equipment test selections, configurations, and test sequences are automated by configuration files. Each configuration file specifies a complete sequence of test and QC operations. During the sequence of operations specified in configuration files, the data from all channels are recorded at a rate of 1 Hz or faster in a raw test results data file. The configuration file and associated data file are identified by a test identification (ID) number. The test ID numbers are assigned based on date and time of day. Each day of testing consists of a pre-test calibration and post-test calibration. When multiple tests are done in one day, the post-test calibration becomes the pre-test calibration for the next test.

Results

This section discusses the test results, including any modification of the plan for testing described in the Project Overview section

Emissions Testing Results

Emissions and flow data were collected in triplicate for the each truck, while running on the two transient cycles discussed in the Laboratory Test (Emissions Test) section, on the CE-CERT dyno seen below (Figure 5).

Figure 5: BDC Conventional Truck on CE-CERT Heavy Duty Chassis Dyno

Testing went well as the driver was able to follow the transient cycles without any difficulty. Simultaneously data was collected with the MEL, the chassis dynamometer and from the Electronic Control Module (ECM). The ECM data included percent load, fuel rate, temperatures, engine torque, and engine speed amongst others. From these data, we calculated the mass emissions rate per unit time, per distance, and per gallon of fuel.

Integrated Gaseous Emission Results

The emission and fuel economy results for the BDC trucks and additional Freightliner hybrid are presented in Table 6 in g/mile, g/gal fuel, and mpg units, respectively. The average emissions and fuel economy presented in Table 6 are not corrected for any differences in the State of Charge of the battery, which is discussed in greater detail in the Service and Maintenance Evaluation section. The emissions and fuel economy are an average of 6 measurements for the conventional truck and three measurements for the hybrid truck. During the testing of the conventional truck on the first day the particulate matter did not get collected because of a problem with flow through the filter. Therefore three additional tests were run a few days later. The Emissions and Fuel Usage Results section presents the integrated data for each of the cycles individually.

Table 6: Emissions and Fuel Economy of Conventional and Hybrid Trucks using g/mile, g/gal fuel, and mpg, respectively

	Emissions (g/mile)						Emissions (g/gal fuel)						Carbon Balance Fuel	
	THC	CH_4	NMHC	CO	NO_x	CO_2	THC	CH_4	NMHC	CO	NO_x	CO_2	ECM	Emis-sions
	BDC Conventional, Light Cycle													
Average	-0.105	0.033	-0.139	0.113	2.897	2469	-0.423	0.134	-0.563	0.461	11.750	9955.7	4.72	4.03
Std. Dev.	0.003	0.006	0.008	0.073	1.470	50	0.018	0.025	0.037	0.306	6.234	0.6	0.12	0.08
	BDC Hybrid, Light Cycle													
Average	-0.093	0.036	-0.131	1.787	2.752	1543	-0.601	0.232	-0.842	11.493	17.709	9938.7	6.40	6.44
Std. Dev.	0.004	0.005	0.005	0.575	0.479	15	0.021	0.032	0.029	3.621	2.911	5.6	0.04	0.07
	BDC Conventional, Heavy Cycle													
Average	-0.078	0.026	-0.106	0.138	3.009	2380	-0.327	0.111	-0.443	0.476	12.551	9955.2	4.68	4.18
Std. Dev.	0.005	0.007	0.008	0.076	0.902	36	0.024	0.031	0.040	0.376	3.640	0.6	0.12	0.06
	BDC Hybrid, Heavy Cycle													
Average	-0.064	0.033	-0.098	2.882	3.939	1645	-0.386	0.201	-0.593	17.369	23.761	9928.8	6.19	6.03
Std. Dev.	0.002	0.002	0.002	0.521	0.365	22	0.005	0.011	0.009	2.945	1.906	4.6	0.05	0.09
	Freightliner Hybrid, New Battery, 20 minutes between Heavy Cycles													
Average	-0.144	-0.001	-0.144	0.163	3.016	1526	-0.964	-0.018	-0.956	1.060	19.606	9956.2	6.27	6.53
Std. Dev.	0.096	0.041	0.057	0.030	0.493	81	0.696	0.274	0.429	0.066	2.295	2.3	0.21	0.35
	Freightliner Hybrid, New Battery, 1 minute between Heavy Cycles													
Average	-0.268	-0.051	-0.219	-0.075	1.757	1336	-1.994	-0.380	-1.630	-0.557	13.120	9961.8	6.50	7.45
Std. Dev.	0.004	0.010	0.006	0.032	0.319	24	0.007	0.065	0.073	0.232	2.610	0.3	0.23	0.13
	Freightliner Hybrid, Old Battery, 20 minutes between Heavy Cycles													
Average	-0.153	-0.002	-0.153	0.311	2.390	1519	-1.020	-0.021	-1.009	2.042	15.728	9954.8	6.08	6.56
Std. Dev.	0.108	0.055	0.054	0.011	0.448	48	0.754	0.369	0.395	0.098	3.385	2.1	0.06	0.21
	Freightliner Hybrid, Old Battery, 1 minute between Heavy Cycles													
Average	-0.288	-0.069	-0.221	-0.175	2.049	1404	-2.043	-0.487	-1.572	-1.241	14.533	9963.0	6.27	7.10
Std. Dev.	0.003	0.008	0.005	0.003	0.146	29	0.020	0.047	0.068	0.005	0.733	0.1	0.07	0.15

This table shows that, on a g/mile basis, the BDC and Freightliner hybrids have lower CO2 emissions and higher fuel economy on a mpg basis than the conventional engine for both cycles. The reductions in CO2 and increases in fuel economy were 37.5 percent and 59.8 percent for the light cycle, and 30.9 percent and 44.3 percent, respectively, for the BDC hybrid. For the Freightliner truck, the reductions in CO2 and increases in fuel economy were 35.9 percent and 56.2 percent, respectively for the new battery with a 20 minute key off soak between cycles. With the old battery, and the 20 minute key off soak, these percentages were 36.2 percent and 56.8 percent, respectively. This is consistent with previous studies that have shown fuel economy reductions for similar hybrid configurations and indicates that the in-use fuel economy improvements and CO2 reductions with the hybrid technology are significant. On a g/gal fuel basis the CO2 emissions are essentially the same for the conventional and the hybrid trucks on both test cycles. This is expected since CO2 is essentially a direct measure of the fuel being used by the engine.

Plots of the modal CO2 emissions are presented in Figure 6 and Figure 7. In these plots the internal combustion engine for the hybrid vehicle is doing less work than the conventional engine when the red line is lower than the black line. In Figure 6 the pneumonics CL1 and HL1 refer to the first test of the conventional and hybrid, respectively, run on the light cycle and in Figure 7 the pneumonics CH1 and HH1 refer to the first test of the conventional and hybrid, respectively, run on the heavy cycle. These figures show that the CO2 emissions for the hybrid are less than those for the conventional vehicle for a majority of the cycle, with the exception of periods when the vehicle shows emissions spikes due to accelerations.

Figure 6: Modal Emissions of CO2 for Conventional and Hybrid Engines over the Light Cycle

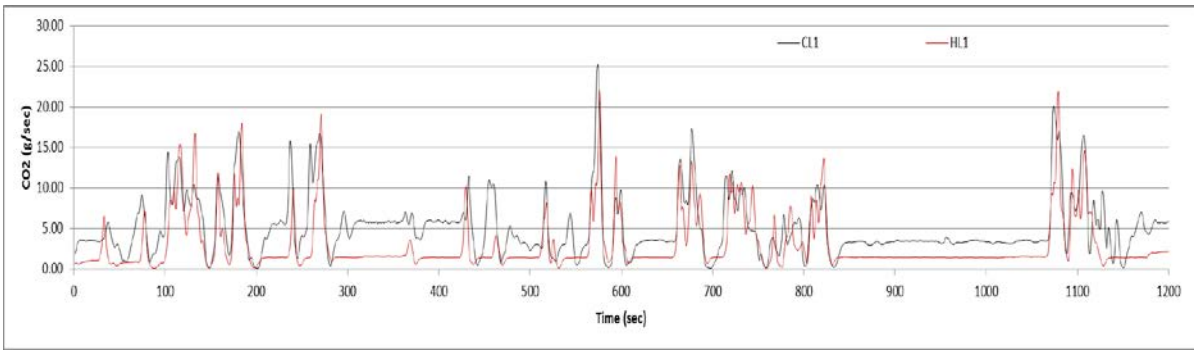
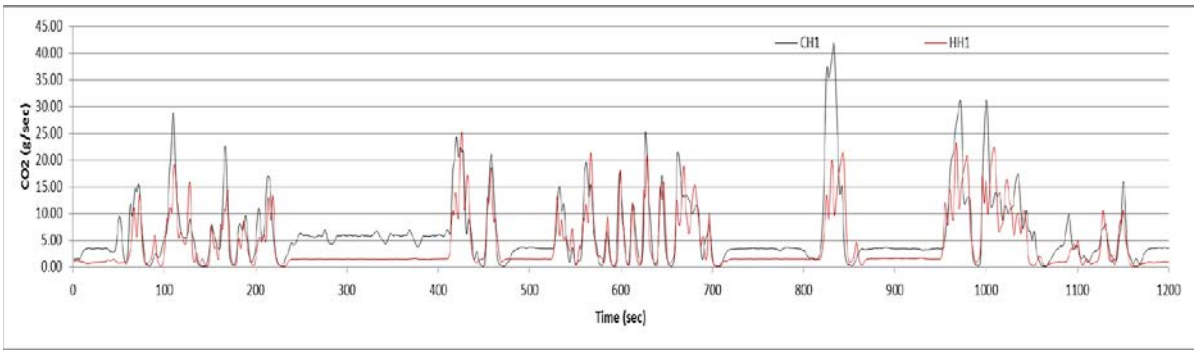


Figure 7: Modal Emissions of CO2 for Conventional and Hybrid Engines over the Heavy Cycle



In Table 6 the fuel economy is reported by the carbon balance based upon reported fuel usage in cc/sec by the engine Electronic Control Module (ECM) (converted to mpg) and as calculated from the measured emissions of CO2, CO, and total hydrocarbons (THC) in g/sec (called the Carbon Balance Method, converted to mpg). While the correlation between ECM based fuel use and emissions based fuel use is quite good, as can be seen in Figure 8 and Figure 9, the calculation based upon emission results is considered to be a better estimate of fuel economy, and is the method used to determine fuel economy in certification tests.

The THC and NMHC emissions were negative for all test conditions. This is due in part to the emissions levels being close to the background levels in the dilution tunnel. This may also indicate that the catalyst destroys 100 percent of the THC and NMHC emitted by the engine and some of the THC and NMHC in the ambient air. The average CH4 emissions were negative for the Freightliner hybrid for all test conditions, so the catalyst on this truck may also be capable of destroying 100 percent of the engine emitted CH4 and some of the CH4 in the ambient air.

Figure 8: Comparison of Fuel Usage by Carbon Balance Based upon Emissions versus Based upon ECM for the Conventional Truck

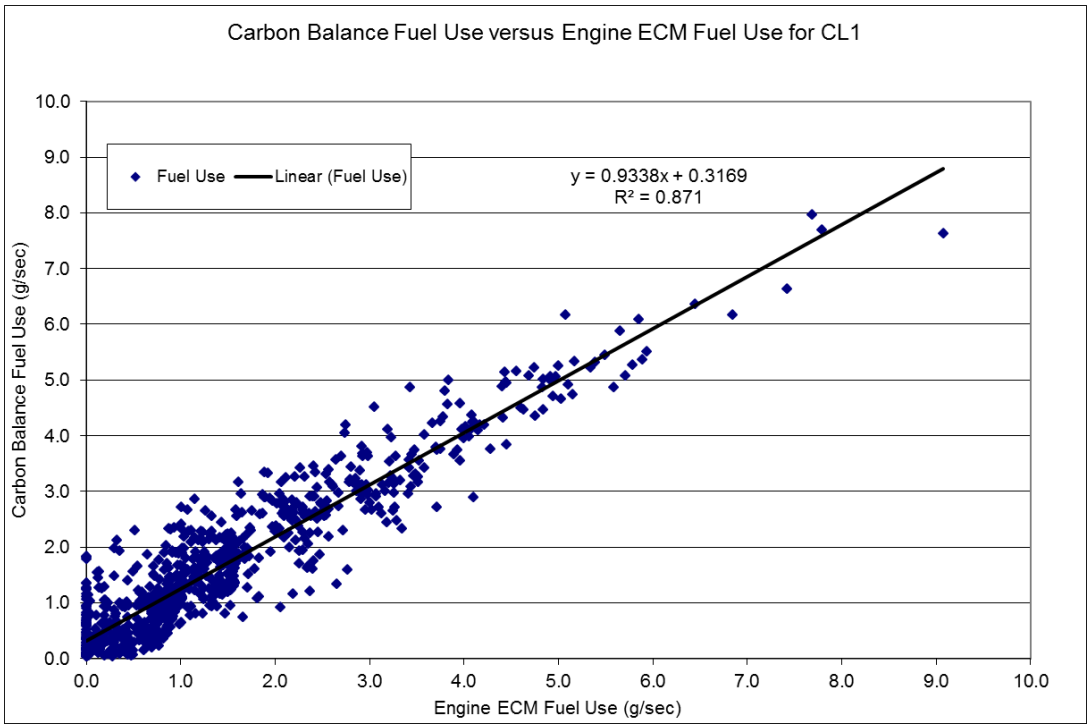
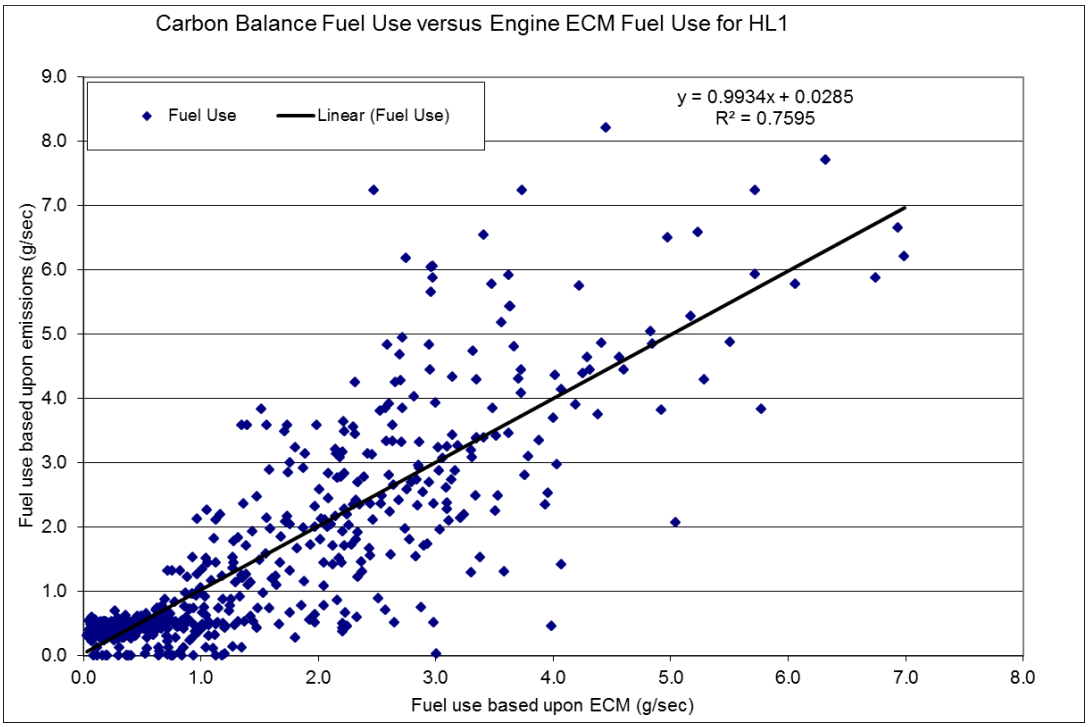


Figure 9: Comparison of Fuel Usage by Carbon Balance Based upon Emissions versus Based upon ECM for the Hybrid Truck



Interestingly, the BDC hybrid had higher CO emissions than the conventional engine for both cycles. The second Freightliner hybrid also had higher CO emissions than the conventional engine when a 20 minute key-off soak was used between the test cycles, although its CO emissions were considerably lower than those for the older technology BDC hybrid. With a 1 minute key-off soak, however, the CO emissions for the Freightliner hybrid were negative. These results were somewhat unexpected, but the disappearance of the CO emissions with a 1 minute key-off soak seems to indicate that the higher CO emissions occur during conditions when the catalyst temperature is at lower levels, as discussed below. It should be noted that the CO emissions for all vehicles appear to be well below the certification levels. The emissions results cannot be directly compared with certification results; however, since the certifications are done on an engine dynamometer, as opposed to on a vehicle chassis.

The NOx emissions for the BDC hybrid were lower for the light cycle and higher for the heavy cycle than the conventional vehicle. The NOx emissions from the Freightliner hybrid were approximately the same as those from the conventional vehicle for the 20 minute key-off soak with the new battery, and lower than the conventional vehicle for the 20 minute key-of soak with the old battery and lower for both batteries for the 1 minute key-off soak.

It should be noted that the relevance of the higher CO and NOx emissions for the hybrid to in-use emissions is not clear since we do not know how often or for how long during a typical day the engines experience a key off hot soak.

Second by Second Results

The high CO emissions for the BDC hybrid truck relative to the conventional truck for both cycles and the high NOx emissions for the hybrid truck relative to the conventional truck for the heavy cycle were unexpected. The modal data (second by second data) were examined in more detail to provide an explanation for these results. Figure 10 through Figure 15 present some plots of the modal results for CO and NOx. The plots for CO show spikes at various points in the cycle for the hybrid, while the conventional truck does not. In general, these spikes occur at the beginning of accelerations from nearly 0 mph to >= 20 mph. The NOx modal results are not as consistent, as over the course of the cycle sometimes the NOx emissions are higher for the conventional truck and sometimes they are higher for the hybrid truck. Additionally, some individual tests results for the NOx for the heavy cycle for the BDC hybrid showed higher emissions than the hybrid for some tests, but not for others.

Figure 10: Comparison of CO Modal Emissions for CL1 and HL1

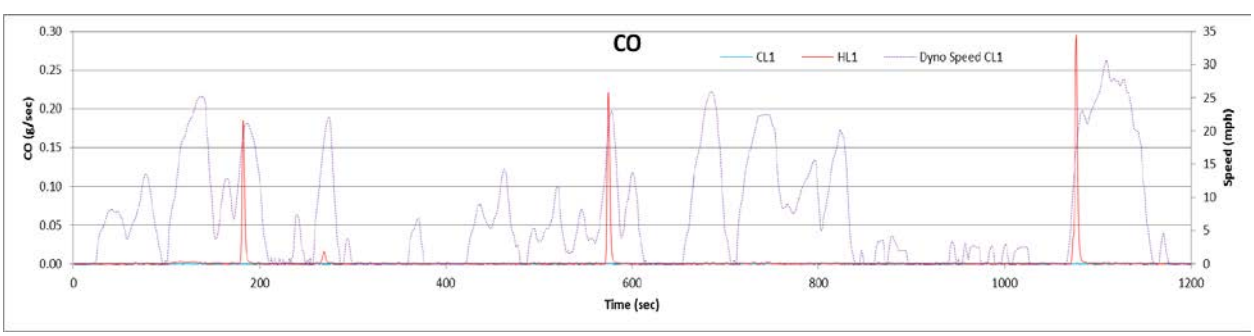


Figure 11: Comparison of CO Modal Emissions for CL1 and HL1 with expanded Vertical Scale

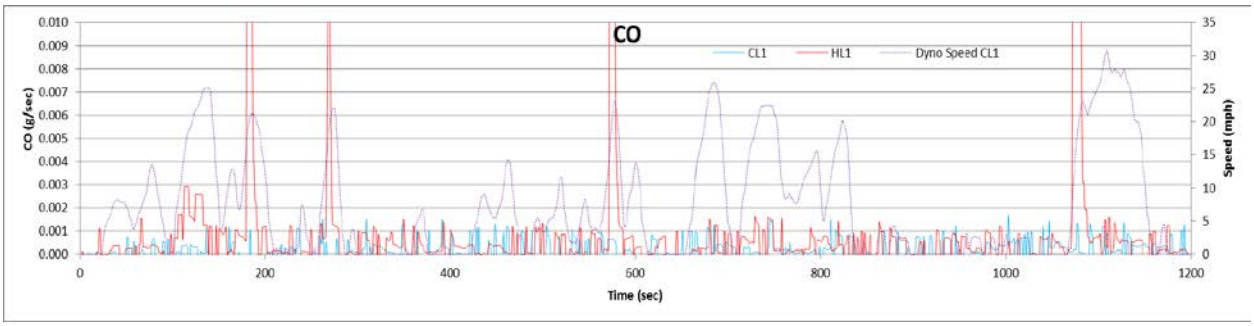


Figure 12: Comparison of CO Modal Emissions for CH1 and HH1

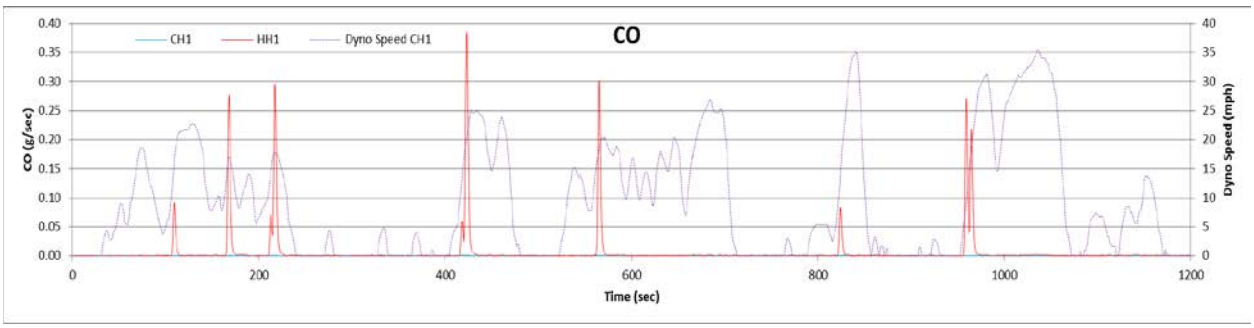


Figure 13: Comparison of CO Modal Emissions for CH1 and HH1 with expanded Vertical Scale

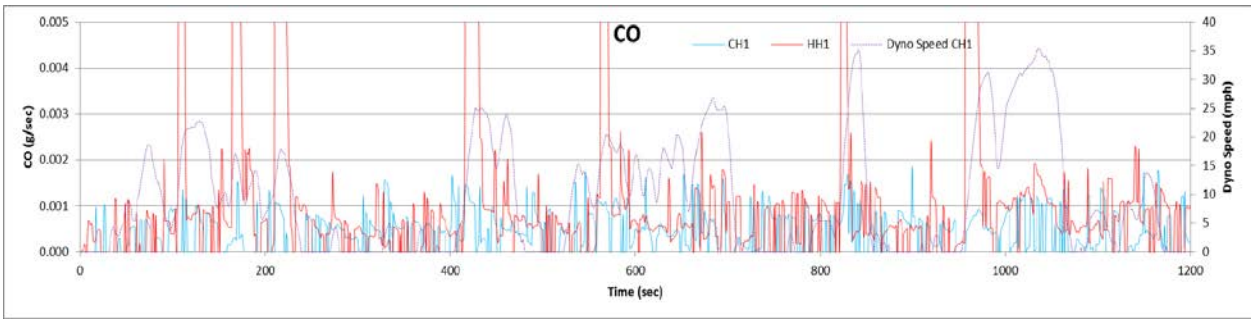


Figure 14: Comparison of NOx Modal Emissions for CL1 and HL1

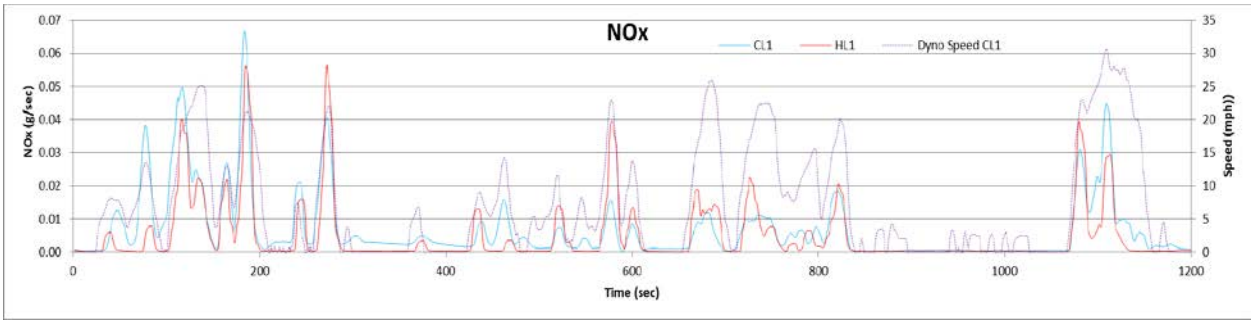
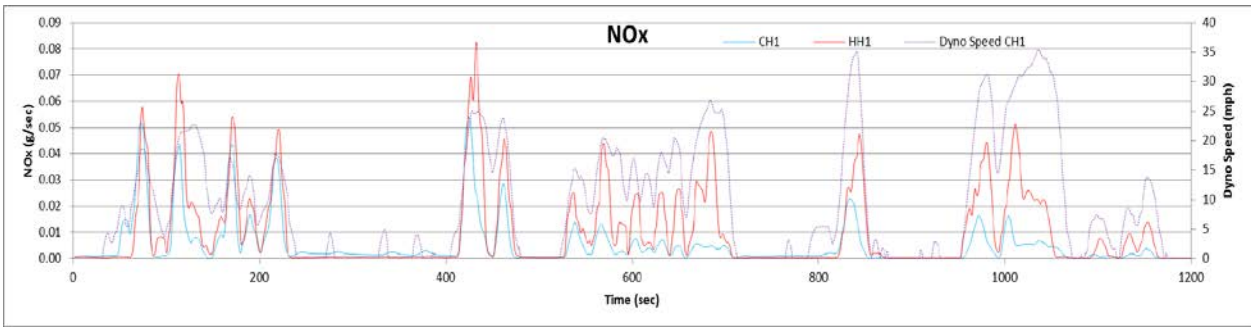


Figure 15: Comparison of NOx Modal Emissions for CH1 and HH1



Further insight into the trends in CO and NOx emissions can be obtained by evaluating the exhaust temperature as a function of time. The DPF and SCR systems both require temperatures of ~200°C-250°C to effectively reduce THC, CO, and the Soluble Organic Fraction (SOF) of PM and NOx, respectively. At elevated temperatures the oxidation of CO to CO2 depends on catalyst size and design. We did not measure the catalyst temperature, the exhaust temperature near the catalyst, or the skin temperature of the catalyst. We did measure the exhaust temperature in our sampling system near the trucks and at the inlet to our CVS system, however. Therefore, we examined the exhaust temperatures to see if they provided a clue as to the high CO and NOx emissions for the hybrid. Figure 16 and Figure 17 show the exhaust temperature measurements near the trucks for tests CL1, HL1 and CH1, HH1, respectively. As can be seen in Figure 5, the conventional truck exhaust came out horizontally behind the cab and our temperature probe was located in our sampling system close to where the sampling system connected to the vehicle exhaust. We do not have a picture of the hybrid vehicle, but the exhaust system on this vehicle vented at the top of the cab. For the hybrid, a U shaped tube was connected to the top of the vehicle exhaust and a straight section back down to an elbow which connected to the horizontal tube, having our temperature sensor, going to our CVS system. Therefore, the exhaust temperature for the hybrid truck was being measured ~14 feet downstream of where it was being measured for the conventional truck. Nevertheless, these temperature plots indicate that the exhaust temperature for the hybrid may not be hot enough in some portions of the cycle to effectively oxidize CO to CO2. However, because the exhaust temperature for the hybrid was measured further downstream, it is not possible to conclusively conclude that the catalyst is not hot enough during some portions of the hybrid testing to remove CO and NOx.

It was also noted that the shifting pattern for the BDC hybrid was rougher than that of the corresponding conventional vehicle. The CO peaks seemed to correlate with hard accelerations where the rough shifting was most noticeable. Therefore, initially, we examined the modal data to determine if there seemed to be a quantitative relationship between shifting and CO spikes. No quantitative relationship was found.

Figure 16: Measured Exhaust Temperatures in Sampling System near to Truck for Tests CL1 and HL1

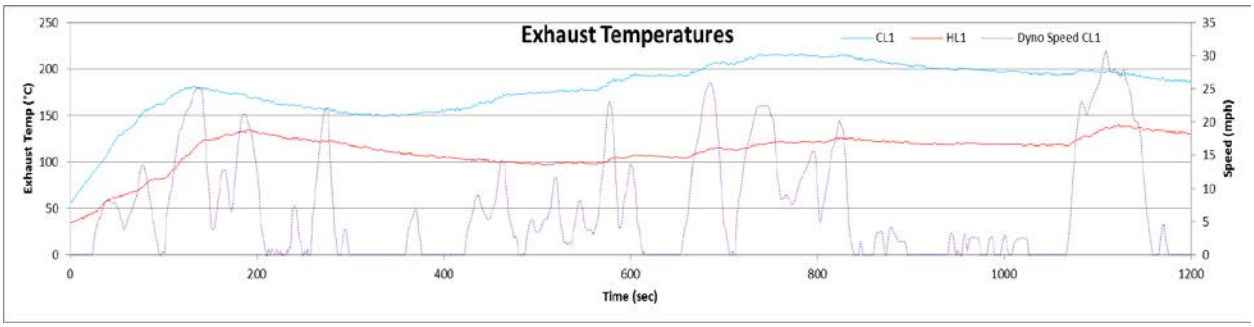
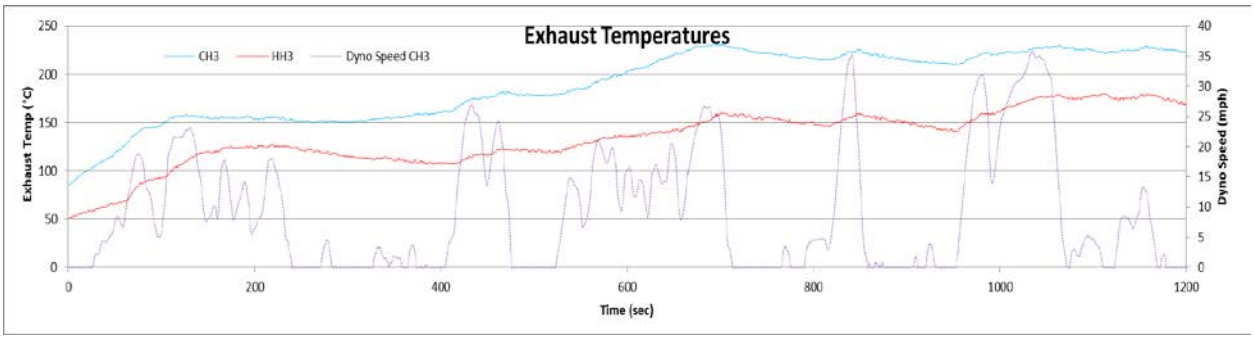


Figure 17: Measured Exhaust Temperatures in Sampling System near to Truck for Tests CH1 and HH1



Plots of the modal CO data for the newer Freightliner are provided in Figure 18 through Figure 27. These figures clearly indicate that the positive CO emissions are related to spikes in the CO concentration which occur in approximately the first 430 seconds of the runs with 20 minute soaks between runs. There are no discernible spikes over the full 1200 seconds of the runs with 1 minute soaks between runs for either the new or the old battery.

For the newer Freightliner thermocouples were installed to measure the temperature before and after the DOC (Figure 35). The average of the temperature measurements before and after the DOC are shown in Figure 18 through Figure 27, and also in Figure 28 and Figure 29 on an expanded vertical scale. With the 20 minute soaks the average DOC temperature was generally below 210°C for the first ~430 seconds of the runs, while with the 1 minute soaks the average DOC temperature was generally above 220°C for the first ~430 seconds of the runs. After the first ~430 seconds of the runs the average DOC temperature for all runs was generally between ~230 °C and ~290 °C. It thus appears reasonable to conclude that the higher CO emissions for the hybrid relative to the conventional are related to the aftertreatment of the exhaust and the catalyst temperature falling below the temperature required for oxidation.

Figure 30 shows the CO modal emissions for all the Freightliner hybrid runs with a 20 minute engine off soak between runs. Figure 31 shows the CO modal emissions for all the BDC hybrid runs with a 20 minute engine off soak between runs. It is noted that beyond 530 seconds there are no CO spikes for the Freightliner data while for the BDC data there are spikes between 550 and 1090 seconds for various runs. While Figure 28 and Figure 29 provide a reasonable

explanation for the lack of CO spikes beyond 530 seconds for the Freightliner data, the reason for CO spikes between 550 and 1090 seconds for the BDC data is not as obvious. Figure 32 through Figure 34 present the temperature at the CVS inlet for the Freightliner tests with the new battery (Figure 32), the old battery (Figure 33), and the BDC tests (Figure 34). This temperature location should be approximately the same distance from the DPF filter exit for both trucks. The CVS inlet temperature for the BDC hybrid runs is generally lower than for the newer Freightliner hybrid runs over the whole range.

Table 7 shows the average CVS Inlet temperature for the first 599 seconds and the last 600 seconds of all hybrid runs with a 20 minute engine off soak between the runs. For the newer Freightliner hybrid the average DOC temperature is shown for the same regions for all runs with a 20 minute engine off soak between the runs. Considering all the data, the CO spikes are consistent with the catalyst temperature being below the temperature required to oxidize the CO to CO2.

Figure 18: CO Modal Emissions for Freightliner Hybrid First Run with New Battery (20 minute soak)

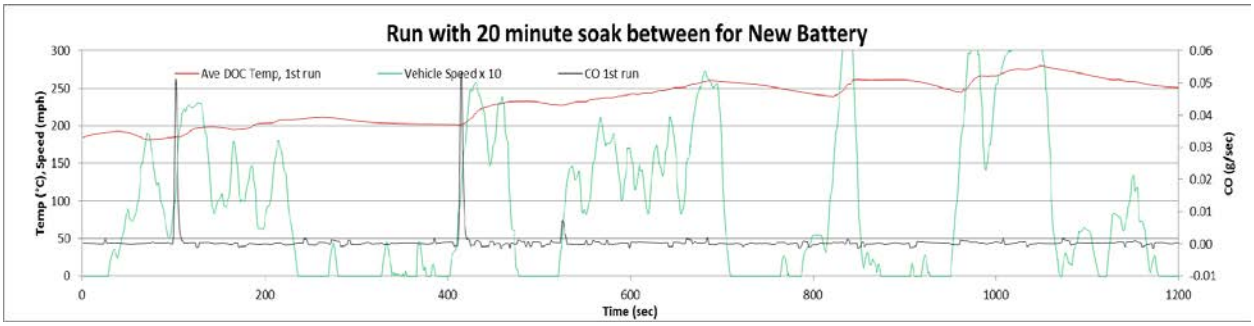


Figure 19: CO Modal Emissions for Freightliner Hybrid Second Run with New Battery (20 minute soak)

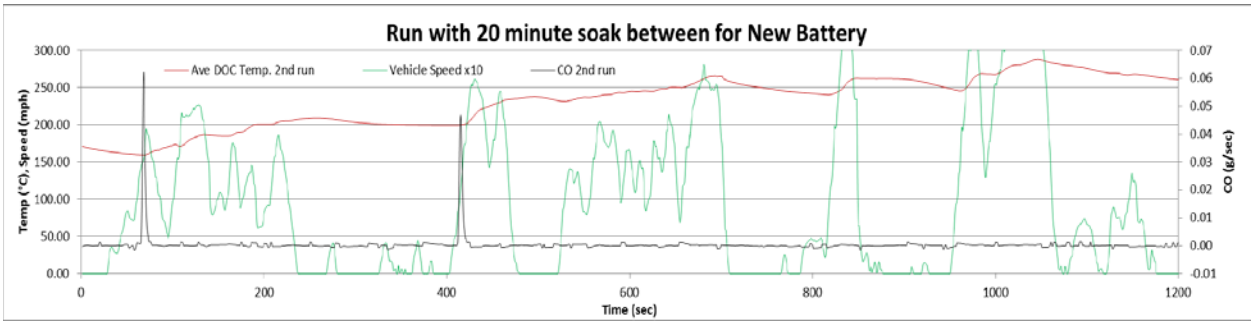


Figure 20: CO Modal Emissions for Freightliner Hybrid Third Run with New Battery (20 minute soak)

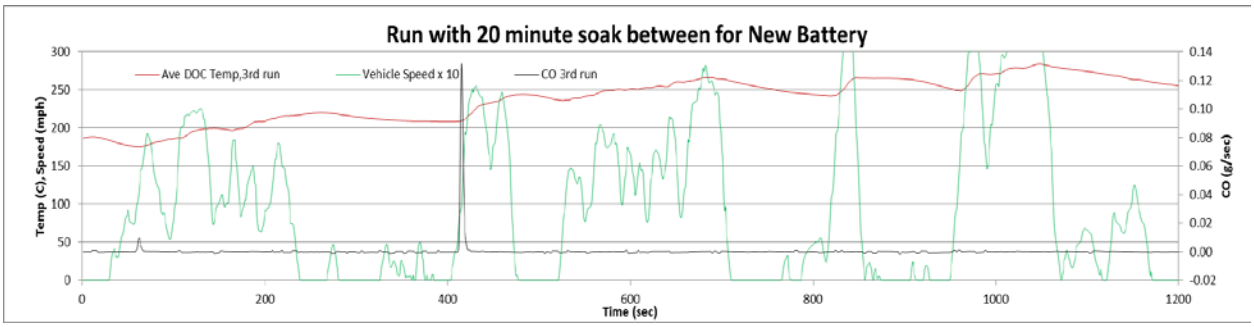


Figure 21: CO Modal Emissions for Freightliner Hybrid Fourth Run with New Battery (1 minute soak)

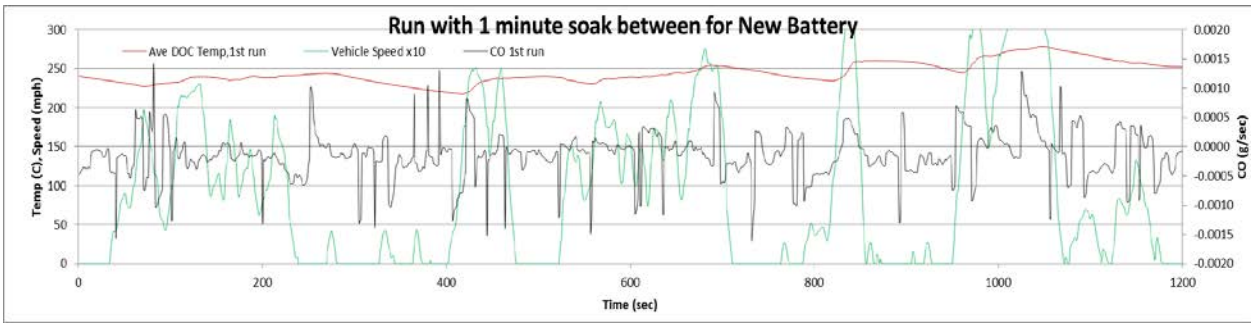


Figure 22: CO Modal Emissions for Freightliner Hybrid Fifth Run with New Battery (1 minute soak)

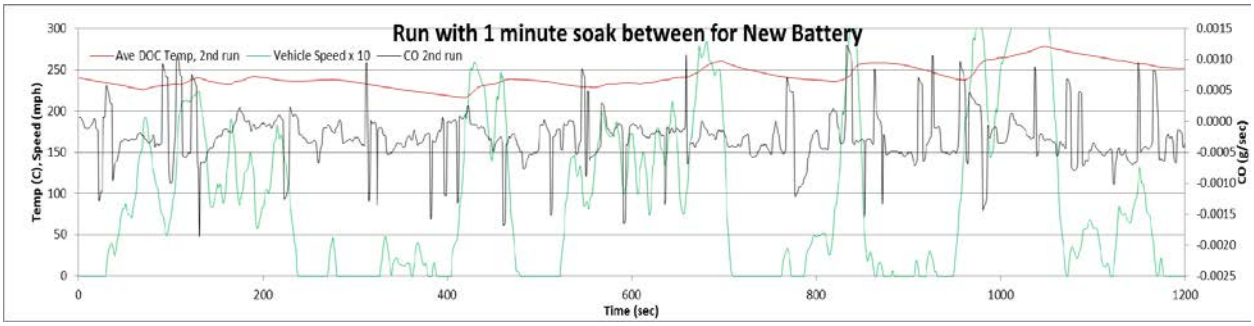


Figure 23: CO Modal Emissions for Freightliner Hybrid First Run with Old Battery (20 minute soak)

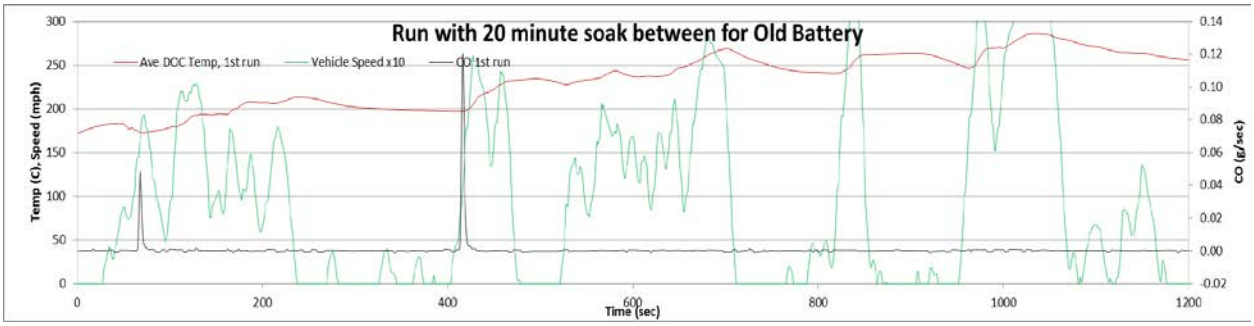


Figure 24: CO Modal Emissions for Freightliner Hybrid Second Run with Old Battery (20 minute soak)

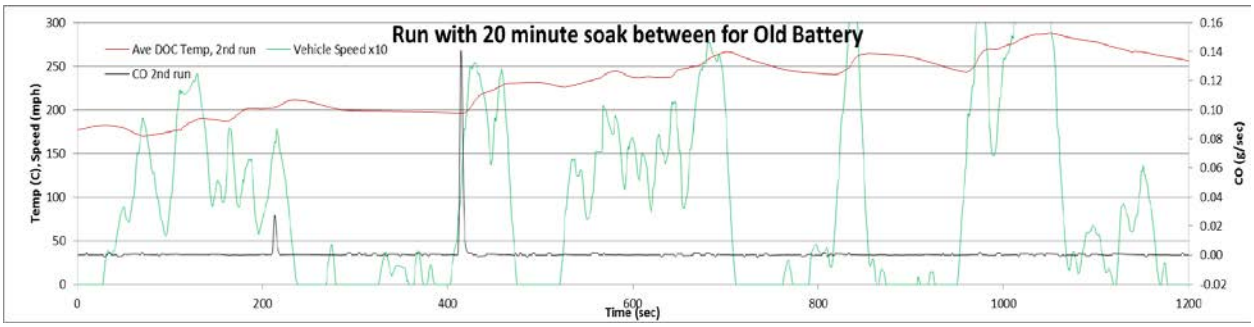


Figure 25: CO Modal Emissions for Freightliner Hybrid Third Run with Old Battery (20 minute soak)

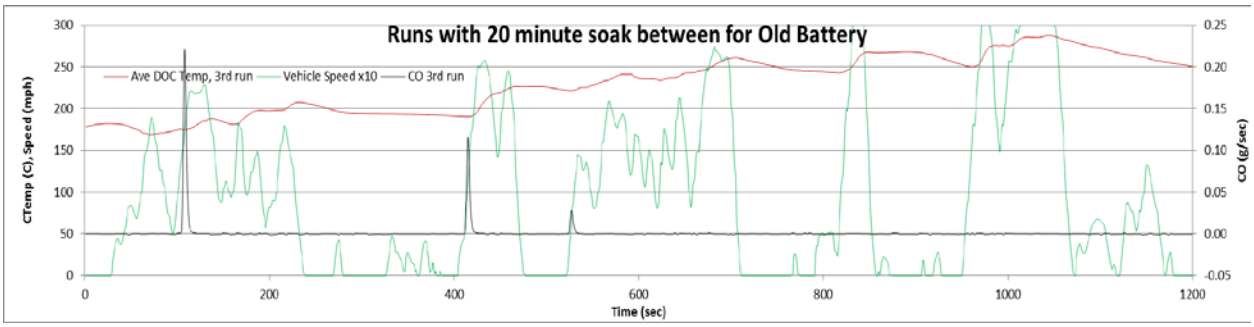


Figure 26: CO Modal Emissions for Freightliner Hybrid Fourth Run with Old Battery (1 minute soak)

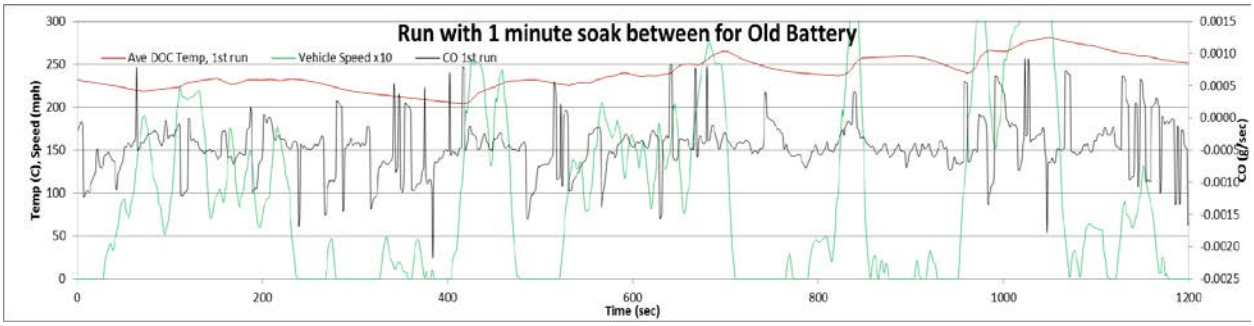


Figure 27: CO Modal Emissions for Freightliner Hybrid Fifth Run with Old Battery (1 minute soak)

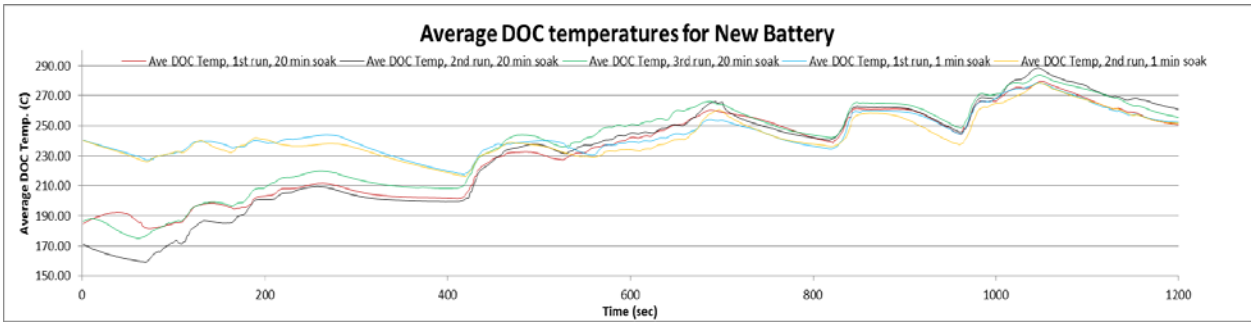


Figure 28: Average DOC Temperatures for runs with the New Battery

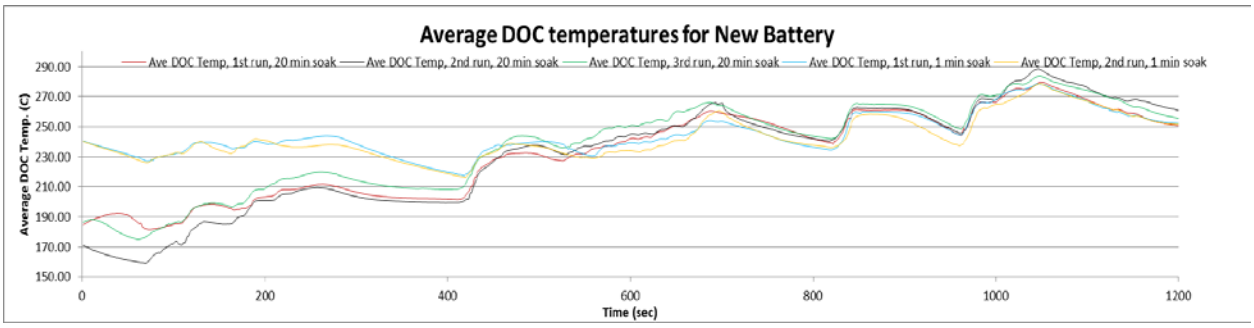


Figure 29: Average DOC Temperatures for runs with the Old Battery

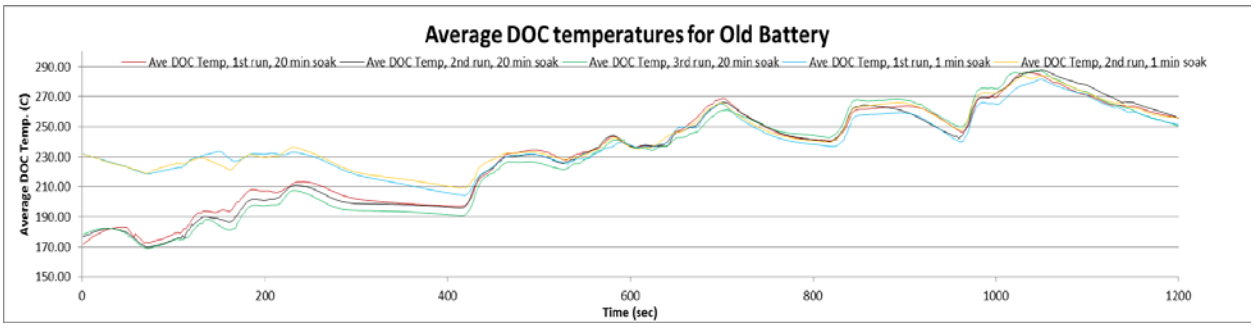


Figure 30: CO Emissions from Freightliner Hybrid for all runs with 20 Minute Engine Off Soak Between Runs

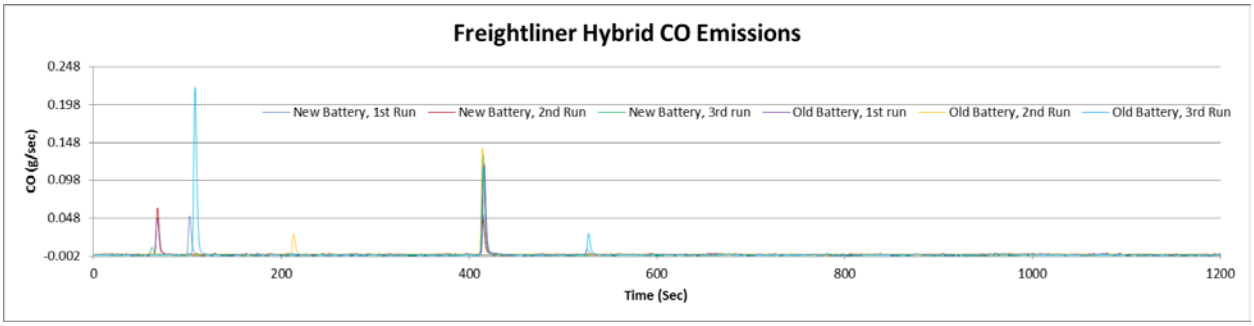


Figure 31: CO Emissions from BDC Hybrid for all Runs

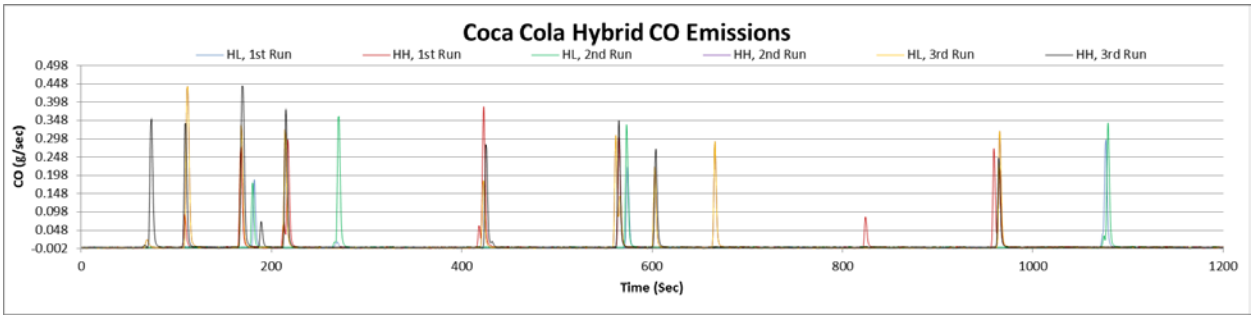


Figure 32: CVS Inlet Temperature for Freightliner hybrid with New Battery

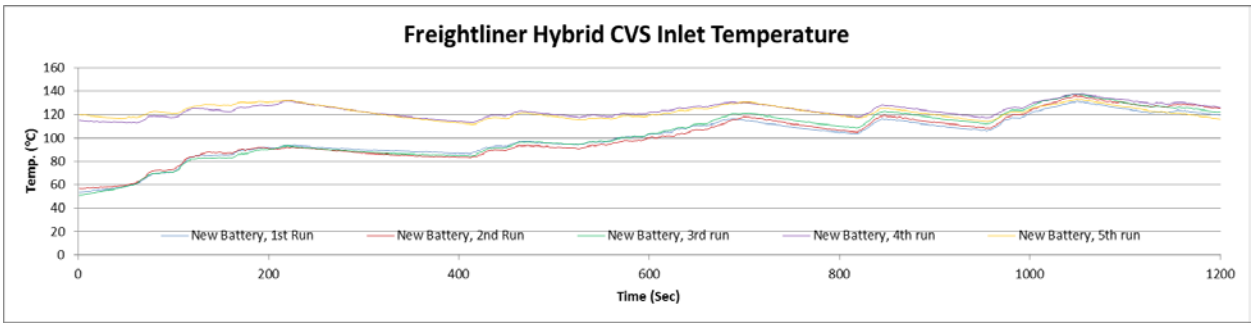


Figure 33: CVS Inlet Temperature for Freightliner hybrid with Old Battery

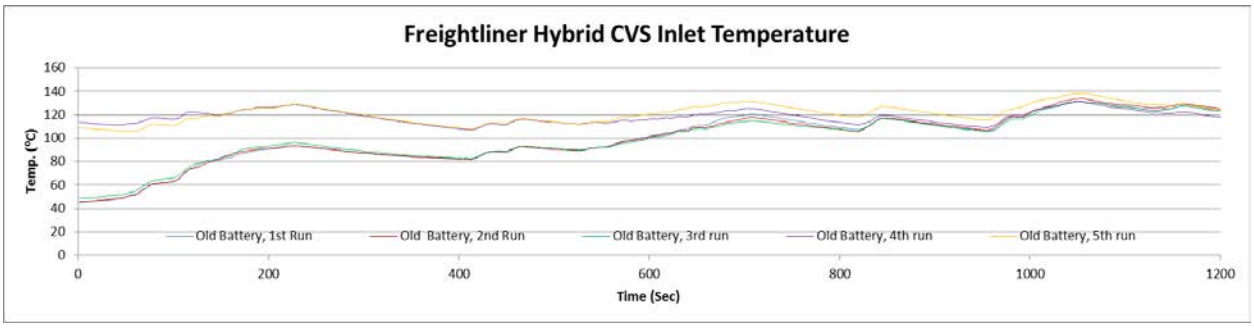


Figure 34: CVS Inlet Temperature for BDC hybrid with Old Battery

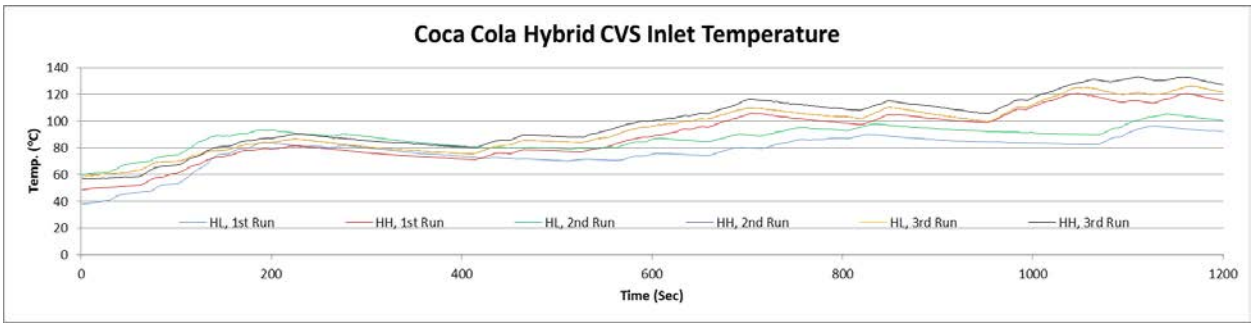


Figure 35: Thermocouple Locations for Measuring Temperatures Before and After the DOC Catalyst

Table 7: Average CVS and DOC Temperatures for all Hybrid runs with 20 minute engine off hot soaks

Average CVS Inlet Temperature (°C)			
Freightliner Hybrid		Coca Cola Hybrid	
1 to 599 Seconds	600 - 1200 Seconds	1 to 599 Seconds	600 - 1200 Seconds
86	115	70	85
85	118	73	106
85	120	82	94
82	117	79	111
82	117	88	101
83	116	82	117
Average DOC Temperature (°C)			
New Battery			
208	258	NM	NM
203	261	NM	NM
213	262	NM	NM
Old Battery			
206	259	NM	NM
204	259	NM	NM
200	260	NM	NM
NM = Not Measured			

State of Charge Considerations

Per SAE J2711[64], the emissions and fuel economy for hybrid vehicles may need correction depending upon the State of Charge (SOC) of the battery. The determination of whether

[64] Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles, SAE J2711, Sept. 2002

correction is needed depends upon the Net Energy Change (NEC) and the Total Cycle Energy (TCE) as shown in equation 1.

$$1\% < \left[\frac{NEC}{TCE}\right](100\%) \leq 5\% \qquad \text{(Eq. 1)}$$

Where:

$$NEC = \left[SOC_{Final} - SOC_{Initial}\right] V_{System} K_1 \qquad \text{(Eq. 2)}$$

$$TCE = TFE - NEC \qquad \text{(Eq. 3)}$$

$$TFE = NHV_{Fuel} m_{Fuel} \qquad \text{(Eq. 4)}$$

SOC_{Final} = Battery SOC at the end of the test run, in ampere-hrs

$SOC_{Initial}$ = Battery SOC at the beginning of the test run, in ampere-hrs

V_{System} = Battery's DC nominal system voltage as specified by the manufacturer, in volts

K_1 = Conversion factor = 3600 (seconds/hour) (not used if SOC_{Final} and $SOC_{Initial}$ values are in amp seconds.)

TFE = Total Fuel Energy

NHV = Net Heating Value of the fuel = 42612 kJ/kg as a typical value for diesel fuel

m_{Fuel} = mass of fuel in kg consumed over the total test cycle

Eaton said the SOC for the 350.4 V battery could be estimated at any time by equation five, and since they did not provide any additional information for the 370 V battery, we used the same equation. However, they were onsite for the Freightliner testing and recorded information from the ECU, including the SOC in their algorithm, and provided that information to us.

$$\%SOC = (V_i - 270)/1.5 \qquad \text{(Eq. 5)}$$

Where V_i = battery voltage at time i

The cycle length for all the BDC hybrid and the Freightliner hybrid tests was 1200 seconds, thus SOC_{Final} and $SOC_{Initial}$ are determined from equation 5 with i = 1200 and i = 0, respectively.

Wayne, et. al.[65] estimated the NEC via equation 6.

$$NEC = \sum_{cycle} (I_{battery} \Delta t) V_{System} K_1 \qquad \text{(Eq. 6)}$$

For measuring emissions and fuel economy of a hybrid, SAE J2711 requires a minimum of 3 test runs over a given driving cycle with determination of the NEC for each cycle. Each emission and fuel economy result is then plotted versus the NEC. Ideally there will be positive and

---

[65] Wayne, W. S., Clark, N. N., Nine, R. D., and Elefante, D., "A comparison of Emissions and Fuel Economy from Hybrid-Electric and Conventional-Drive Transit Buses", Energy & Fuels, 2004, 18, 257-270

negative values for NEC so that each emission can be corrected to NEC = 0 by interpolation instead of extrapolation. When this technique is employed one ends up with a single result for each emission and therefore does not have three values to average and determine a standard deviation and a coefficient of variation. Therefore SAE J2711 suggests determining the coefficient of determination, R^2, of the linear best fit to determine if the collected data is valid. For that purpose the R^2 should be ≥ 0.80.

Table 8 summarizes the NEC from the 3 methods and the tolerance based on the 3 methods. The highlighted tolerances are in the range where SAE J2711 requires a NEC correction. Table 9 summarizes the NEC corrected values for CO_2, CO, and NO_x, the R^2 values, and compares the corrected values with the range based on the average of the three tests ± the standard deviation. The highlighted R^2 in this table equal or exceed the SAE J2711 requirement of 0.80. The corrected values based on equation 5 and based on the Eaton data are essentially the same. With the exception of the Hybrid Heavy Cycle, the corrected values using equation 6 are approximately the same as equation 5. However, in those cases where 3 tests were available the R^2 values were slightly too far below 0.80. Because the ranges based on the standard deviation of the averages generally encompassed the NEC corrected values, and because several NEC corrected values showed a poor R^2, it was decided not to use the corrected values for any comparisons.

Table 8: NEC and NEC Tolerances Based on Three Methods

	NEC from Eq. 5 (kJ)	NEC from Eaton	NEC from Eq. 6 (kJ)	Tolerance from Eq. 5 (%)	Tolerance from Eaton	Tolerance from Eq. 6 (%)
Hybrid Heavy Cycle	-1645	NA	855	2.53	NA	1.30
Hybrid Heavy Cycle	-934	NA	738	1.38	NA	1.08
Hybrid Heavy Cycle	-234	NA	784	0.34	NA	1.17
Hybrid Light Cycle	934	NA	1503	1.95	NA	3.18
Hybrid Light Cycle	234	NA	758	0.46	NA	1.52
Hybrid Light Cycle	-234	NA	811	0.47	NA	1.66
Freightliner New Battery, 20 min soak	-72	134.125	117	0.11	0.20	0.18
Freightliner New Battery, 20 min soak	-5	NA	-120	0.01	NA	0.19
Freightliner New Battery, 20 min soak	10	158.175	-28	0.02	0.26	0.05
Freightliner New Battery, 1 min soak	-99	-176.675	243	0.18	0.32	0.44
Freightliner New Battery, 1 min soak	-20	-12.025	-140	0.04	0.02	0.25
Freightliner Old Battery, 20 min soak	2222	2590	-647	3.59	4.21	1.00
Freightliner Old Battery, 20 min soak	-320	-370	41	0.49	0.57	0.06
Freightliner Old Battery, 20 min soak	-266	-370	-17	0.43	0.60	0.03
Freightliner Old Battery, 1 min soak	1011	1110	-269	1.80	1.98	0.47
Freightliner Old Battery, 1 min soak	-593	-740	148	0.98	1.22	0.25

Table 9: CO2, CO, and NOx Emissions Corrected for NEC Tolerance

		Corrected for NEC Tolerance					
		CO2	R^2	CO	R^2	NOx	R^2
Hybrid Heavy Cycle	Eq. 5	1671	0.74	3.57	1.00	4.42	0.97
	Eq. 6	1925	0.85	7.14	0.37	7.53	0.53
Range based on average ± standard deviation		1623 - 1667		2.36 - 3.40		3.57 - 4.31	
Hybrid Light Cycle	Eq. 5	1549	0.61	2.09	0.99	2.93	0.51
	Eq. 6	1580	0.96	3.11	0.87	3.88	0.91
Range based on average ± standard deviation		1527 - 1558		1.21 - 2.36		2.27 - 3.23	
Freightliner New Battery, 20 min soak	Eq. 5	1490	0.78	0.151	0.66	2.76	1.00
	Eq. 6	1530	0.24	0.164	0.14	3.05	0.72
Range based on average ± standard deviation		1445 - 1608		0.133 - 0.193		2.523 - 3.509	
Freightliner Old Battery, 20 min soak	Eq. 5	1512	0.12	0.315	0.87	2.54	0.74
	Eaton	1512	0.14	0.315	0.86	2.53	0.76
	Eq. 6	1511	0.09	0.317	0.91	2.59	0.69
Range based on average ± standard deviation		1445 - 1608		0.133 - 0.193		2.52 - 3.51	
Freightliner Old Battery, 1 min soak	Eq. 5	1409	1.00	-0.1753	1.00	2.08	1.00
	Eaton	1408	1.00	-0.1752	1.00	2.07	1.00
	Eq. 6	1410	1.00	-0.1754	1.00	2.08	1.00
Range based on average ± standard deviation		1374 - 1433		-0.172 - (-0.178)		1.90 - 2.19	

PM Emissions

The PM emissions for the BDC trucks were measured by the typical method of collecting the PM on a Teflon filter over the full cycle and by a Dekati Mass Monitor (DMM-230) a real time PM instrument that provides second-by-second information about particle total mass. The average results for these measurements in g/mile are given in Table 10. The average PM emissions are less than 0.004 g/mile for both vehicles on both cycles. Analysis of Variance (ANOVA) indicates that the PM Dekati results for the light cycle and the PM filter results for the heavy cycle are not statistically significantly different between the conventional and the hybrid vehicle. The PM filter results for the light cycle and the PM Dekati results for the heavy cycle are just statistically significantly different for the hybrid vs. the conventional at the 95 percent confidence level. The PM emissions were not measured for the Freightliner.

Table 10: Average Emissions of PM by Filter Method and Dekati DMM

	Emissions (g/mile)	
	PM Filter	PM Dekati
	Conventional, Light Cycle	
Average	1.04E-03	5.60E-04
Std. Dev.	8.13E-04	6.96E-04
COV	78.5%	124.2%
	Hybrid, Light Cycle	
Average	4.04E-03	7.30E-05
Std. Dev.	1.51E-03	2.10E-05
COV	37.2%	28.8%
Hybrid % Improvement	-290.5	87.0
	Emissions (g/mile)	
	PM Filter	PM Dekati
	Conventional, heavy Cycle	
Average	1.81E-03	2.32E-04
Std. Dev.	1.85E-03	9.54E-05
COV	101.9%	41.1%
	Hybrid, heavy Cycle	
Average	3.69E-03	8.54E-05
Std. Dev.	2.40E-03	1.71E-05
COV	65.1%	20.0%
Hybrid % Improvement	-103.3	63.2

Accelerations to 20 mph

Table 11 summarizes the results of the dyno accelerations from 0 to ~20 mph. The data was recorded for every second. The table presents the time for the dyno to reach the first reading equal to or greater than 20 mph. For conventional test CL2 the highest speed reached was 19.4 mph. The mph were divided by the time to determine an average acceleration in mph/sec. On average the hybrid is 24 percent slower time wise in reaching ~20 mph and has ~20 percent slower acceleration from 0 to 20 mph for the heavy cycle. On average the hybrid is 48 percent slower time wise in reaching ~20 mph and has ~31 percent slower acceleration from 0 to 20 mph for the light cycle.

Table 11: Results of Acceleration Tests from 0 to 20 mph

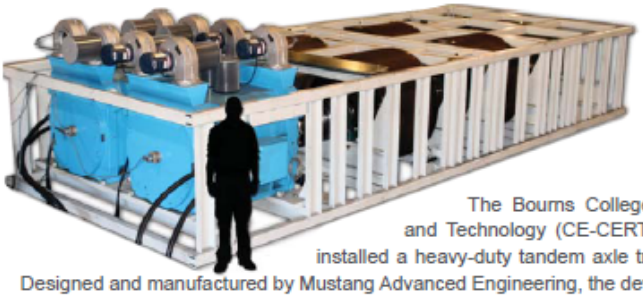
Heavy Cycle									
Conventional	Hybrid	Time to Accelerate to x mph							
		Conventional			Hybrid				
Filename	Filename	x	Time (sec)	Accel-eration (mph/sec)	x	Time (sec)	Accel-eration (mph/sec)	Hybrid % Time Slower to 20 mph	Hybrid % Slower Accel-eration
201111080911_20MPH_CH1	201111100907_20mph_HH1	20.2	19	1.06	20.2	23	0.88	-21.1%	-17.4%
201111081036_20MPH_CH2	201111101032_20mph_HH2	20.4	18	1.13	20.1	23	0.87	-27.8%	-22.9%
201111081221_20MPH_CH3	Not Available	20.1	17	1.18					
	Average	20.2	18.0	1.1	20.2	23.0	0.9	-24.4%	-20.1%
	Standard Deviation	0.2	1.0	0.1	0.1	0.0	0.0	4.8%	3.9%
	COV	0.75%	5.56%	5.32%	0.35%	0.00%	0.35%	-19.5%	-19.3%
Light Cycle									
Conventional	Hybrid	Time to Accelerate to x mph							
		Conventional			Hybrid				
Filename	Filename	x	Time (sec)	Accel-eration (mph/sec)	x	Time (sec)	Accel-eration (mph/sec)	Hybrid % Time Slower to 20 mph	Hybrid % Slower Accel-eration
201111080819_20MPH_CL1	201111100821_20mph_HL1	20.7	13	1.59	20.3	17	1.19	-30.8%	-25.0%
201111080953_20MPH_CL2	201111100950_20mph_HL2	19.4	14	1.39	20.2	23	0.88	-64.3%	-36.6%
201111081136_20MPH_CL3	201111101115_20mph_HL3	20.2	13	1.55	20.2	17	1.19	-30.8%	-23.5%
	Average	20.1	13.3	1.5	20.2	19.0	1.1	-47.5%	-30.8%
	Standard Deviation	0.7	0.6	0.1	0.1	3.5	0.2	23.7%	8.2%
	COV	3.26%	4.33%	7.27%	0.29%	18.23%	16.62%	-49.9%	-26.6%

Specifications for UCR's Motored Chassis Dynamometer

From Mustang Publication "Project Spotlights" March 2010

Figure 36: Specifications For UCR's Motored Chassis Dynamometer

Mustang Advanced Engineering delivers a newly designed 48" Electric AC Heavy-Duty Truck Chassis Dynamometer with dual, direct-connected 300-hp AC motors to The University of California - Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT).



The science of measuring emissions from mobile and other sources has evolved significantly over the past several years. The most important changes in the nature of emissions measurement science has been a shift to examining emissions from diesel sources and to understanding emissions under in-use driving conditions.

The Bourns College of Engineering – Center for Environmental Research and Technology (CE-CERT) at The University of California Riverside has recently installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area. Designed and manufactured by Mustang Advanced Engineering, the development of this chassis dynamometer design was based on targeting vehicles in the medium to heavy-duty diesel vehicle range. Heavy-duty applications that can be tested at the facility include on-highway trucks, buses, waste haulers, yard tractors, and more - under test conditions representative of their specific in-use operations. The facility couples the new heavy-duty chassis dynamometer from Mustang Advanced Engineering with CE-CERT's Mobile Emissions Laboratory (MEL), to perform precise vehicle simulation and in-operation emissions measurements.

The first research conducted on the new facility will be a comparison of federally mandated diesel fuel formulas versus the stricter formulation required in California. The program calls for 10 heavy-duty trucks to be tested with several different fuels.

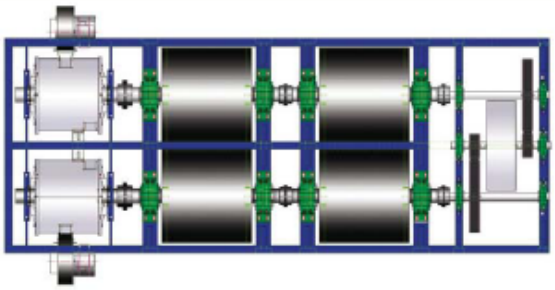
The new dynamometer will simulate on-road driving conditions for any big rig using its 48" precision rollers with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies the appropriate loading to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving conditions. An additional large inertia weight was incorporated into the dynamometer to increase the base mechanical inertia and enable the dynamometer to provide precise on-road simulation for a wide range of vehicle weights. The driver accelerates and decelerates according to a driving trace which specifies the speed and time over a wide range of vehicle simulation cycles. As the on-road driving conditions are being simulated on the dynamometer, emissions measurements will be collected with CE-CERT's Mobile Emissions Laboratory (MEL).

"This adds new capabilities in California that are only available at a limited number of facilities around the country," said Tom Durbin, who with J. Wayne Miller, are the principle investigators for the project. At both the state and federal levels, scientific requirements for emissions testing are trending away from steady state engine testing in favor of transient conditions found in typical driving, Durbin explained. "This addition will significantly expand our laboratory and measurement capabilities and help us continue our role as leading experts in the field of emissions research," said CE-CERT Director Matthew Barth.

CE-CERT's new heavy-duty chassis dynamometer will allow the testing of a variety of heavy vehicles under loaded and transient in-use conditions with corresponding emissions measurements. The dynamometer configuration is capable of meeting the inertia simulation range requirements of 10,000 to 80,000 lb for each of the cycles listed below. This includes acceleration rates up-to 6 mph/sec, as found in the UDDS Section D Drive Schedule and deceleration rates of up to 7 mph/sec as required for the WHM Refuse Drive Schedule. The dynamometer can also provide a load in excess of 600 HP @ 70 mph. The dynamometer also has the ability to continuously handle 200 Hp @ 15 mph for applications such as yard tractors.

The Dynamometer system is designed to meet the Heavy Duty Drive Schedules for diesel trucks in the weight range of 10,000 to 80,000 lb with acceleration rates for the following cycles:

- CARB HHDDT Cruise Mode Drive Schedule
- UDDS (Urban Dynamometer Drive Schedule)
- CARB 50 mph HHDDT Cruise Cycle
- HHDDT Transient Mode Drive Schedule
- WHM Refuse Drive Schedule
- Bus cycles such as, the CBD, OC Bus cycle, NY bus cycle
- In-use cycles for applications such as yard tractors.



"As part of our strategic plan, Mustang has developed a cost effective series of diesel, petroleum and hybrid certification grade dynamometer systems to address the needs of the global emissions and R&D market. There is a clear and present demand for a full performance cost effective dynamometer systems that offer all of the capabilities and confidence of a certification system at a price point that makes it no longer cost-prohibitive for organization to perform critical emissions studies, hybrid system calibration development, performance evaluation and other cutting edge research technologies. Researchers are in need of dynamometer systems to develop the next generation technologies which mimic the capabilities of the certification requirements, but at a fraction of the cost of a true certification system. That is what we are developing with this series of dynamometers and universities are lining up for them", said Executive Vice President, Donald Ganzhorn.

Emissions and Fuel Usage Results

Table 12 presents the emissions and fuel economy for each test cycle for the BDC Truck Tests.

Table 12: BDC Truck Emissions and Fuel Economy for each Test Cycle

				Emissions (g/mile)						Fuel Economy by Carbon Balance (g/mile)		Fuel Economy by Carbon Balance (mpg)	
	Unit Tested	Test Cycle	File Name	THC	CH_4	NMHC	CO	NO_x	CO_2	ECM	Emissions	ECM	Emissions
CL1	Conventional	Light	201111080819	-0.104	0.032	-0.138	0.010	3.130	2507.2	681.1	791.2	4.61	3.97
CL2	Conventional	Light	201111080953	-0.110	0.033	-0.144	0.179	1.912	2424.9	652.0	765.3	4.82	4.10
CL3	Conventional	Light	201111081136	-0.104	0.037	-0.143	0.188	5.766	2389.9	638.8	754.3	4.92	4.16
CL4	Conventional	Light	201111150931	-0.100	0.033	-0.135	0.106	2.127	2497.6	675.6	788.2	4.65	3.98
CL5	Conventional	Light	201111151106	-0.107	0.041	-0.150	BDL	2.373	2491.9	674.2	786.4	4.66	3.99
CL6	Conventional	Light	201111151239	-0.103	0.023	-0.128	0.083	2.075	2505.2	667.9	790.6	4.70	3.97
HL1	Hybrid	Light	201111100821	-0.089	0.037	-0.127	1.153	2.237	1525.5	493.9	481.9	6.36	6.52
HL2	Hybrid	Light	201111100950	-0.097	0.031	-0.129	1.934	3.183	1555.4	489.8	491.8	6.41	6.39
HL3	Hybrid	Light	201111101115	-0.095	0.040	-0.136	2.275	2.836	1547.2	488.1	489.3	6.43	6.42
CH1	Conventional	Heavy	201111080911	-0.085	0.027	-0.113	0.130	1.862	2324.8	698.9	733.7	4.49	4.28
CH2	Conventional	Heavy	201111081036	-0.084	0.024	-0.109	0.075	2.213	2366.9	652.8	747.0	4.81	4.20
CH3	Conventional	Heavy	201111081221	-0.074	0.028	-0.103	0.259	4.378	2399.6	666.9	757.4	4.71	4.15
CH4	Conventional	Heavy	201111150842	-0.076	0.013	-0.091	BDL	3.470	2433.2	687.1	767.9	4.57	4.09
CH5	Conventional	Heavy	201111151016	-0.075	0.035	-0.111	0.073	2.947	2371.2	660.8	748.4	4.75	4.20
CH6	Conventional	Heavy	201111151156	-0.076	0.031	-0.108	0.152	3.186	2386.6	664.8	753.2	4.72	4.17
HH1	Hybrid	Heavy	201111100907	-0.062	0.033	-0.096	2.359	3.543	1619.2	505.6	512.1	6.21	6.13
HH2	Hybrid	Heavy	201111101032	-0.065	0.032	-0.098	2.886	4.012	1658.2	512.1	524.7	6.13	5.98
HH3	Hybrid	Heavy	201111101159	-0.065	0.035	-0.101	3.400	4.263	1657.7	504.5	524.8	6.22	5.98

Table 13 presents the PM results for each test cycle for the BDC Truck Tests

Table 13: BDC Truck PM Emissions for each Test Cycle

				Emissions (g/mile)	
	Unit Tested	Test Cycle	File Name	PM Filter	PM Dekati
CL1	Conventional	Light	201111080819	NA	1.30E-04
CL2	Conventional	Light	201111080953	NA	1.25E-04
CL3	Conventional	Light	201111081136	NA	1.80E-03
CL4	Conventional	Light	201111150931	1.46E-03	1.90E-04
CL5	Conventional	Light	201111151106	9.80E-05	1.23E-04
CL6	Conventional	Light	201111151239	1.55E-03	9.96E-04
HL1	Hybrid	Light	201111100821	2.80E-03	6.32E-05
HL2	Hybrid	Light	201111100950	3.62E-03	9.72E-05
HL3	Hybrid	Light	201111101115	5.71E-03	5.87E-05
CH1	Conventional	Heavy	201111080911	NA	1.51E-04
CH2	Conventional	Heavy	201111081036	NA	1.71E-04
CH3	Conventional	Heavy	201111081221	NA	2.73E-04
CH4	Conventional	Heavy	201111150842	3.64E-03	1.76E-04
CH5	Conventional	Heavy	201111151016	1.84E-03	2.17E-04
CH6	Conventional	Heavy	201111151156	-4.94E-05	4.06E-04
HH1	Hybrid	Heavy	201111100907	6.39E-03	1.05E-04
HH2	Hybrid	Heavy	201111101032	2.84E-03	7.61E-05
HH3	Hybrid	Heavy	201111101159	1.82E-03	7.49E-05

Table 14 presents the emissions and fuel economy for each heavy test cycle for the Freightliner Hybrid Truck Tests.

Table 14: Freightliner Hybrid Emissions and Fuel Economy for each test cycle

				Emissions (g/mile)									
Battery	Run #	Time betw Runs (Min)	File Name	THC	CH4	NMHC	CO	NOx	CO2	Fuel Economy by Carbon Balance (g/mile)		Fuel Economy by Carbon Balance (mpg)	
New	1	20	201205100839	-0.089	0.028	-0.118	0.188	3.578	1600.5	484.0	505.1	6.49	6.22
New	2	20	201205100922	-0.088	0.016	-0.105	0.172	2.812	1539.4	516.6	485.9	6.08	6.46
New	3	20	201205101005	-0.256	-0.048	-0.210	0.130	2.657	1439.6	502.3	454.2	6.25	6.91
New	4	1	201205101029	-0.265	-0.044	-0.223	-0.052	1.982	1319.3	471.1	416.1	6.66	7.55
New	5	1	201205101050	-0.270	-0.058	-0.214	-0.098	1.531	1353.3	494.9	426.8	6.34	7.36
Old	1	20	201205101128	-0.090	0.037	-0.128	0.299	1.940	1539.0	522.0	485.8	6.02	6.46
Old	2	20	201205101210	-0.091	0.022	-0.115	0.322	2.395	1552.7	511.4	490.1	6.14	6.41
Old	3	20	201205101251	-0.278	-0.065	-0.215	0.313	2.836	1464.4	515.6	462.1	6.09	6.80
Old	4	1	201205101314	-0.286	-0.063	-0.225	-0.173	1.945	1383.0	504.7	436.1	6.22	7.20
Old	5	1	201205101336	-0.290	-0.074	-0.218	-0.177	2.152	1424.3	497.3	449.2	6.31	6.99

APPENDIX 4A:
Battery Electric Truck On-Road Testing Report

INTERNAL

CALSTART EV Delivery Van
Freightliner Custom Chassis MT E-Cell

Project Report No. TC-12-249-TR01
Revision No. 1

Performance Characterization Report, April 2013

SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL® Company

ISO 9001

Electric Vehicle Technical Center
An ISO 9001 Registered Facility

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1.0 EXECUTIVE SUMMARY

1.1 Background

The Freightliner Custom Chassis MT E-cell is an all-electric delivery van undergoing evaluation with the project partner as a delivery vehicle. CALSTART is providing the data analysis for the project under the CalHEAT initiative for the California Energy Commission (CEC). Southern California Edison, a CALSTART member, is providing CALSTART with a controlled test evaluation.

1.2 Key Results

The key test-based results outlined in the statement of work with CALSTART are summarized in Table 1-1 below.

Table 1-1 Key Results

Test	Result
Payload	4,740 +/- 80 lb
Urban range, unloaded	54 miles until low battery indicator light came on, 66 miles until vehicle began limiting power.
Urban Range, loaded	45 miles until low indicator light came on, 56 miles until vehicle began limiting power.
Delivery route range	46 miles until low battery indicator came on, 57 miles until vehicle began limiting power.
Charge Duration, typical	The bulk of the charge took 13 to 14 hours drawing 5.6 kW, however, the vehicle continued to draw 260 to 300 watts until it was unplugged.
Charge Energy, typical	67 AC kWh
SOC meter Evaluation	SOC (state of charge) meter is difficult to read: the lack of gradations makes it hard for the driver to estimate the remaining range. There is no separate range meter.
12 V systems	DC/DC converter provides enough power to keep battery charged during all operational modes

2.0 INTRODUCTION

CALSTART is an organization that promotes clean transportation for industry. CALSTART has over 140 corporate members, including Southern California Edison. As part of a CalHEAT Center project to evaluate EV drive trains in delivery vehicles, funded by the California Energy Commission, CALSTART is supporting the data acquisition for the project. The project includes the Freightliner Custom Chassis MT E-cell and Navistar's eStar EV delivery van. The vehicles have been in a demonstration in the project partner fleet, and EVTC testing will provide standardized testing data that CALSTART can use for comparison on range, performance, and effectiveness of the platforms, as well as the system impacts of charging of large electric vehicles. These vehicles may potentially be used more extensively in the project partner fleet, and used by other fleets, including the SCE fleet. This report covers the testing of the Freightliner Custom Chassis MT E-cell delivery van. This particular unit was not part of the project partner fleet, but was loaned from Freightliner because the project partner unit was out of service.

The Freightliner van supports an all-aluminum body by Morgan Olson, an Enova drivetrain, and three 20 kWh Tesla Motors packs, for a total of 60 kWh of battery capacity. The body is outfitted for package delivery.

3.0 OBJECTIVES

3.1 Tasks and Deliverables

The key tasks and deliverables as laid out in the statement of work with CALSTART are given in Table 3-1.

Table 3-1 Tasks and Deliverables

Item #	Tasks and Deliverables Description
1	Receiving and inspection
2	Performance Testing – Acceleration, max speed and braking
3	UR1 - Urban Range Test at Minimum Payload
4	UR3 - Urban Range Test at Maximum Payload
5	Delivery Route
6	Charger Performance Test
7	SOC Meter Evaluation
8	12 V standby testing
9	Report

3.2 Key parameters

This report will include the following key parameters:

- Range (mi)
- Energy recharge (AC kWh)
- Energy economy (kWh/mi)
- Recharge power quality parameters (system impact) (charge time, power, current, voltage, power conversion efficiency, PF, THD)
- Stand-by (hotel) load
- 12V system characterization
- Subjective evaluation

3.3 Inspection Requirements:

Inspection shall consist of, but is not limited to:

- Initial condition of vehicle
- Nameplate data
- Weight
- Overall dimensions
- Turning circle, "curb to curb" and "wall to wall"
- Ground Clearance

3.4 Measurement Requirements and Uncertainty

The key metrics to be reported include:

- Range (mi) ± 5%
- Energy Recharge (kWh) ± 0.5%
- Energy Economy (kWh/mi)
- Performance ± 1%
- Power Quality ± 0.5%
- Current THD ± 0.5%
- Voltage THD ± 0.5%
- Power Factor ± 0.5%

4.0 TEST SET-UP/PROCEDURE

4.1 Performance Testing – Acceleration, max speed and braking

The performance testing consisted of two acceleration tests, one starting at 80% SOC, and the other starting at 40% SOC. In both tests the vehicle was accelerated from rest until it reached 55 mph and the times required to reach 30 mph and 55 mph were recorded. Each test consisted of alternating runs in opposite directions (north and south) to compensate for grade. Between these two acceleration tests, a braking test was performed. The vehicle was driven at a constant 25 mph and then brought to a complete stop; the stopping distance was recorded in feet.

4.2 Range Tests

All range tests were performed by an experienced driver, driving the vehicle in a moderate style that was not too aggressive or too soft, and as compatible as possible with the flow of traffic. The distance driven when the low battery SOC (state of charge) warning came on was recorded as well as the distance when power limiting occurred and the final distance. The distance of the low warning indicator is used to determine the useful range, and the total distance was used to calculate the energy economy (AC kWh/mi). The urban route distances were recorded from the vehicle odometer and correlated with the SCE tabulated distances (Appendix A) to determine the accuracy of the vehicle odometer and a correction factor.

4.2.1 UR1 - Urban Range Test at Minimum Payload

For the Urban Range at Minimum Payload (driver and test equipment only) test, the MT E-cell was driven on the "Urban Pomona Loop" without using auxiliary loads. The data needed to determine distance per charge and AC kWh/mile were recorded. The DC data were not recorded.

The "Urban Pomona Loop" is a local street route of about 20 miles with approximately 60 stop signs and traffic lights. Refer to Appendix A for a map and elevation profile. The actual distance around the loop was used for range results, not the odometer reading, and is referred to as the corrected distance in the results.

4.2.2 UR3 - Urban Range Test at Maximum Payload

For the Urban Range Test at Maximum Payload, the MT E-cell was driven on the "Urban Pomona Loop" without using auxiliary loads and with an almost full payload of 4520 pounds. The data needed to determine distance per charge and AC kWh/mile were recorded. The DC data were not recorded.

4.2.3 Delivery Route

The delivery route was designed to simulate a more intensive duty cycle, similar to a newspaper delivery route, with more stops and starts in a given distance than the SCE urban loop. The delivery loop was driven without using auxiliary loads and at minimal payload.

4.3 Charger Performance Test

After a test drive, the MT E-cell was charged normally, and the charge was monitored with power quality instrumentation. SCE did not have access to any DC data or measurements; therefore we did not analyze the charger efficiency.

4.4 SOC Meter Evaluation

The SOC meter on the FCCC NT E-cell was read and recorded over the course of a delivery route test drive.

The MT E-cell meter did not have gradations or a numeric readout, so to improve readability SCE had to use the expedient of marking a clear piece of plastic and measuring the SOC in terms of 1/16 of an inch. Normally, this would not be done in a fleet setting.

4.5 12 V standby testing

The 12 V standby testing was accomplished by measuring the current flowing into and out of the 12 V auxiliary battery under five conditions: With the vehicle plugged in after finishing charging, with the vehicle off and not plugged in, with the vehicle on and idling, with the vehicle charging before the cooling fans came on, and with the vehicle charging after the cooling fans came on.

5.0 RESULTS AND ANALYSIS

5.1 Receiving and Inspection

The only damage found upon receipt of the vehicle was on the charge cord, which is detailed in Section 5.5.1. The MT E-cell weighed 9460 pounds as delivered, and with its GVWR of 14,200 pounds, had a payload of 4740 pounds. More inspection results are in Table 5-1.

Table 5-1 Inspection Results

Gross Vehicle Weight Rating (lb)	14,200
Curb Weight (lb)	9460 ± 80
Available payload (lb)	4740 ± 80
Turning Circle (curb to curb) (ft)	46
Turning Circle (body path) (ft)	49
Length (in)	248
Width (in)	114
Height (in)	117
Wheelbase (in)	139
Ground Clearance (in)	8

5.2 *Ergonomics and driver response*

5.2.1 Major Ergonomic Factors

Figure 5-1 View of right-hand mirror

The view of the exterior mirrors was partially blocked by the door frames, leaving large blind spots that could pose a challenge when changing lanes (Figures 5-1 and 5-2).

Figure 5-2 View of left hand mirror

5.2.2 Driver Comments

The following comments are the subjective evaluation of the SCE technician assigned to the MT E-cell test.

Figure 5-3 View of gages

- "The steering wheel doesn't tilt all the way down, and it obstructs the view of the bottom half of the cluster." See Figure 5-3.

Figure 5-4 SOC gage

- "When depleting the battery the SOC gauge drops down in very small increments making it harder to read the SOC."
- "At low SOC the only warning light you get is the "Low" sign at about 20% SOC; after that vehicle goes into Limiting Power Mode."

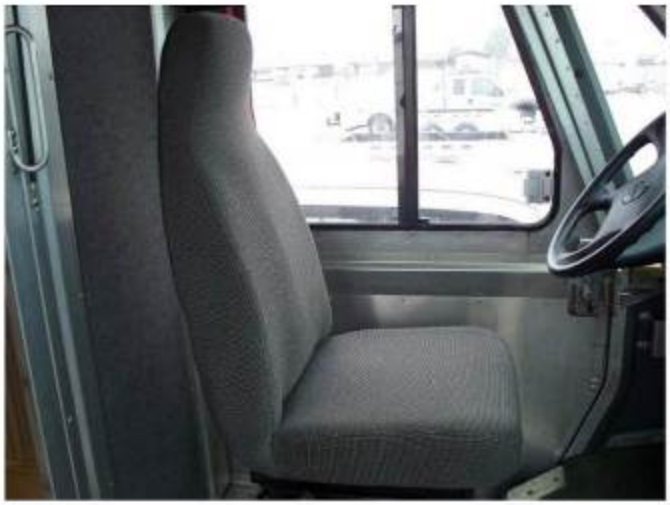

Figure 5-5 Cabin interior

- "I really like the driver seat. It is very comfortable and reduces the bouncing that comes with a stiff suspension that most work vans/trucks have."
- "I also like the regenerative braking. It's noticeable but not too aggressive. Hardly used the service brakes due to it and in turn it prolongs the life of the brakes."
- "I did notice that after about 50% SOC there is a very noticeable loss in power. This was proven when doing the 0-55 mph test and on urban drives going up the Carnelian Hill."

5.3 Performance Testing – Acceleration, max speed and braking

The MT E-cell showed an increase in acceleration times as the SOC decreased. This can be seen when comparing the results in Table 5-2 and Table 5-3. In Table 5-2 the north and southboundtimes for the 0-55 mph test differ by approximately 10 seconds. In Table 5-3 the north and southbound times for the same test differ by nearly 30 seconds. The maximum speed of the MT E-cell was 66 mph on a level road.

Table 5-2 Acceleration Times, 80% SOC

Starting SOC:~80%		Ending SOC:60%	
Run	**0-30 mph time (sec)**	**0-55 mph time (sec)**	**Direction**
1	6.52	42.34	North
2	6.02	31.13	South
3	6.59	44.58	North
4	6.31	33.64	South
Average	**6.4**	**38**	

Table 5-3 Acceleration Times, 40% SOC

Starting SOC: 40%		Ending SOC: 30%	
Run	**0-30 mph time (sec)**	**0-55 mph time (sec)**	**Direction**
1	7.22	64.14	North
2	6.42	36.89	South
3	7.37	67.59	North
4	6.59	34.98	South
Average	**6.9**	**51**	

The MT E-cell had an average braking distance of 42.5 feet from 25 mph to a complete stop.

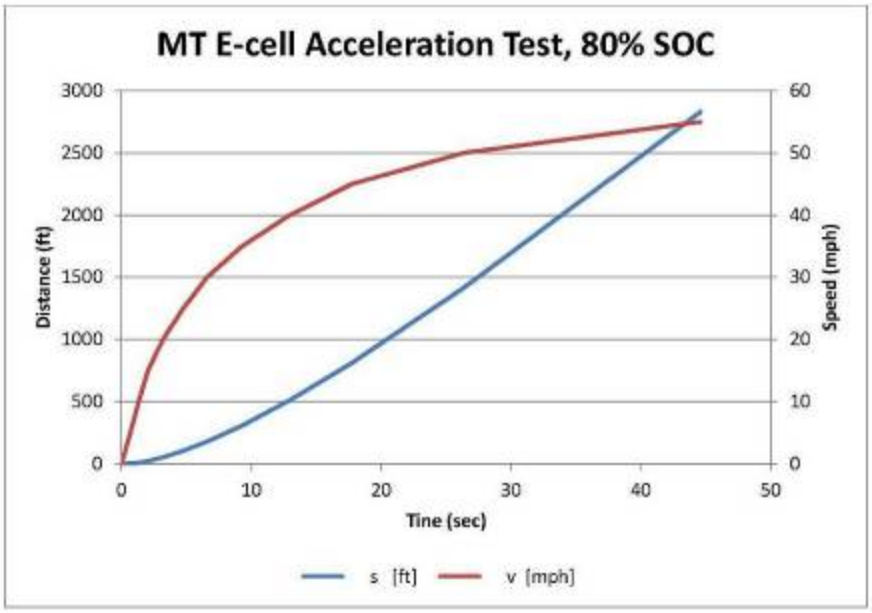

Figure 5-6 Typical acceleration profile

Figure 5-6 shows a typical acceleration profile when the vehicle is near 80% SOC.

5.4 *Range Testing*

5.4.1 UR1 - Urban Range Test at Minimum Payload

Table 5-4 Urban 1 Range Test Results

Test	UR1
Duration of Drive (hr:min)	2:52
Net Odometer (mi)	70.4
Corrected Distance, miles	67.6
SOC Start	100%
SOC END	0%
Flashing Low Indicator Light (mi)	55.8
Corrected Low Indicator Range (mi)	53.6
Power Limiting (mi)	68.9
Power Limiting (mi) Corrected	66.1
Total Distance Traveled (mi)	67.6
Charge Duration (bulk of charge, h:mm)	13:15
Charge AC kWh	66.8
AC kWh/mi Overall	0.99

The charge durations in Table 5-4 and Table 5-5 are approximations. The FCCC MT E-cell continued to draw about 260 to 300 watts until it was unplugged. This is a significant hotel load and the total energy consumed by it depended upon when the user unplugged the vehicle. The energy presented in this table is for the bulk of the charge, until it dropped to a steady value for the hotel load.

5.4.2 UR3 - Urban Range Test at Maximum Payload

Table 5-5 Urban 3 Range Results

Test	UR3
Payload (lbs)	4520
Duration of Drive (hr:min)	2:15
Net Odometer	58.6
Corrected Distance, miles	56.2
SOC Start	100%
SOC END	0%
Low Indicator Light ON (mi)	46.8
low Indicator Light ON (mi) Corrected	44.9
Power Limiting (mi)	58.15
Power Limiting (mi) Corrected	55.8
Charge Duration (bulk of charge, h:mm)	13:45
Charge AC kWh	67.51
AC kWh/mi Overall	1.2

As with Table 5-4, Table 5-5 reports the energy consumed during the bulk of the charge. For every hour the vehicle remains plugged in after completing the charge, it consumes another 0.3 AC kWh of electricity. The range when the low SOC indicator light came on during the UR3 test was 16% lower than in the UR1test while the energy consumption (AC kWh/mi) was 21% higher.

5.4.3 Delivery Route

Table 5-6 shows the results of the Delivery Route test. The range result for the low SOC indicator was 15% lower than the UR1 test while the energy consumption (AC kWh/mi) was 16% higher. The AC energy needed to charge the vehicle was 0.8% higher for the delivery route.

Table 5-6 Delivery Route Range Results

Test	Del. Route
Duration of Drive (hr:min)	3:28
Net Odometer (mi)	58.8
Corrected Distance, miles	56.5
SOC Start	100%
SOC END	0%
Low Indicator Light ON (mi)	47.5
Low Indicator Light ON (mi) corrected	45.6
Power Limiting (mi)	56.8
Power Limiting (mi) corrected	54.5
Charge Duration (bulk of charge, hr:min)	13:20
Charge AC kWh	67.36
AC kWh/mi Overall	1.15

5.5 Charger Performance Test

5.5.1 Safety

5.5.1.1 Electrical safety

The Freightliner MT E-cell was delivered with a charge cord that did not meet the voluntary Society of Automotive Engineers J1772™ standard. This means the E-cell is not compatible with most of the EVSEs (electric vehicle supply equipment) on the market. The MT E-cell as delivered did not support Article 625 of the National Electric Code because it did not meet the following requirements[1]:

- Interlock that de-energizes the electric vehicle connector when disconnected from vehicle. The E-cell can be unplugged at full current flow. This may cause a spark or shock hazard.
- Automatic de-energization of cable upon over-exposure to strain.
- Overcurrent protection. There is nothing to limit the amount of current if the vehicle is plugged into a lower rated circuit, as with an adapter.

[1] National Electric Code Handbook, 2008, Article 625

- Personnel protection system against electric shock. There is no GFCI incorporated into the EVSE provided with the E-cell.

The EVSE provided with the MT E-cell was simply a section of cord with a twist-lock plug wired directly into the charger. The cord was wound around a fluid reservoir and the hood of the E-cell had to be opened to access it. Furthermore, the cord as shipped was damaged by extensive crushing, which resulted in arcing and overheating. The cord had been plugged into an extension cord, which is definitely not recommended, and SCE technicians initially noticed the heating discoloration on the extension cord socket. See Figure 5-7.

Figure 5-7 Heating damage to extension cord socket.

The SCE technicians then inspected the plug attached to the vehicle cord and found further evidence of heating. One of prongs had recessed when the plastic supporting it had melted. See Figure 5-8.

Figure 5-8 Exterior of damaged plug

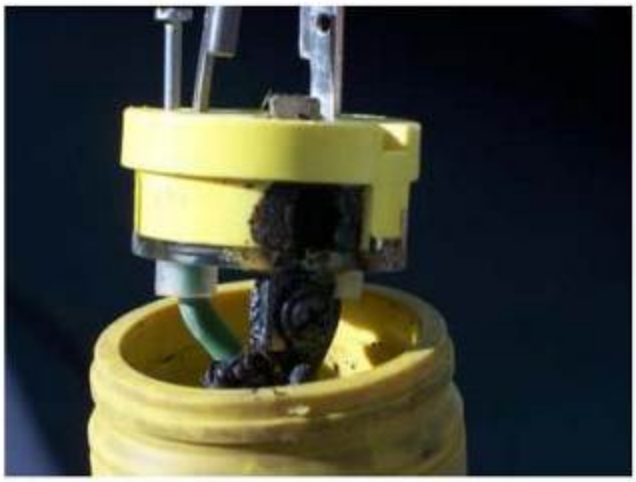

Figure 5-9 Interior of damaged plug.

Figure 5-9 shows the interior of the damaged plug, where the extent of the melting is more evident. If the vehicle had been plugged directly into a socket built into a building, there would have been potential for a structure fire.

5.5.1.2 Drive away protection

Another important safety feature is drive-away protection. The MT E-cell had drive-away protection that engaged when voltage was present and prevented the vehicle from turning on. When the voltage was removed and the vehicle still plugged in, the E-cell could be started and

driven away. This could cause structural damage in a fleet setting in the event of a circuit trip or power outage.

5.5.2 Power Quality

The results of the charger characterization are given in Table 5-7. At maximum power, the power factor is 1.0 and both the current and voltage total harmonic distortions (THD) are well below the SAE J2894/1™ recommended values of 10% (see Table 5-8). At minimum power, the power factor drops to 0.85 and the current total harmonic distortion rises to 24%, but the power level is low at 0.26 kW. This may cause some difficulty with sensitive equipment if a large number of such vehicles were connected at a single location.

Table 5-7 Freightliner MT E-Cell Charger Power Quality

Test Info	
Test date	11/1/2012
Nominal Voltage (V)	240
Energy Consumption (AC kWh)	67.80
Min. Voltage (V)	235.08
Max. Voltage (V)	242.85
Charge Duration (hr:min)	17:32

Power Quality Parameters	**Maximum Power**	**Minimum Power**
Voltage (V)	242.34	241.10
Current A (A)	23.24	1.30
Frequency (Hz)	60.00	59.99
Active Power (kW)	5.61	0.26
Reactive Power (kVAR)	-0.35	-0.15
Apparent Power (kVA)	5.63	0.31
Power Factor	1.00	-0.85
Max Voltage THD (%)	1.43	1.34
Max Current THD (%)	3.31	23.91

Note:
**All max power values are 5 min average around selected data point*

Table 5-8 SAE J2894 Power Quality Requirements for Plug-In Electric Vehicle Chargers[2]

Power Quality Parameters	Level 1	Level 2
Total Power Factor (minimum)	95%	95%
Power Conversion Efficiency	90%	90%
Total Harmonic Current Distortion (maximum)	10%	10%

SCE did not have access to the DC data and was not able to provide information on the charger efficiency.

5.5.3 Charge duration

The Freightliner literature on the MT E-cell claims a charge time of 6 to 8 hours, but the vehicle provided to SCE had a charge duration of up to 17 ½ hours, with the bulk of the charge taking 12-14 hours. The E-cell continued to draw power in the range of 250 W to 300 W until it was unplugged. See Figure 5-10 for a typical charge profile. In fleet use, the E-cell may not have time to fully recharge before the next day, especially in a scenario of demand-response or off-peak charge control, and this could lead to a situation where the vehicle doesn't have the range to complete its tasks. SCE prefers to see a vehicle that can recharge in less than 8-hours.

[2] SAEJ2894/1 EV Power Quality Requirements for Plug-In Electric Vehicle Chargers, 2011-12-08

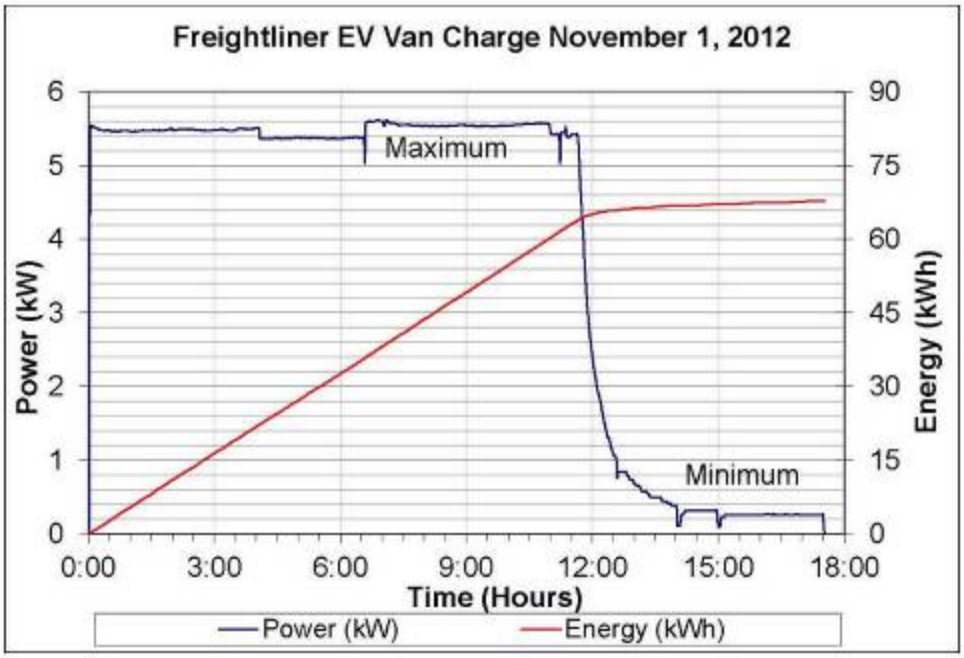

Figure 5-10 Freightliner MT E-Cell charging profile.

5.6 SOC Meter Evaluation

The Freightliner MT E-cell uses a LCD display to show an analog representation of the state of charge (See Figure 5-4). This representation has no gradations and is difficult for a driver to read and estimate the remaining range. In order to perform the SOC meter evaluation, SCE divided the meter into 9 parts, each 1/8 of inch wide (Figure 5-11). This made it easier for the driver to estimate the SOC (to the nearest 1/16 of an inch), although it was still far from perfect. In the same space as the current SOC meter, the MT E-cell could use a large-format numerical SOC gage that would be much easier to read.

Figure 5-11 SOC meter with gradations added.

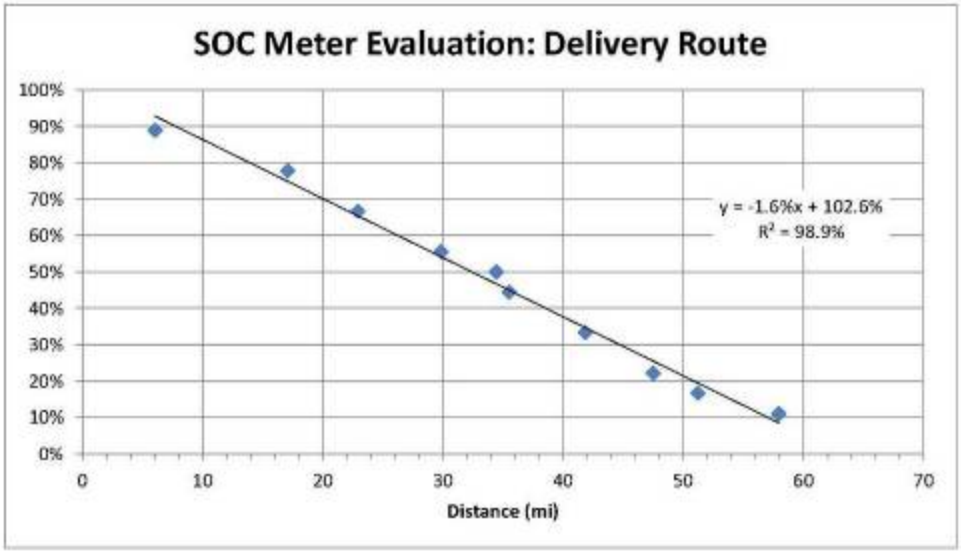

Figure 5-12 SOC Meter evaluation

Figure 5-12 shows the results of the meter evaluation during the delivery route driving test. The decrease in SOC is fairly linear, given the difficulty in reading the meter. A driver can estimate that every mile will reduce the SOC by 1.6%, or that each 10% of SOC can result in 6.3 miles of range. The mileage used in Figure 5-12 is the corrected mileage, not the odometer reading.

5.7 12 V standby testing

SCE monitored the current into and out of the 12 V battery under the conditions listed in Table 5-9. The DC/DC converter provided sufficient power in all test conditions to support the voltage. Any communications systems used by the project partner fleet for delivery were not active, so SCE was not able to test the effect of that demand on the 12 V system. Note that the system maintains the 12 V battery under both driving and charging states, but not in the charge maintenance mode.

Table 5-9 12 V Standby Tests

Condition	Net current (Amps)
EVSE/Charger (Plugged-in after finished charging/Maintain Mode)	0.0
Vehicle off (not plugged-in)	0.0
Vehicle on (Idling)	2.3
Vehicle Charging (Before fans off)	4.8
Vehicle Charging (Fans on)	1.3

6.0 CONCLUSION AND RECOMMENDATIONS

The Freightliner MT E-cell has potential for a successful delivery vehicle with good cargo volume and payload but has significant issues that must be addressed prior to inclusion as a main fleet vehicle.

6.1 Conclusions

1. The MT E-cell is capable of delivering payload of up to 4700 pounds with an energy economy of 1.0 to 1.2 AC kWh/mi.
2. It has a useful range of 57 to 69 miles, depending on the payload and duty cycle.
3. It has acceptable power quality at a high rate of charge. At lower power, the current THD rises above 20%.
4. It has a 13 hour to 14 hour charge time and a continuous power draw of 260 W to 300 W after the charge has completed, until it was unplugged. The long duration of this charge could cause problems with vehicle availability in fleet use.
5. As delivered it did not meet the SAE J1772 recommendations for vehicle charging. The MT E-cell did not support the requirements of Article 625 of the National Electric Code because it did not properly incorporate sufficient ground fault and drive-away protection in the EVSE.

6.2 Recommendations

1. The manufacturer of the MT E-cell should ensure that the E-cell supports the requirements of NEC Article 625 for safety.
2. SCE would prefer that the MT E-cell adhere to the SAE J1772 standards for vehicle charging. This would have the advantage of allowing the MT E-cell to use infrastructure in common with other electric vehicles.
3. The charging rate should be increased to reduce the charge time to less than 8 hours.

APPENDIX A. SCE TEST LOOPS

C.1 Urban Loop Map and elevation profile

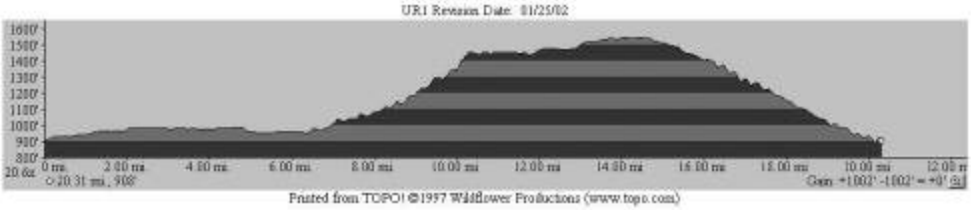

Figure C-1 Urban Loop Elevation Profile

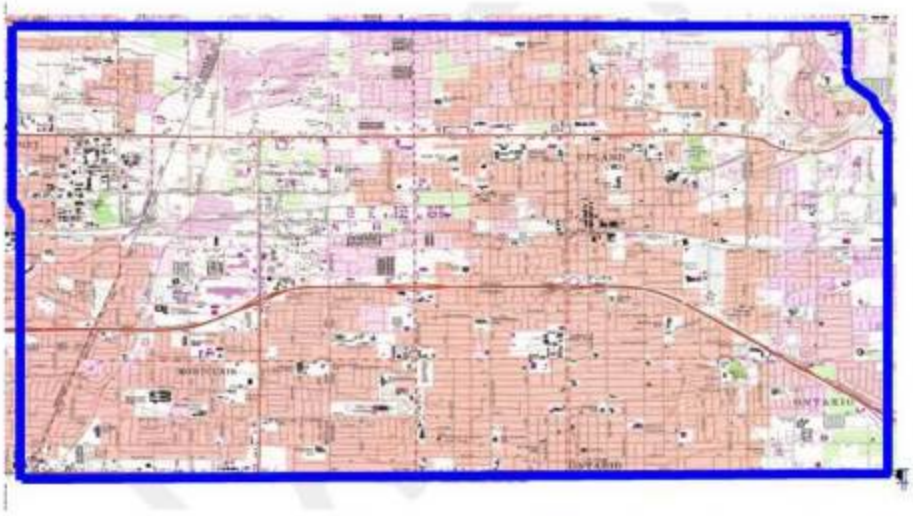

Figure C-2 Pomona Loop Map

Table C-1 Urban Loop Tabulated Data

Stop No.	Distance from Start (miles)	Type	Distance from Previous stop	Comments
0	0.0	light	0.00	East End & Holt
1	0.1	light	0.10	
2	0.2	light	0.05	Mills & Holt
3	0.8	light	0.65	
4	1.3	light	0.50	
5	1.8	light	0.50	
6	2.3	light	0.50	
7	2.9	light	0.60	
8	3.5	light	0.60	
9	3.7	light	0.20	
10	4.0	light	0.30	
11	4.0	light	0.01	
12	4.3	light	0.29	
13	4.6	light	0.30	
14	4.8	light	0.20	
15	4.8	light	0.02	
16	5.3	light	0.48	
17	6.3	light	1.00	Vineyard & Holt
18	6.7	light	0.36	
19	6.7	light	0.04	
20	6.8	light	0.10	
21	6.9	light	0.10	
22	7.3	light	0.40	
23	7.8	light	0.50	
24	8.3	light	0.50	
25	8.6	light	0.30	
26	8.8	light	0.20	
27	9.3	light	0.50	
28	9.5	light	0.20	
29	9.6	light	0.10	
30	9.7	light	0.10	
31	10.4	light	0.70	Carnelian & Baseline
32	10.7	light	0.30	
33	10.9	light	0.20	
34	11.6	light	0.70	
35	11.9	light	0.30	
36	12.3	light	0.40	
37	12.5	light	0.20	
38	12.7	light	0.20	
39	13.0	light	0.30	
40	13.6	light	0.60	
41	14.1	light	0.50	Baseline & Benson
42	14.9	light	0.78	Baseline & CA-210
43	15.1	light	0.22	Baseline & Padua
44	15.6	light	0.50	Baseline & Mills
45	16.4	light	0.75	Indian Hill
46	16.6	light	0.23	IH & Radcliff
47	16.9	light	0.29	

Stop No.	Distance from Start (miles)	Type	Distance from Previous stop	Comments
48	17.4	light	0.48	Indian Hill & Foothill
49	17.6	light	0.26	
50	17.7	light	0.13	IH & 8th St
51	18.0	light	0.22	
52	18.1	light	0.14	IH & Bonita
53	18.2	light	0.06	
54	18.2	light	0.06	IH & 1st St
55	18.3	light	0.05	
56	18.5	light	0.24	IH & Arrow
57	18.8	light	0.25	
58	19.0	light	0.25	
59	19.1	light	0.07	IH & WB I-10 ramp
60	19.1	light	0.05	IH & EB I-10 ramp
61	19.2	light	0.05	
62	19.3	light	0.08	IH & W. American
63	19.3	light	0.07	
64	19.5	light	0.18	IH & San Bernardino Ave.
65	19.9	light	0.34	IH & Lincoln
66	20.1	light	0.27	IH & Kingsley
67	20.4	light	0.26	IH & Holt

C.3 Delivery Route

Figure C-3 Delivery route map

Appendix 4B: Battery Electric Truck Chassis Dynamometer Testing Report

Final Report

Assessment of the Performance of a Class 5 Battery Electric Commercial Truck

Chassis Dynamometer Testing

June 2013

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Disclaimer

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Executive Summary

Battery-electric vehicles hold significant promise for reducing emissions and fuel consumption in package delivery vehicles. To assess the benefits and operational impacts of battery-electric vehicles, the California Hybrid, Efficient and Advanced Truck (CalHEAT) research center contracted with the Center for Environmental Research and Technology (CE-CERT) of the University of California, Riverside's College of Engineering to evaluate the performance and energy use of a Class 5 battery electric urban delivery vehicle over 2 standardized driving cycles and a steady state range test on a chassis dynamometer. Funding for this project was provided by the California Energy Commission.

The test vehicle, a Smith Electric Newton Step Van, was tested on 2 standardized drive cycles (the Hybrid Truck Users Forum Parcel Delivery Class 4 and the Orange County Bus Cycle) and a steady state range test. Testing was carried out on the University of California, Riverside Heavy-Duty Chassis Dynamometer. Table E-1 summarizes the results of the chassis dynamometer testing.

Test Cycle	Total Test Miles	Total Charging Time	Overall AC Energy Consumption	Overall DC Energy Consumption
HTUF4	36.06 miles	4 hours 49 minutes	0.81 AC kWh/mile	0.67 DC kWh/mile
OCBC	32.34 miles	4 hours 38 minutes	0.88 AC kWh/mile	0.72 DC kWh/mile
Steady State	91.62 miles	14 hours 21 minutes	0.98 AC kWh/mile	0.80 DC kWh/mile

Table E-1: Summary of chassis dynamometer test results.

From the steady state range test, the total battery capacity was estimated as 89.64 AC kWh.

Please note that due to testing site infrastructure limitations, we were not able to use the charging current recommended by Smith Electric Vehicles to recharge the Newton Step Van. Therefore, the charging times recorded in this report are longer than what one would expect at a customer site equipped with the recommended charging infrastructure. In addition, using a different charge rate may affect the charger efficiency and thus, the overall energy consumption calculated in this report may be larger than if the vehicle had been charged at the recommended charging rate.

Actual electric range and overall energy consumption will vary widely with driving conditions such as drive cycle and vehicle accessories utilization. The numbers presented in this report are representative of specific drive cycles and driving conditions and were derived from testing done in a controlled environment. They should not be used to predict electric range and overall energy consumption in different driving conditions. We recommend that further testing be carried on to analyze all factors influencing actual electric range and overall energy consumption.

1. Overview

The California Hybrid, Efficient and Advanced Truck (CalHEAT) Research Center (www.calheat.org) is a California-based resource center for research, development, demonstration and commercialization of advanced, efficient truck technologies and systems. The center works as a partnership of diverse stakeholder groups developing and implementing an overall research and a market transformation plan to inform manufacturers and suppliers on clean truck technology status, gaps, and needs for commercialization as well as guide state investment and funding for hybrid, efficient and advanced truck technologies.

Medium- and heavy-duty vehicles are critical to the economy, yet remain a real and growing challenge for fuel use, greenhouse gases, and criteria emissions. Medium- and heavy-duty on-road truck traffic serving urban and goods movement needs, combined with heavy-duty off-road vehicle use at distribution centers and ports, contribute significantly to fuel use, poor regional air quality, and are a sizable source of greenhouse gas emissions. Urban delivery trucks are an important category of trucks contributing to the challenge.

The goal of this study was to evaluate the performance and energy use of a Class 5 battery electric urban delivery vehicle over 2 standardized driving cycles and a steady state range test on a chassis dynamometer. In particular, the test identifies:

- The energy usage in kWh from the battery output (DC energy, kWh);
- The energy usage in kWh from the point when electricity is introduced from the electrical outlet (AC energy, kWh);
- the total time to recharge the vehicle battery; and
- the estimated battery capacity.

The testing was performed by the Center for Environmental Research and Technology (CE-CERT) of the University of California, Riverside's College of Engineering.

2. Vehicle

The vehicle tested was a Smith Electric Newton Step Van (see Figure 1 below), provided by a parcel delivery fleet, partner for this project. The Newton Step Van has a Gross Vehicle Weight Rating (GVWR) of 16,500 lbs. and a payload of 5,570 lbs. The vehicle is equipped with a SAE J1772 compliant charge port and an on-board charger fitted for 220V / 63A or 208V / 75A. Additional information about the vehicle is shown in Table 1.

Figure 1: The Smith Electric Newton Step Van

Model	Newton Step Van
Model Year	2013
Manufacturer	Smith Electric Vehicles
Motor	180 bhp (134 kW) Peak 480 lb-ft (650 Nm) Peak Smith Drive Brushless Permanent Magnet
Controller	Smith Drive Vector controlled AC system with regenerative braking
Battery	Smith Power Lithium-ion (iron phosphate) – 80 kWh
Rated Maximum Battery Capacity	240 Ah (at 100% SOC)
Nominal Battery Voltage	343V
Maximum Battery Voltage	354V
Charger	On-board, fully automatic SAE J1772
Charging Time (From 0 to 100% SOC)	At 75A: 6 to 8 hours[1] At 30A: about 20 hours[2]
Braking	2 stage regenerative braking puts energy back into battery during coasting & braking
GVWR	16,500 lbs.
Vehicle Curb Weight	10,930 lbs.
Payload (including driver weight)	5,570 lbs.
Cargo Space	684 cubic feet
Overall Length	268 in.
Overall Height	94 in.
Overall Width	87 in.
Wheelbase	154 in.
Chassis Configuration	4 x 2 (Rear Wheel Drive)
Range	Up to 80 miles
Top Speed	~63 MPH

Table 1: Specifications of the test vehicle.

[1] Charging current recommended by Smith Electric Vehicles.

[2] Due to the testing site infrastructure limitations, this is the charging current that we used for this testing.

3. Heavy-Duty Diesel Chassis Dynamometer Test Facility

Testing was carried out on the University of California, Riverside Heavy-Duty Chassis Dynamometer (HDCD) (see Appendix A for details). The dynamometer is designed to handle a range of vehicles and vehicle loads at on-road driving conditions. It includes a 48" Electric AC Chassis Dynamometer with dual, direct connected 300 horsepower motors attached to each roll set (see Figure 2). The dynamometer applies appropriate loads to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving. A driver accelerates and decelerates following a driving trace while the vehicle is chained to the dynamometer.

- Performance
  - 5,000 lb 0-15 mph
  - 600 hp 45-80 mph
  - 200 hp 15 mph
- Acceleration 6 mph/sec
- Inertia Simulation
  - 10 lb increments
  - 10,000 lb – 80,000 lb range
  - 45,000 lb base inertia
- Speed accuracy +/- 0.01 mph
- Acceleration accuracy +/- 0.02 mph/sec
- Response time 44 to 100 ms

Figure 2: Selected Data for the UCR HDCD

4. Drive Cycles Used for Testing

4.1 Hybrid Truck Users Forum Parcel Delivery Class 4

Testing was conducted on the vehicle using two drive cycles: 1) the Hybrid Truck Users Forum Parcel Delivery Class 4 (HTUF4) driving schedule and, 2) the Orange County Bus Cycle (OCBC). These drive cycles have been used in a previous study we conducted in partnership with the National Renewable Energy Laboratory (NREL) to evaluate gasoline/electric hybrid parcel delivery trucks[3].

The HTUF4 has three phases, phase 1 from 0 to 419 seconds, phase 2 from 420 to 1877 seconds, and phase 3 from 1878 to 3336 seconds. Phase 3 is an exact duplicate of phase 2 and NREL chose to run only phase 1 and 2. CE-CERT also chose to run only phase 1 and 2. The drive cycle, which includes 5 periods of engine off time, is shown in Figure 3.

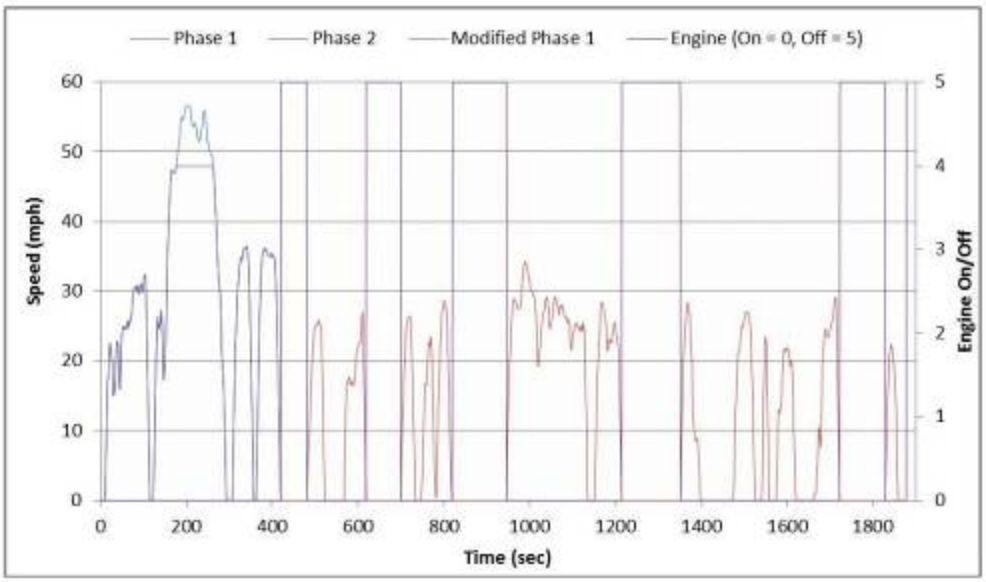


Figure 3: HTUF Class 4 Driving Schedule

[3] *Barnitt R.*, "FedEx Express Gasoline Hybrid Electric Delivery Truck Evaluation: 12-Month Report", National Renewable Energy Laboratory, December 2010

4.2 Orange County Bus Cycle

The second cycle is the Orange County Bus Cycle (OCBC). This is a continuous cycle from 0 to 1909 seconds with accelerations and decelerations from 0 to speeds between ~8 and ~40 MPH as seen in Figure 4.

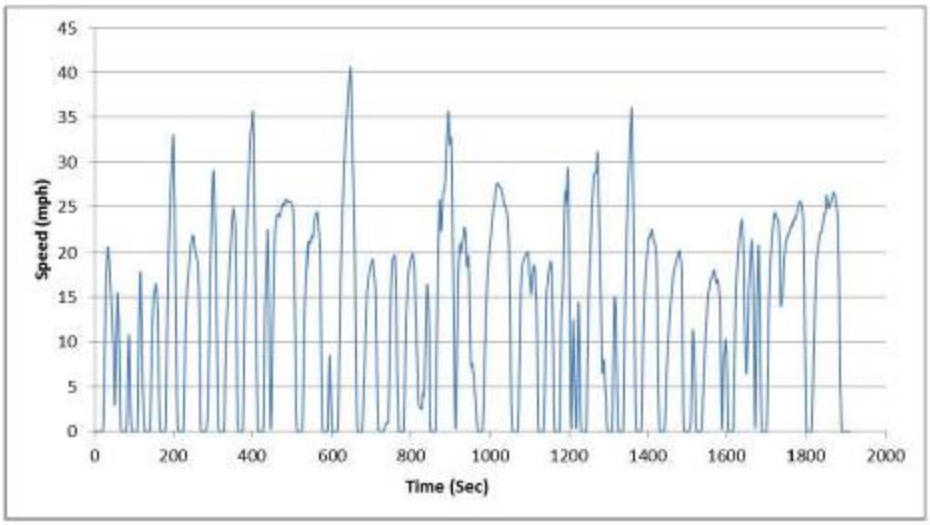


Figure 4: Orange County Bus Cycle

4.3 Steady-State Range Test

The CARB procedure to test zero-emission and hybrid electric vehicles specifies that the vehicle needs to be tested on a chassis dynamometer until "[it] is no longer able to maintain the speed and time requirements specified [...]"[4]. Given the drive cycles that we selected for this test and the vehicle range, this would prove impractical. For instance, if we assume that the vehicle has a total range of 100 miles, the vehicle will need to run 16 OCBC drive cycles consecutively to fully deplete the battery. Including 15 10-minute soak between tests, it would take a total of 10 hours and 59 minutes to complete this test.

[4] *California Environmental Protection Agency - Air Resources Board*, "California Exhaust Emission Standards and Test Procedures for 2009 and Subsequent Model Zero-Emission Vehicles and Hybrid Electric Vehicles, in the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes", December 2, 2009

In order to circumvent this long test time, we decided to follow a different approach described by Lohse-Busch[5]. We decided to run the vehicle on a 1909-second steady-state drive cycle at 55 MPH (see Figure 5 below).

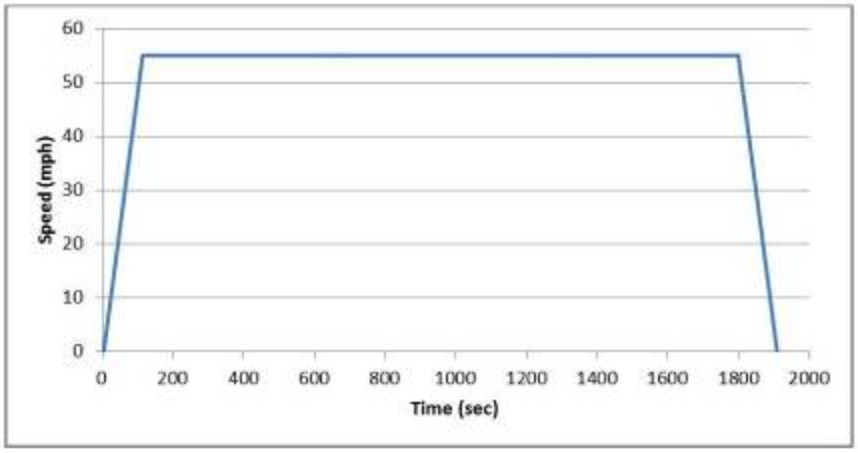


Figure 5: CALSTART Steady State Range Test

Once the vehicle was no longer able to maintain the test and time requirement specified, it was brought to a stop and plugged in to be fully recharged. The following parameters were recorded to estimate the total battery capacity:

- AC energy required to fully charge the battery after the Steady State Range Test from the point where electricity is introduced from the electric outlet to the battery charger,
- DC energy required to fully charge the battery after the Steady State Range Test from the point where electricity is introduced from the battery charger to the battery.

Using the overall energy consumption (kWh/mile) for the HTUF4 and OCBC drive cycles and the estimate of total battery capacity (kWh), the total vehicle range for the HTUF4 and OCBC drive cycles can be estimated.

[5] Lohse-Busch, Henning, "Testing and Evaluation Challenges of Electrified Vehicles", Argonne National Laboratory, April 2011

Table 2 below presents some metrics of the 3 drive cycles used:

	HTUF4 (no engine off)	OCBC	Steady-State
Average Speed (MPH)	14.01	12.33	51.74
Standard Deviation of Speed	15.31	10.30	10.51
Maximum Speed (MPH)	56.59	40.63	55.00
Maximum Acceleration (MPH/sec)	5.00	4.06	0.50
Maximum Deceleration (MPH/sec)	-5.00	-5.13	-0.50
Total Time (sec)	1877	1909	1909
Idle Time (sec)	794	406	4
Total Distance (miles)	7.31	6.54	27.42
Number of Idle Periods	17	32	2
Number of Stops	16	31	1
% Idle	42.30	21.27	0.21

Table 2: Metrics of the HTUF4, OCBC and Steady-State Cycles

4.4 Note about Vehicle Accessories and Weather Conditions

While the Newton Step Van was tested on 2 different standardized driving cycles and a steady state range test, it was decided that for all three test cycles, air conditioning and cabin fan would be switched off. In addition it was not possible to assess the influence of ambient temperature and other weather conditions.

Actual electric range and overall energy consumption will vary widely with driving conditions such as drive cycle and vehicle accessories utilization. The numbers presented in this report are representative of specific drive cycles and driving conditions and were derived from testing done in a controlled environment. They should not be used to predict electric range and overall energy consumption in different driving conditions. We recommend that further testing be carried out to analyze all factors influencing actual electric range and overall energy consumption.

5. Methodology

5.1. Coast down data

Coast down parameters were calculated using the frontal area calculation approach[5]. The frontal area was 56.79 square feet and the vehicle weight chosen for this testing was 13,175 lbs., which is the vehicle curb weight plus one half of the vehicle payload. The calculated coast down data is shown in Table 3 and the dynamometer coefficients for the tests in Table 4.

Vehicle Weight (lbs)	Seconds to coast down for MPH range				
	65 - 55	55 - 45	45 - 35	35 - 25	25 - 15
13,175	12.94	17.12	23.26	32.26	44.58

Table 3: Calculated Coast Down Data

Load	A	B:	C:	Hp @ 50
lbs.	lbs./MPH	lbs./MPH	lbs./MPH	
13,175	97.41	-7×10^{-14}	0.1071	48.7

Table 4: Dynamometer Coefficients for the Tests

The results of the coast down calculations were used to set the coefficients for the chassis dynamometer testing.

5.2. Regenerative braking

The Smith Electric Newton Step Van is equipped with a 2-stage regenerative braking system that puts energy back into the battery pack during coasting and braking. In addition, the vehicle has a regenerative braking switch to activate/deactivate the regenerative braking system (see Figure 6). The partner fleet specified that drivers will be required to use the vehicle with the regenerative braking switch in the ON position at all times. Thus, the regenerative braking switch was left in the ON position for the entire testing.

Figure 6: The Newton Step Van control panel

[5] Draft test plan, "In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines", Prepared for Adewale Oshinuga, South Coast Air Quality Management District, RFP #P2011-6, October 2011

5.3. Test cycle data

The vehicle was equipped with a proprietary Smith Link data acquisition system which was set to record the following vehicle parameters at a 1Hz sampling period:

- Date and Time in Greenwich Mean Time (GMT),
- Ambient temperature (°C),
- Electric motor rotation speed (RPM),
- Accelerator pedal position,
- Brake pedal position,
- Battery current (A),
- Battery voltage (V),
- Battery State of Charge (%),
- Battery management system mode (0 = key-off, 1 = charging, 2 = driving)

Note that by convention, negative battery current values indicate energy used from the batteries to move the vehicle and power the accessories and positive battery current values indicate energy added to the batteries through regenerative braking or charging.

The Smith Link logging was continuous throughout the day and transmitted wirelessly to remote servers. After each testing day an engineer from Smith Electric Vehicles sent all the testing files in .csv format for processing in Microsoft Excel.

In addition, the chassis dynamometer was set to measure and record the following parameters:

- Relative time in seconds from the beginning of the run,
- Speed in MPH,
- Distance in miles,
- Other variables as needed.

At the end of the driving schedule, the chassis dynamometer data was saved and later exported to a .csv file for processing.

5.4. Vehicle charging data

A portable J1772 EVSE (see Figure 7 on the left) was supplied for this testing. The EVSE came mounted on a cart and equipped with a revenue grade meter which recorded both grid energy (AC kWh) and power (kW) at 15 minute intervals.

Figure 7: Portable EVSE used for recharging the vehicle

Both the facility electrical system and the EVSE used for this testing were limited in the grid current that could be used for charging. Due to these testing site infrastructure limitations, we were not able to use the charging current recommended by Smith Electric Vehicles to recharge the Newton Step Van. Therefore, the charging times recorded in this report are longer than what one would expect at a customer site equipped with the recommended charging infrastructure. In addition, using a different charge rate may affect the charger efficiency and thus, the overall energy consumption (in kWh/mile) calculated in this report may be larger than if the vehicle had been charged at the recommended charging rate.

At the end of each test day, the vehicle was put into charge using the portable EVSE until the vehicle dashboard displayed a charge complete window (see Figure 8).

Figure 8: The Newton Step Van dashboard showing a charge complete

At the end of the full testing period, data was downloaded through optical ports on the front of the meter, using a special software tool. Grid energy (in AC kWh) was manually read from the digital display of the meter attached behind the portable EVSE (see Figure 7 on the right) before plugging and unplugging the portable EVSE.

5.5. Definition of calculated parameters

Using the test cycle data and the vehicle charging data described in sections 5.3 and 5.4 above, a wide variety of parameters were calculated to describe the test results.

- *Test Run*

A test run (or a run) represents one run through one of the 3 test cycles (HTUF4, OCBC or Steady State).

- *Test Day*

A test day represents a complete chassis dynamometer test for one of the 3 test cycles (HTUF4, OCBC or Steady State). It is composed of several test runs and several 10-minute soak periods between each test run.

- *Vehicle Speed*

Vehicle speed (in MPH) was derived from the Electric Motor Rotation Speed (in RPM) following equation (1) below:

$$\text{Vehicle Speed (MPH)} = \text{A x Electric Motor Rotation Speed (RPM)} \qquad (1)$$

Where A was calculated using vehicle tire diameter and overall drive reduction per Smith Electric Vehicles specifications.

- *Total Dyno. Miles*

The total miles driven during a particular test run recorded by the chassis dynamometer instruments.

- *Total ECM Miles*

The total miles driven during a particular test run calculated from the Vehicle Speed using equation (2) below:

$$\text{Total ECM Miles} = \sum_{i=1}^{n} \frac{\text{Vehicle Speed (MPH)}}{3600\ (\frac{\text{sec}}{\text{hr}})} \qquad (2)$$

Where *n* is the number of seconds in the test run.

- *Net DC Energy*

The total DC energy in kWh that was sent to and from the vehicle battery for a particular test run, calculated from the Battery Current and Battery Voltage using equation (3) below:

$$\text{Net DC Energy (DC kWh)} = \frac{\text{Battery Current (A)} \times \text{Battery Voltage (V)}}{1000\ (\frac{\text{W}}{\text{kW}}) \times 3600\ (\frac{\text{seconds}}{\text{hour}})} \qquad (3)$$

- *DC Energy Output (kWh)*

The negative DC energy in kWh that was sent from the vehicle battery for a particular test run, calculated from the Battery Current and Battery Voltage using equation (4) below:

$$\text{DC Energy Output (DC kWh)} = \text{Min}\left(0, \frac{\text{Battery Current (A)} \times \text{Battery Voltage (V)}}{1000\left(\frac{\text{W}}{\text{kW}}\right) \times 3600\left(\frac{\text{seconds}}{\text{hour}}\right)}\right) \quad (4)$$

- *DC Energy Input (kWh)*

The positive DC energy in kWh that was sent to the vehicle battery for a particular test run, calculated from the Battery Current and Battery Voltage using equation (5) below:

$$\text{DC Energy Input (DC kWh)} = \text{Max}\left(0, \frac{\text{Battery Current (A)} \times \text{Battery Voltage (V)}}{1000\left(\frac{\text{W}}{\text{kW}}\right) \times 3600\left(\frac{\text{seconds}}{\text{hour}}\right)}\right) \quad (5)$$

- *SOC Test Start*

The Battery State Of Charge when a particular test run starts.

- *SOC Test End*

The Battery State Of Charge when a particular test run ends.

- *Net DC Energy Consumption*

The energy consumption rate in DC kWh/mile for a particular test run, calculated from the Net DC Energy (kWh) and the Total Dyno. Miles using equation (6) below:

$$\text{Net DC Energy Consumption (DC kWh/mile)} = \frac{Net\ DC\ Energy\ (kWh)}{Total\ Dyno\ Miles} \quad (6)$$

- *DC Energy Output (kWh/mile)*

The negative DC energy in kWh/mile that was sent from the vehicle battery for a particular test run, calculated from the DC Energy Output (kWh) and the Total Dyno. Miles using equation (7) below:

$$\text{DC Energy Output (DC kWh/mile)} = \frac{DC\ Energy\ Output\ (kWh)}{Total\ Dyno\ Miles} \quad (7)$$

- *DC Energy Input (kWh/mile)*

The positive DC energy in kWh/mile that was sent to the vehicle battery for a particular test run, calculated from the DC Energy Input (kWh) and the Total Dyno. Miles using equation (8) below:

$$\text{DC Energy Input (DC kWh/mile)} = \frac{DC\ Energy\ Input\ (kWh)}{Total\ Dyno\ Miles} \quad (8)$$

- *Charge Starting*

The moment when the vehicle is plugged-in to the portable EVSE, identified on the battery current by a change from a null or negative value to a positive value. By convention, the time when the charge is starting is assigned to 0:00:00.

- *Bulk Charging*

Bulk Charging is achieved when the Battery SOC first reaches 100%.

- *Total Charging*

Total Charging is achieved when the Battery SOC first reaches 100% and the Battery Current first drops to 0.

- *Vehicle Unplugged*

Vehicle Unplugged is achieved when the battery management system mode goes from 1 to 0 or 2. It represents the instant when the vehicle is unplugged from the portable EVSE.

- *Recorded Time*

The time (in hh:mm:ss PDT) that was recorded at a particular event.

- *Cumulative Time*

The cumulative time (in hh:mm:ss) since the charge started.

- *AC Energy Charged*

The total energy in AC kWh recorded by the revenue grade meter at the back of the portable EVSE for a particular charging event (i.e. from the Charge Starting Recorded Time to the Bulk / Total Charging or Vehicle Unplugged Recorded Time). Since the meter recorded at 15-minute intervals, we used the nearest superior 15-minute reading. For instance, if the Bulk Charging Time was 21:47:00, we used the AC kWh reading for 22:00:00.

- *AC Energy Charged (manual reading)*

The total energy in AC kWh manually read from the meter before and after the vehicle was plugged to the portable EVSE.

- *DC Energy Charged*

The total DC energy in kWh that was sent to the vehicle battery for a particular charging event (i.e. from the Charge Starting Recorded Time to the Bulk / Total Charging or Vehicle Unplugged Recorded Time). It is calculated from the Battery Current and Battery Voltage using equations (9) and (10) below:

$$\text{DC Energy (kWh)} = \frac{\text{Battery Current (A)} \times \text{Battery Voltage (V)}}{1000\left(\frac{\text{W}}{\text{kW}}\right) \times 3600\left(\frac{\text{seconds}}{\text{hour}}\right)} \quad (9)$$

$$\text{DC Energy Charged (kWh)} = \sum_{i=1}^{n} DC \text{ Energy (kWh)} \quad (10)$$

Where *n* is the number of seconds in the test run.

- *Overall AC Energy Consumption*

The energy consumption rate in AC kWh/mile for a particular test day, calculated from the AC Energy Charged recorded at Total Charging and the sum of Total Dyno. Miles for all test runs using equation (11) below:

$$\text{Overall AC Energy Consumption (AC kWh/mile)} = \frac{AC\ Energy\ Charged\ (kWh)}{\sum_{i}^{n}(Total\ Dyno\ Miles)i} \quad (11)$$

Where *n* is the number of test runs done for each particular test day.

- *Overall DC Energy Consumption*

The energy consumption in DC kWh/mile for a particular test day, calculated from the DC Energy Charged recorded at Total Charging and the sum of Total Dyno. Miles for all test runs using equation (12) below:

$$\text{Overall DC Energy Consumption (DC kWh/mile)} = \frac{DC\ Energy\ Charged\ (kWh)}{\sum_{i}^{n}(Total\ Dyno\ Miles)i} \quad (12)$$

Where *n* is the number of test runs done for each particular test day.

- *Maximum Charging Power*[7]

The maximum grid power in kW recorded by the revenue grade meter at the back of the portable EVSE for a particular charging event (i.e. from the Charge Starting Recorded Time to the Vehicle Unplugged Recorded Time).

[7] Please note that this was limited by the charging infrastructure available for this testing.

5.6. Soak Period

A 10-minute soak period was included between each test run. During this soak period, it was decided to leave the vehicle in the key-on position to avoid loss of data from the Smith Link data acquisition system. We noticed that the vehicle drew a small amount of energy from the vehicle battery while idling. We estimated this energy consumption at idle between 0.50 and 1.00 AC kWh per an entire test day (including 4 10-minute soak periods).

The grid energy supplied to recharge the vehicle after each test day (AC Energy Charged and DC Energy Charged) does include this energy consumption during the soak periods in addition to the energy expended during the test runs.

6. Test Results

6.1. HTUF4 (Test #1)

The HTUF4 test #1 was completed on March 27th, 2013. The test day consisted of 5 consecutive HTUF4 test runs and a 10-minute soak in between each run. The first run started at 7:17:33 AM and the 5th run ended at 10:35:55 AM. The entire test day took 3:18:22. Average ambient temperature during each run varied from 59.4°F to 71.9°F. Battery charging began about 36 minutes after the completion of the last HTUF4 test run.

After the HTUF4 test, the engineer from Smith Electric Vehicles reported issues in the data that was collected by the Smith Link data acquisition system. During the long periods of idle, the vehicle was keyed-off to represent more realistic fleet operations. Due to data buffering issues, data "froze" to the last valid number recorded a few seconds before and after the key-off event. Therefore, the recorded Smith Link data was deemed invalid and is not reported in this section.

The HTUF4 test was repeated on March 28th, 2013 following the OCBC test without turning the key off. In addition, to ensure there was no data loss, the vehicle was keyed-on 1-2 minutes before beginning any test run and up to 10 minutes at the end of the test day.

Table 5 below summarizes the charging data for this test.

	Charge Starting	Bulk Charging	Total Charging	Vehicle Unplugged
Recorded Time (hh:mm:ss PDT)	11:11:55 (3/27)	15:41:30 (3/27)	15:59:39 (3/27)	7:21:47 (3/28)
Cumulative Time (hh:mm:ss)	0:00:00	4:29:35	4:47:44	20:09:52
AC Energy Charged	0.0000	29.0145	29.8476	30.8937
AC Energy Charged (manual reading)	0	-	-	31
DC Energy Charged	0.00	23.49	24.36	24.36

Table 5: Summary of charging data following the HTUF4 Test #1 on 3/27/13

The chassis dynamometer recorded a total of 36.06 miles driven for the 5 test runs. From Table 5, the Overall AC Energy Consumption was calculated as **0.83 AC kWh/mile** and the Overall DC Energy Consumption as **0.68 DC kWh/mile**.

Figure 9 below shows the cumulative AC and DC energy consumed to recharge the battery, the vehicle SOC and the AC charging rate in kW.

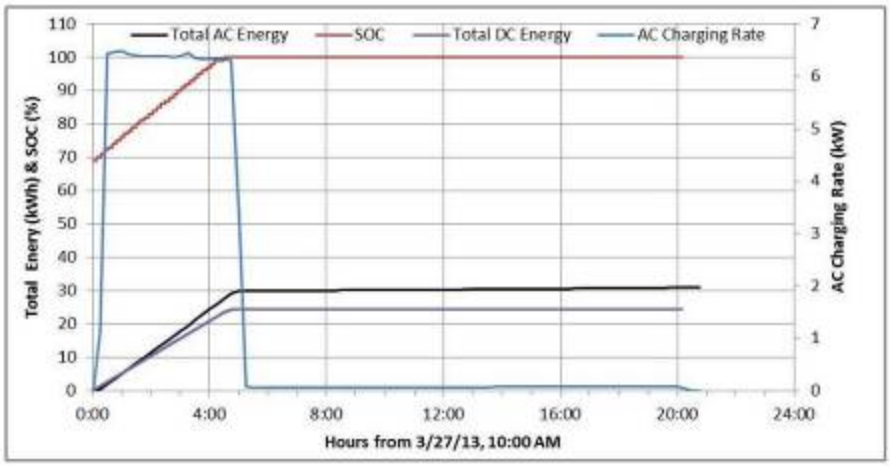


Figure 9: Total AC Energy, SOC, Total DC Energy, and AC Charging Rate for HTUF4 Test

Maximum charging power was recorded as **6.49 AC kW**. Once the SOC reached 100% and the battery current dropped to 0 (indicating total charge time), the vehicle continued to draw a small amount of current from the grid until it was unplugged. A total of 1.05 AC kWh was consumed from the time the vehicle reached the total charging time and the time the vehicle was unplugged from the charger.

6.2. OCBC & HTUF4 (Test #2)

The OCBC test was completed on March 28th, 2013. The testing consisted of 5 consecutive OCBC runs and a 10-minute soak in between each run. The first run started at 7:21:47 AM and the 5th run ended at 10:53:33 AM. The entire OCBC testing took 3:18:22. Average ambient temperature during each run varied from 59.0°F to 76.9°F. The HTUF4 test cycle was repeated after a 10-minute soak following OCBC Run #5. Therefore, battery charging was not started after the completion of the last OCBC test run

Table 6 below summarizes the results for each of the 5 consecutive runs, the average for the 5 runs and the 95% confidence interval.

	OCBC – 3/28/13							
	Run #1	Run #2	Run #3	Run #4	Run #5	Total	Avg. Cycle	95% CI
Total Dyno. Miles (miles)	6.51	6.32	6.48	6.51	6.52	32.34	6.47	0.10
Total ECM Miles (miles)	6.56	6.43	6.56	6.56	6.55	32.67	6.53	0.07
Net DC Energy (kWh)	-4.33	-4.08	-3.91	-3.78	-3.77	-19.86	-3.97	0.29
DC Energy Output (kWh)	-6.60	-6.41	-6.29	-6.13	-6.10	-31.53	-6.31	0.25
DC Energy Input (kWh)	2.27	2.33	2.38	2.35	2.34	11.67	2.33	0.05
SOC Test Start (%)	99	93	88	83	78	-	-	-
SOC Test End (%)	93	88	83	78	73	-	-	-
Net DC Energy Consumption (kWh/mile)	-0.67	-0.65	-0.60	-0.58	-0.58	-	-0.61	0.05
DC Energy Output (kWh/mile)	-1.01	-1.01	-0.97	-0.94	-0.94	-	-0.97	0.05
DC Energy Input (kWh/mile)	0.35	0.37	0.37	0.36	0.36	-	0.36	0.01

Table 6: Summary of results for the OCBC test on 3/28/13

Figures 10 to 14 below show battery current, voltage and SOC, vehicle speed and time for each OCBC test run.

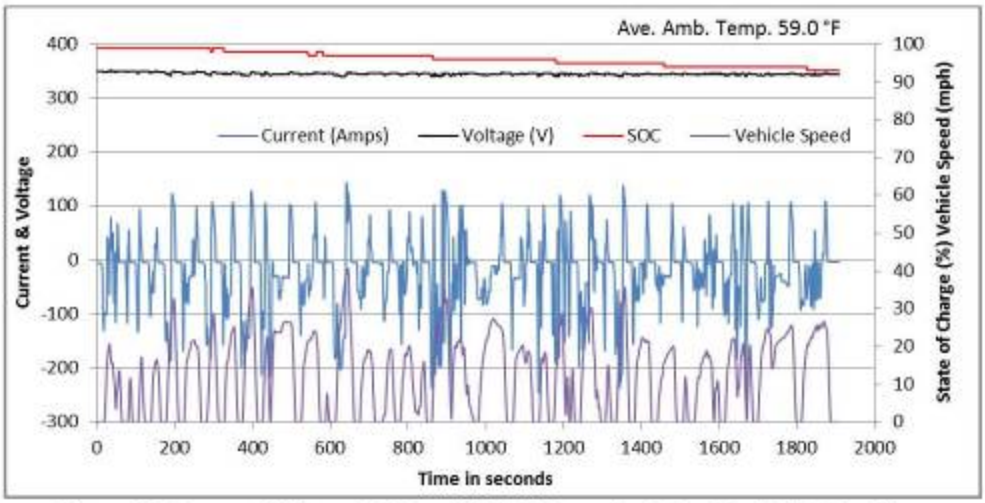


Figure 10: Current, Voltage, SOC, and Vehicle Speed vs. Time for OCBC Run #1

During the 2nd test run through the OCBC cycle on March 28th, 2013, the vehicle lost power for 61 seconds after 2/3 of the cycle was completed.

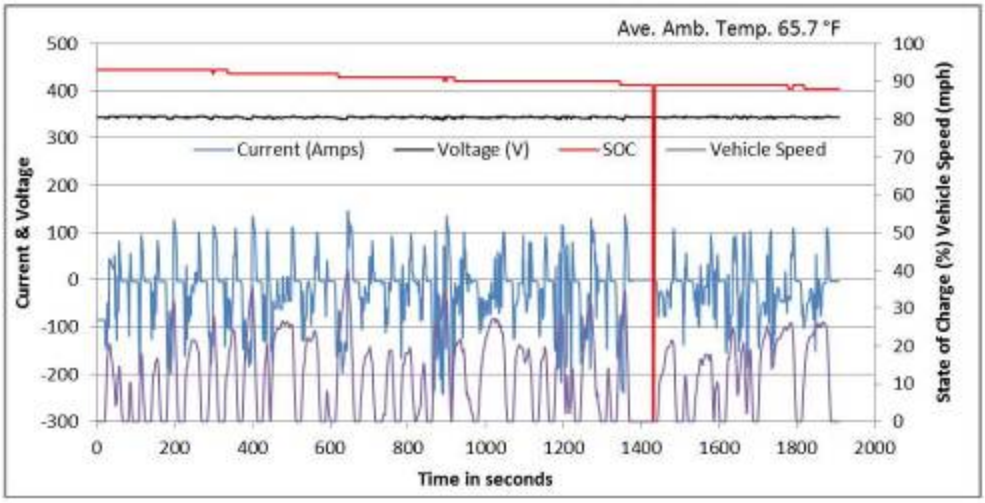


Figure 11: Current, Voltage, SOC, and Vehicle Speed vs. Time for OCBC Run #2

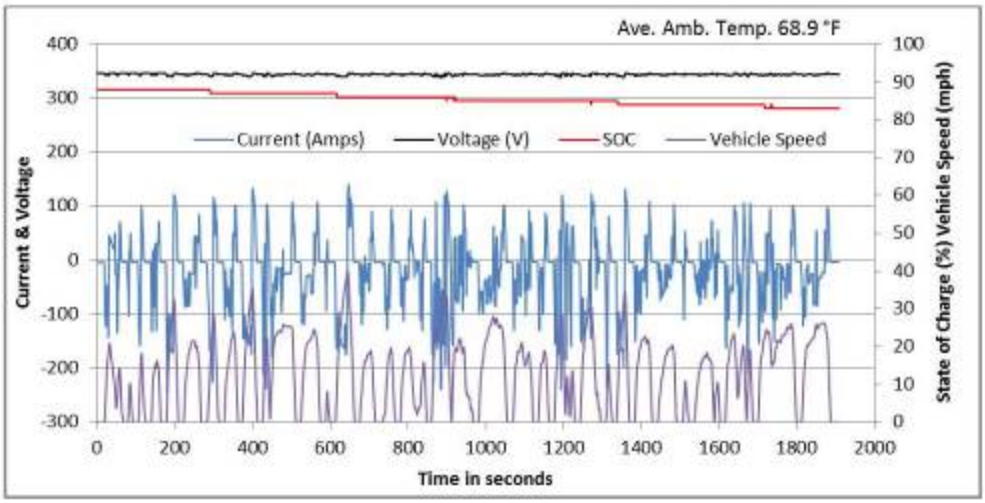


Figure 12: Current, Voltage, SOC, and Vehicle Speed vs. Time for OCBC Run #3

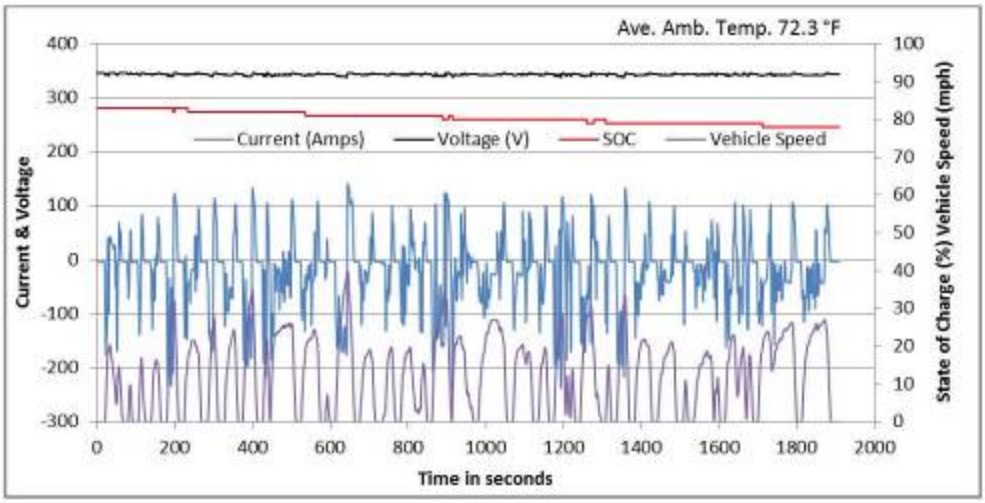


Figure 13: Current, Voltage, SOC, and Vehicle Speed vs. Time for OCBC Run #4

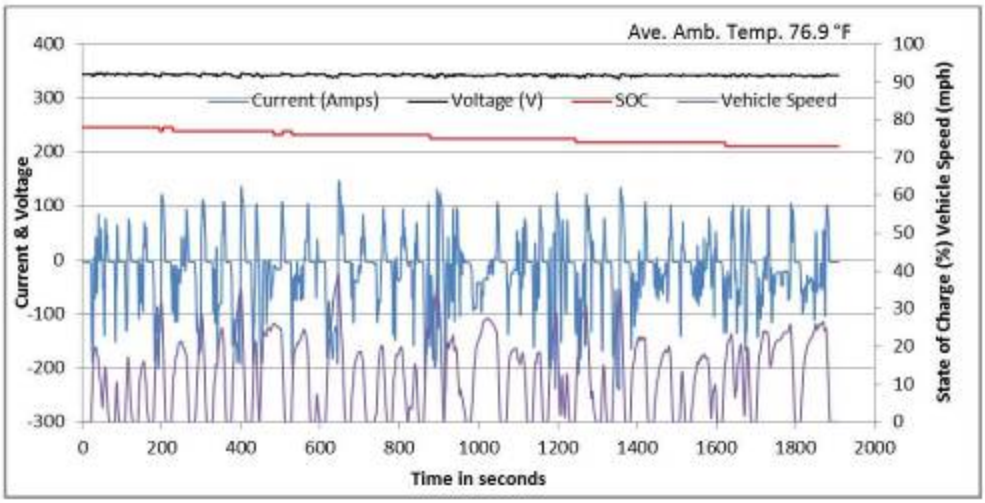


Figure 14: Current, Voltage, SOC, and Vehicle Speed vs. Time for OCBC Run #5

The HTUF4 test #2 was completed on March 28th, 2013. The testing consisted of 5 consecutive HTUF4 runs and a 10-minute soak in between each run. The first run started at 11:34:42 AM and the 5th run ended at 14:55:45 PM. The entire HTUF 4 testing took 3:21:03. Average ambient temperature during each run varied from 79.9°F to 87.2°F. Battery charging began less than 7 minutes after the completion of the last HTUF4 test run.

Table 7 below summarizes the results for each of the 5 consecutive runs, the average for the 5 runs and the 95% confidence interval.

	HTUF4 (Test #2) – 3/28/13							
	Run #1	Run #2	Run #3	Run #4	Run #5	Total	Avg. Cycle	95% CI
Total Dyno. Miles (miles)	7.24	7.22	7.20	7.17	7.23	36.06	7.21	0.03
Total ECM Miles (miles)	7.30	7.28	7.29	7.25	7.30	36.42	7.28	0.03
Net DC Energy (kWh)	-3.82	-4.56	-4.48	-4.57	-4.77	-22.20	-4.44	0.45
DC Energy Output (kWh)	-6.09	-6.51	-6.53	-6.53	-6.95	-32.62	-6.52	0.38
DC Energy Input (kWh)	2.27	1.94	2.05	1.96	2.18	10.42	2.08	0.18
SOC Test Start (%)	73	67	61	54	48	-	-	-
SOC Test End (%)	67	61	54	48	42	-	-	-
Net DC Energy Consumption (kWh/mile)	-0.53	-0.63	-0.62	-0.64	-0.66	-	-0.62	0.06
DC Energy Output (kWh/mile)	-0.84	-0.90	-0.91	-0.91	-0.96	-	-0.90	0.05
DC Energy Input (kWh/mile)	0.31	0.27	0.29	0.27	0.30	-	0.29	0.02

Table 7: Summary of results for the HTUF4 test #2 on 3/28/13

Figures 15 to 19 below show battery current, voltage and SOC, vehicle speed and time for each HTUF4 test run.

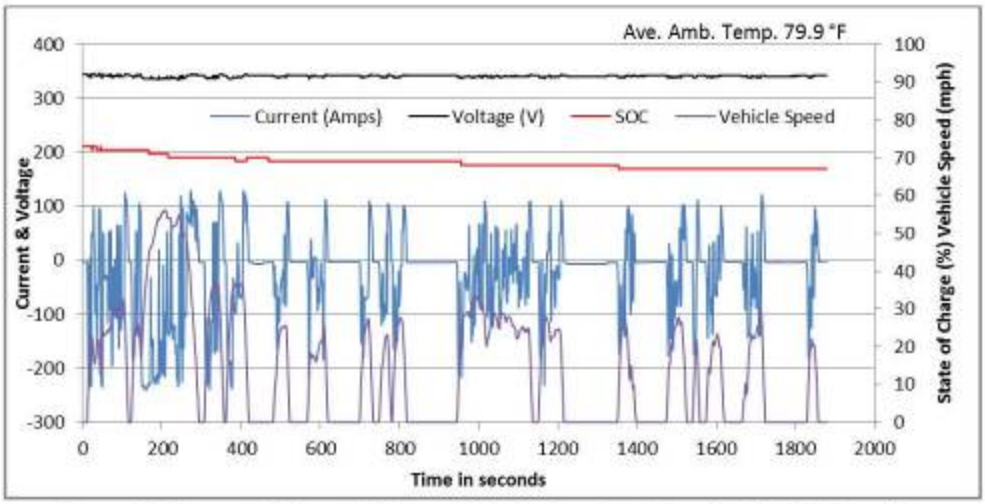


Figure 15: Current, Voltage, SOC, and Vehicle Speed vs. Time for HTUF4 Run #1

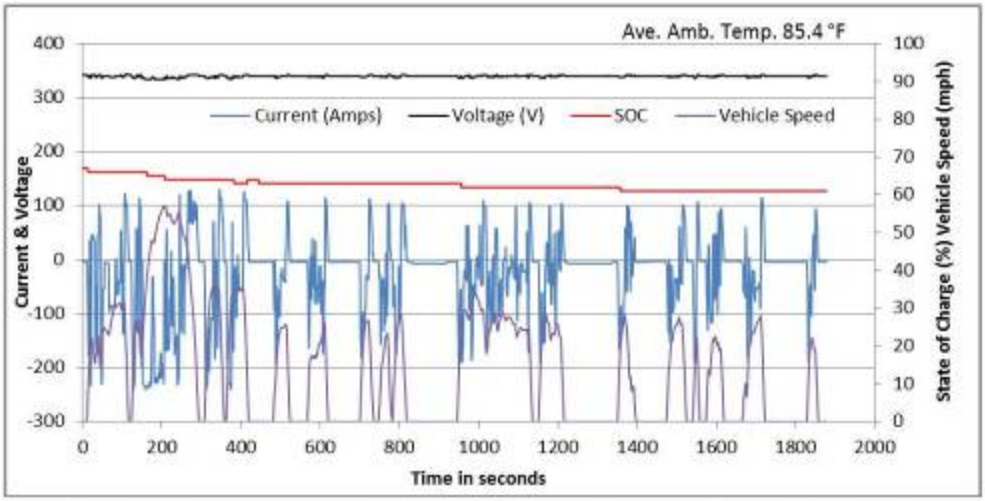


Figure 16: Current, Voltage, SOC, and Vehicle Speed vs. Time for HTUF4 Run #2

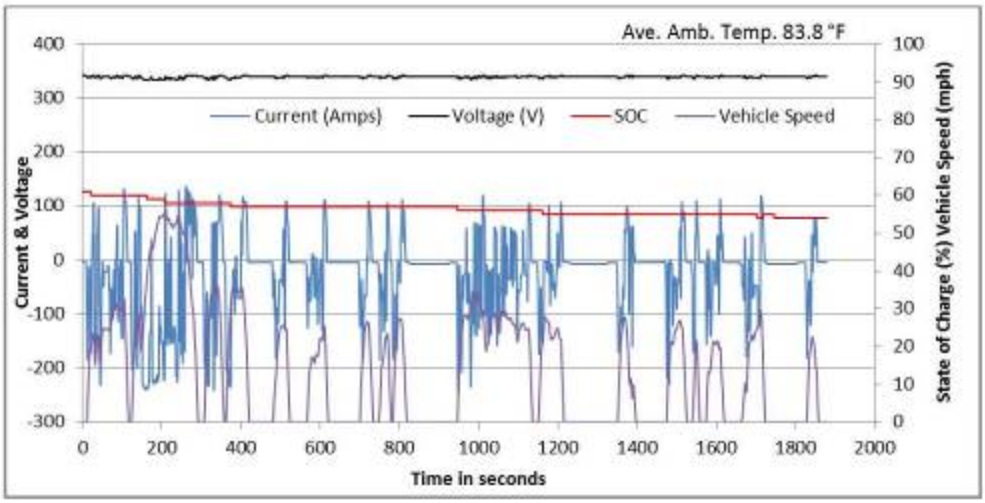


Figure 17: Current, Voltage, SOC, and Vehicle Speed vs. Time for HTUF4 Run #3

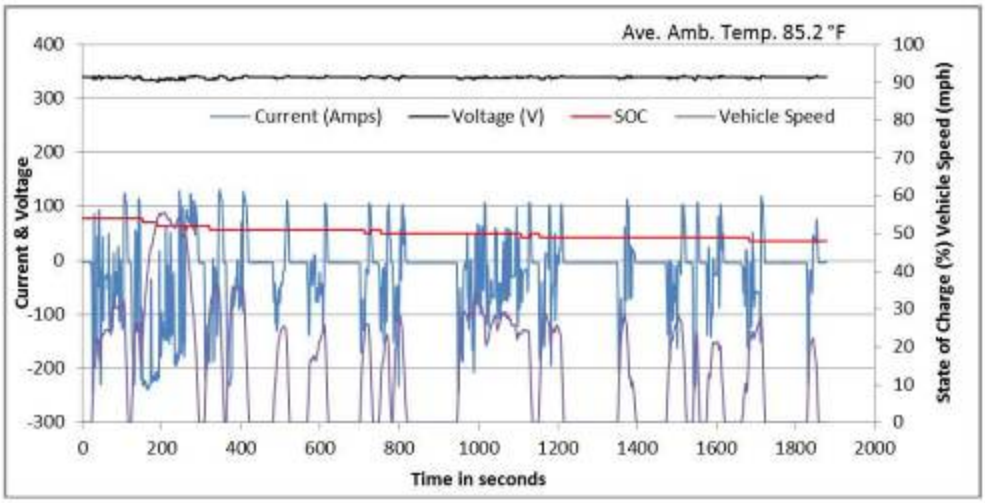


Figure 18: Current, Voltage, SOC, and Vehicle Speed vs. Time for HTUF4 Run #4

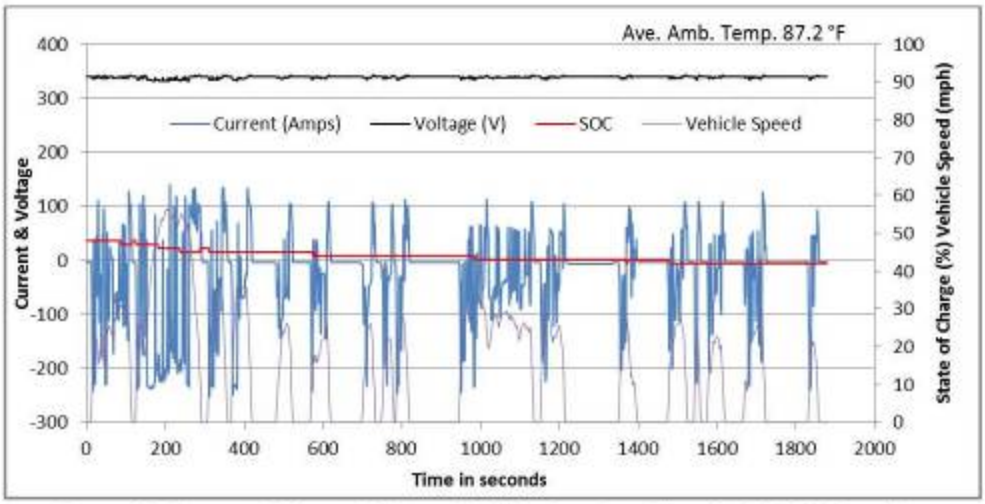


Figure 19: Current, Voltage, SOC, and Vehicle Speed vs. Time for HTUF4 Run #5

Table 8 below summarizes the charging data for the full day of testing (including the OCBC and repeat of the HTUF4 cycle test).

For OCBC / HTUF4(#2)	Charge Starting	Bulk Charging	Total Charging	Vehicle Unplugged
Recorded Time (hh:mm:ss PDT)	15:02:00 (3/28)	23:25:23 (3/28)	23:57:42 (3/28)	7:21:56 (4/1)
Cumulative Time (hh:mm:ss)	0:00:00	8:23:23	8:55:42	88:19:56
AC Energy Charged	0.0000	53.6313	55.5936	63.7089
AC Energy Charged (manual reading)	0	-	-	64
DC Energy Charged	0.00	43.54	45.56	N/A

Table 8: Summary of charging data following the OCBC & HTUF4 test #2 on 3/28/13

From Tables 6, 7 and 8, the Overall AC Energy Consumption was calculated as **0.81 AC kWh/mile** and the Overall DC Energy Consumption as **0.67 DC kWh/mile**. Please note that these numbers are for the full day of testing, including the OCBC and repeat of the HTUF4 cycle test.

Figure 20 below shows the cumulative AC and DC energy consumed to recharge the battery, as well as the vehicle SOC and the AC charging rate in kW.

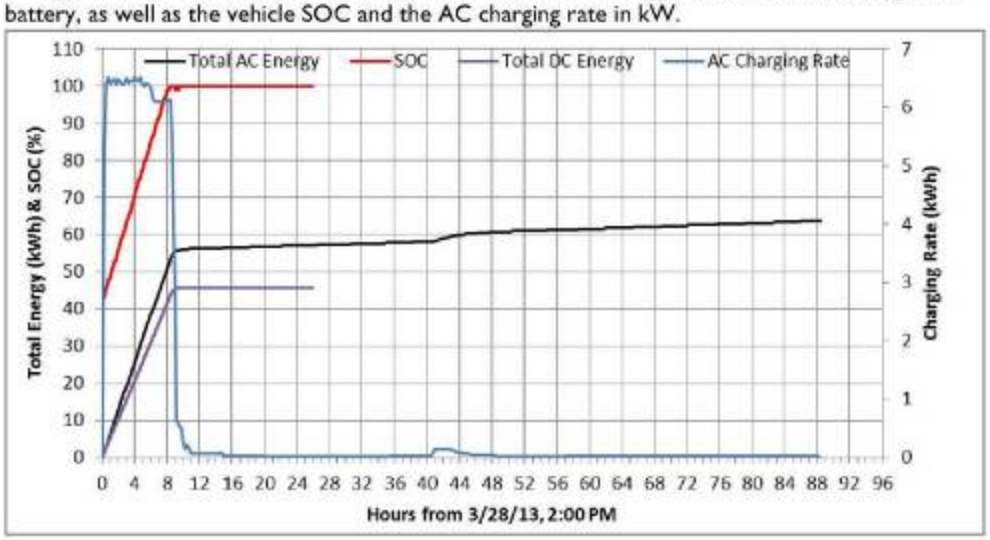


Figure 20: Total AC Energy, SOC, Total DC Energy, and AC Charging Rate for OCBC & HTUF4 Test #2

Maximum charging power was recorded as **6.53 AC kW**. Once the SOC reached 100% and the battery current dropped to 0 (indicating total charge time), the vehicle continued to draw a small amount of current from the grid until it was unplugged. A total of 8.12 AC kWh was consumed from the time the vehicle reached the total charging time to the time the vehicle was unplugged.

As the OCBC and HTUF4 tests were conducted consecutively before recharging the vehicle, we needed to estimate from the total energy used to recharge the batteries, which portion corresponds to the energy used for the OCBC test and which one corresponds to the energy used for the HTUF4 test. Table 7 shows that the HTUF4 test occurred between 73% and 42% battery SOC, while Table 6 shows that the OCBC test occurred between 100% and 73% SOC. In order to estimate the charging energy corresponding to each test (OCBC and HTUF4), we made the following assumptions summarized in Figure 21 below:

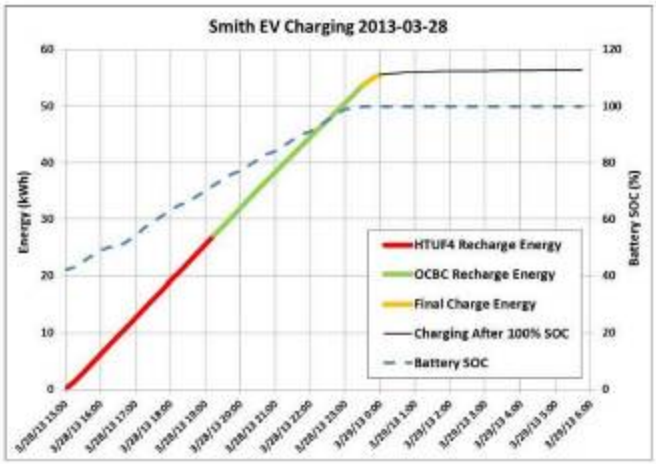


Figure 21: Allocation of Cumulative Charging Energy on 3/28/2013

- The portion in red in Figure 21 corresponds to the energy used to recharge the battery from a SOC of 42% until it first reaches 73%. It represents the bulk charging energy for the HTUF4 test.

Recorded Time (hh:mm:ss PDT)	19:19:11 (3/28)
AC Energy Charged	27.1386
DC Energy Charged	22.13

Table 9: Summary of charging data for the HTUF4 test #2 on 3/28/13

- The portion in green in Figure 21 corresponds to the energy used to recharge the battery from a SOC of 73% until it first reaches 100%. It represents the bulk charging energy for the OCBC test.

Recorded Time (hh:mm:ss PDT)	23:25:23 (3/28)
AC Energy Charged	26.4927
DC Energy Charged	21.41

Table 10: Summary of charging data for the OCBC test on 3/28/13

- The portion in orange in Figure 21 corresponds to the energy used to recharge the battery from a SOC of 100% until the battery current first reaches 0. It represents the final charge energy and we assume this final charge energy is needed each time the vehicle is recharged.

Recorded Time (hh:mm:ss PDT)	23:57:42 (3/28)
AC Energy Charged	1.9623
DC Energy Charged	2.01

Table 11: Summary of charging data for final charge on 3/28/13

- The total charging energy used to recharge the vehicle batteries after the HTUF4 test is the bulk charging energy for the HTUF4 test plus the final charge energy.

For HTUF4 (Test #2)	Charge Starting	Bulk Charging	Total Charging Start	Total Charging End
Recorded Time (hh:mm:ss PDT)	15:02:00 (3/28)	19:19:11 (3/28)	23:25:24 (3/28)	23:57:42 (3/28)
Cumulative Time (hh:mm:ss)	0:00:00	4:17:11	4:17:12	4:49:30
AC Energy Charged	0.0000	27.1386	27.1386	29.1009
DC Energy Charged	0.00	22.13	22.13	24.14

Table 12: Summary of estimated charging data for the HTUF4 test #2 on 3/28/13

From tables 9, 11 and 12, the Overall AC Energy Consumption for the HTUF4 test was calculated as **0.81 AC kWh/mile** and the Overall DC Energy Consumption for the HTUF4 test as **0.67 DC kWh/mile**.

- Similarly, the total charging energy for the OCBC test is the OCBC recharge energy plus the final charge energy.

For OCBC	Charge Starting	Bulk Charging	Total Charging Start	Total Charging End
Recorded Time (hh:mm:ss PDT)	19:19:11 (3/28)	23:25:23 (3/28)	23:25:24 (3/28)	23:57:42 (3/28)
Cumulative Time (hh:mm:ss)	0:00:00	4:06:12	4:06:13	4:38:31
AC Energy Charged	0.0000	26.4927	26.4927	28.455
DC Energy Charged	0.00	21.41	21.41	23.42

Table 13: Summary of estimated charging data for the OCBC test on 3/28/13

From tables 10, 11 and 13, the Overall AC Energy Consumption for the OCBC test was calculated as **0.88 AC kWh/mile** and the Overall DC Energy Consumption for the OCBC test as **0.72 DC kWh/mile.**

6.3. Steady State Range Test

The steady state range test was completed on April 1st, 2013. Testing continued until the vehicle was no longer able to maintain the speed in the test schedule. The test day consisted of 4 consecutive steady state runs and a 10-minute soak in between each run. The first run started at 7:21:57 AM and the 4th run ended at 9:42:19 AM. The entire test (going from 100 to 0% SOC) took 2:20:22. Average ambient temperature during each run varied from 67.5°F to 79.9°F. Battery charging began less than 4 minutes after the completion of the last steady state test run.

Table 14 below summarizes the results for each of the 4 consecutive runs, the average for the 4 runs and the 95% confidence interval.

	Steady State Range Test – 4/1/13						
	Run #1	Run #2	Run #3	Run #4	Total	Avg. Cycle	95% CI
Total Dyno. Miles (miles)	27.48	27.33	27.35	9.46	91.62	22.90	14.26
Total ECM Miles (miles)	27.89	27.33	27.67	9.60	92.48	23.12	14.35
Net DC Energy (kWh)	-22.05	-19.70	-19.71	-6.83	-68.29	-17.07	11.01
DC Energy Output (kWh)	-22.25	-19.87	-19.93	-6.83	-68.88	-17.22	11.16
DC Energy Input (kWh)	0.20	0.16	0.22	0.00	0.59	0.15	0.16
SOC Test Start (%)	100	70	44	17	-	-	-
SOC Test End (%)	70	44	17	0	-	-	-
Net DC Energy Consumption (kWh/mile)	-0.80	-0.72	-0.72	-0.72	-	-0.75	0.06
DC Energy Output (kWh/mile)	-0.81	-0.73	-0.73	-0.72	-	-0.75	0.07
DC Energy Input (kWh/mile)	0.01	0.01	0.01	0.00	-	0.01	0.01

Table 14: Summary of results for the Steady State test on 4/1/13

The large values for confidence intervals calculated for this test were caused by run #4 which was interrupted at vehicle SOC equal to 0% before it could be completed.

Table 15 below summarizes the charging data for this test.

	Charge Starting	Bulk Charging	Total Charging	Vehicle Unplugged
Recorded Time (hh:mm:ss PDT)	9:46:15 (4/1)	22:45:04 (4/1)	0:07:00 (4/2)	7:24:34 (4/2)
Cumulative Time (hh:mm:ss)	0:00:00	12:58:49	14:20:45	21:38:19
AC Energy Charged	0.0000	81.9813	89.6412	90.6456
AC Energy Charged (manual reading)	0	-	-	90
DC Energy Charged	0.00	67.50	73.29	73.29

Table 15: Summary of charging data following the Steady State test on 4/1/13

From tables 14 and 15, the Overall AC Energy Consumption was calculated as **0.98 AC kWh/mile** and the Overall DC Energy Consumption as **0.80 DC kWh/mile**.

Figures 22 to 25 below show battery current, voltage and SOC, vehicle speed and time for each steady state test run.

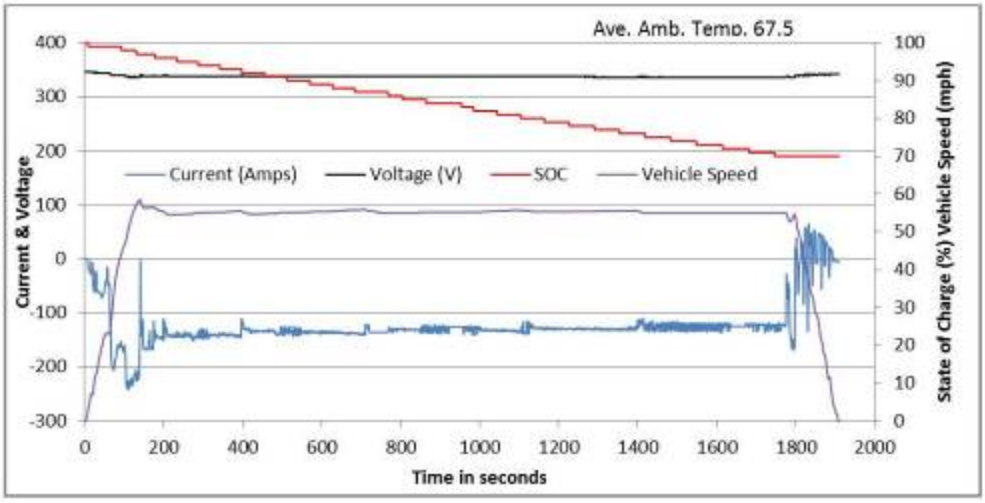


Figure 22: Current, Voltage, SOC, and Vehicle Speed vs. Time for Steady State Run #1

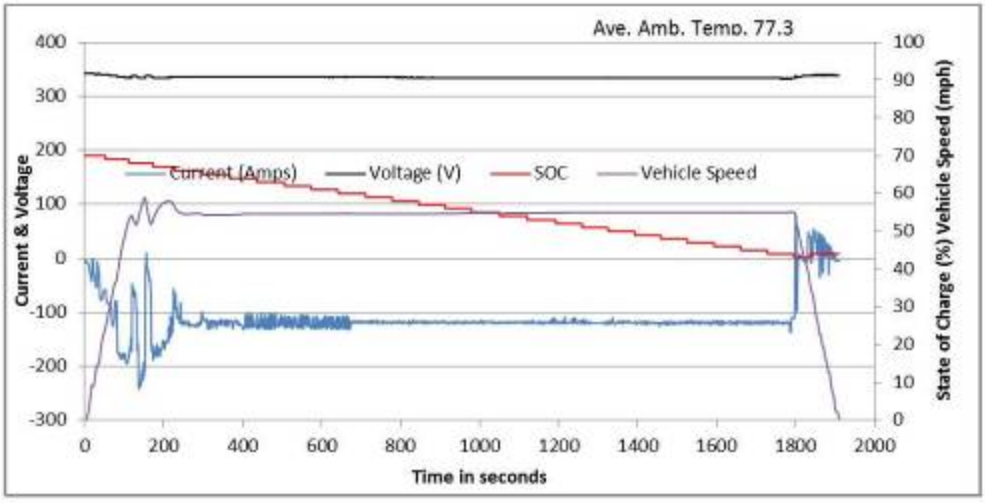


Figure 23: Current, Voltage, SOC, and Vehicle Speed vs. Time for Steady State Run #2

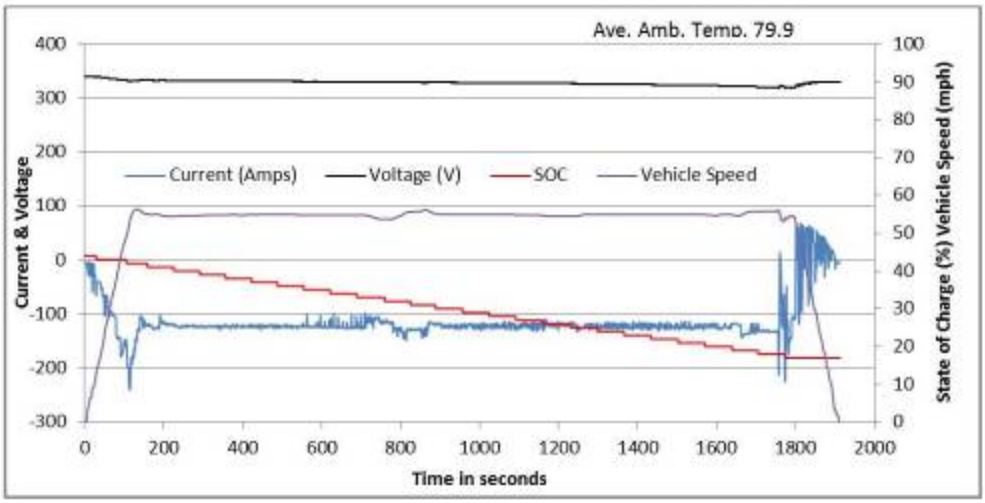


Figure 24: Current, Voltage, SOC, and Vehicle Speed vs. Time for Steady State Run #3

During the 4th run (see figure 25 below), the battery current and voltage dropped to 0 before the test could be completed.

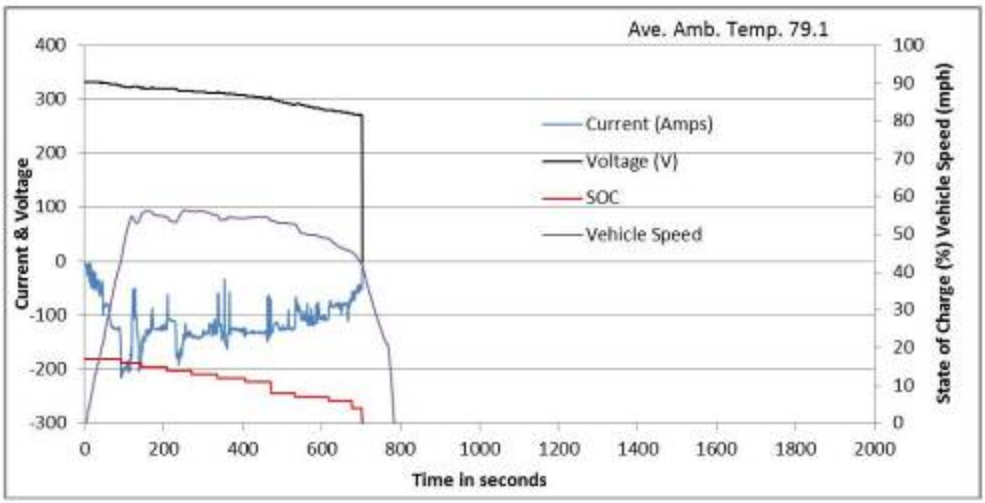


Figure 25: Current, Voltage, SOC, and Vehicle Speed vs. Time for Steady State Run #4

Figure 26 below shows the cumulative AC and DC energy consumed to recharge the battery, as well as the vehicle SOC and the AC charging rate in kW.

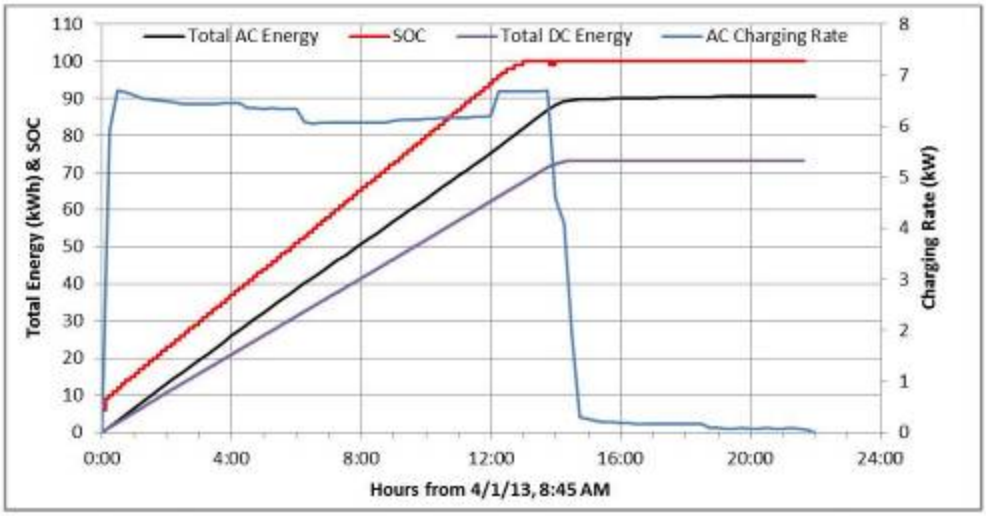


Figure 26: Total AC Energy, SOC, Total DC Energy, and AC Charging Rate for Steady State Test

Maximum charging power was recorded as **6.70 AC kW**. Once the SOC reached 100% and the battery current dropped to 0 (indicating total charge time), the vehicle continued to draw a small amount of current from the grid until it was unplugged. A total of 1.00 AC kWh was consumed from the time the vehicle reached the total charging time and the time the vehicle was unplugged from the charger.

APPENDIX A: Specifications for UCR Motored Chassis Dynamometer

From Mustang Publication "Project Spotlights" March 2010:

Mustang Advanced Engineering delivers a newly designed 48" Electric AC Heavy-Duty Truck Chassis Dynamometer with dual, direct-connected 300-hp AC motors to The University of California - Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT).

The science of measuring emissions from mobile and other sources has evolved significantly over the past several years. The most important changes in the nature of emissions measurement science has been a shift to examining emissions from diesel sources and to understanding emissions under in-use driving conditions.

The Bourns College of Engineering – Center for Environmental Research and Technology (CE-CERT) at The University of California Riverside has recently installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area. Designed and manufactured by Mustang Advanced Engineering, the development of this chassis dynamometer design was based on targeting vehicles in the medium to heavy-duty diesel vehicle range. Heavy-duty applications that can be tested at the facility include on-highway trucks, buses, waste haulers, yard tractors, and more - under test conditions representative of their specific in-use operations. The facility couples the new heavy-duty chassis dynamometer from Mustang Advanced Engineering with CE-CERT's Mobile Emissions Laboratory (MEL), to perform precise vehicle simulation and in-operation emissions measurements.

The first research conducted on the new facility will be a comparison of federally mandated diesel fuel formulas versus the stricter formulation required in California. The program calls for 10 heavy-duty trucks to be tested with several different fuels.

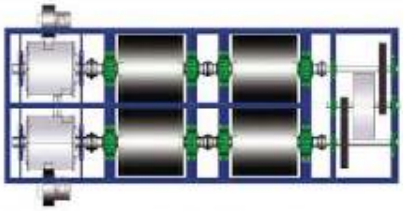
The new dynamometer will simulate on-road driving conditions for any big rig using its 48" precision rollers with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies the appropriate loading to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving conditions. An additional large inertia weight was incorporated into the dynamometer to increase the base mechanical inertia and enable the dynamometer to provide precise on-road simulation for a wide range of vehicle weights. The driver accelerates and decelerates according to a driving trace which specifies the speed and time over a wide range of vehicle simulation cycles. As the on-road driving conditions are being simulated on the dynamometer, emissions measurements will be collected with CE-CERT's Mobile Emissions Laboratory (MEL).

"This adds new capabilities in California that are only available at a limited number of facilities around the country," said Tom Durbin, who with J. Wayne Miller, are the principle investigators for the project. At both the state and federal levels, scientific requirements for emissions testing are trending away from steady state engine testing in favor of transient conditions found in typical driving, Durbin explained. "This addition will significantly expand our laboratory and measurement capabilities and help us continue our role as leading experts in the field of emissions research," said CE-CERT Director Matthew Barth.

CE-CERT's new heavy-duty chassis dynamometer will allow the testing of a variety of heavy vehicles under loaded and transient in-use conditions with corresponding emissions measurements. The dynamometer configuration is capable of meeting the inertia simulation range requirements of 10,000 to 80,000 lb for each of the cycles listed below. This includes acceleration rates up-to 6 mph/sec, as found in the UDDS Section D Drive Schedule and deceleration rates of up to 7 mph/sec as required for the WHM Refuse Drive Schedule. The dynamometer can also provide a load in excess of 600 HP @ 70 mph. The dynamometer also has the ability to continuously handle 200 Hp @ 15 mph for applications such as yard tractors.

The Dynamometer system is designed to meet the Heavy Duty Drive Schedules for diesel trucks in the weight range of 10,000 to 80,000 lb with acceleration rates for the following cycles:

- CARB HHDDT Cruise Mode Drive Schedule
- UDDS (Urban Dynamometer Drive Schedule)
- CARB 50 mph HHDDT Cruise Cycle
- HHDDT Transient Mode Drive Schedule
- WHM Refuse Drive Schedule
- Bus cycles such as, the CBD, OC Bus cycle, NY bus cycle
- In-use cycles for applications such as yard tractors.



"As part of our strategic plan, Mustang has developed a cost effective series of diesel, petroleum and hybrid certification grade dynamometer systems to address the needs of the global emissions and R&D market. There is a clear and present demand for a full performance cost effective dynamometer systems that offer all of the capabilities and confidence of a certification system at a price point that makes it no longer cost-prohibitive for organization to perform critical emissions studies, hybrid system calibration development, performance evaluation and other cutting edge research technologies. Researchers are in need of dynamometer systems to develop the next generation technologies which mimic the capabilities of the certification requirements, but at a fraction of the cost of a true certification system. That is what we are developing with this series of dynamometers and universities are lining up for them", said Executive Vice President, Donald Ganzhorn.

APPENDIX 4C:
Battery Electric Truck Driver Evaluation Survey

As part of the electric trucks (e-truck) deployment and testing period we would like to hear your input and evaluation of the e-truck. It will help us evaluate the performance of the e-truck and identify areas that need improvement. Please take 15 minutes to provide your evaluation of the e-truck by answering the following questions. For each question check the box that best fits your rating.

We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Jean-Baptiste Gallo, (626) 744-5605 or jgallo@calstart.org.

First Name: _____

Last Name: _____

Occupation/Position: _____

Location: _____

Today's Date: _____

1) **Please provide a brief description of the route the EV is operating on:**

Average miles / Number of stops / Hours of operation / Type of customers / Drive to the airport / Other

2) **Performance**

Property of the e-truck compared to a similar conventional truck	**Much worse**	**Somewh at worse**	**Same**	**Better**	**Much better**
Initial launch from stand still	☐	☐	☐	☐	☐
Maneuverability at slow speeds	☐	☐	☐	☐	☐
Acceleration	☐	☐	☐	☐	☐
Shift quality of the transmission	☐	☐	☐	☐	☐
Pulling power with load	☐	☐	☐	☐	☐
Coasting / Deceleration	☐	☐	☐	☐	☐
Overall braking behavior	☐	☐	☐	☐	☐
Productivity (able to cover routes quicker)	☐	☐	☐	☐	☐

3) **Operation**

Property of the e-truck compared to a similar conventional truck	**Much worse**	**Somewh at worse**	**Same**	**Better**	**Much better**
Cold Start	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Inside noise level	☐	☐	☐	☐	☐
Outside noise level	☐	☐	☐	☐	☐
Issues with pedestrian traffic	☐	☐	☐	☐	☐
In-cab ergonomics (control, switches, access doors…)	☐	☐	☐	☐	☐

4) **Did you have any issues with electric range (ran out of battery, battery running low at the end of the shift…)?**

5) **Did you have any issues with charging (vehicle not charging when plugged in, vehicle discharged in the morning, vehicle not fully charged in the morning…)**

6) **Please provide an overall rating of the e-truck.**

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

Suggestions and Comments

7) Please provide suggestions or recommendations of performance areas that need improvement in the e-truck.

8) Please share any additional comments you have concerning the e-truck.

(Thank you for your participation!)

APPENDIX 4D:
Battery Electric Truck Fleet Maintenance Evaluation Survey

As part of the electric trucks (e-truck) deployment and testing period we would like to hear your input and evaluation of the e-truck. It will help us evaluate the performance of the e-truck and identify areas that need improvement. Please take 15 minutes to provide your evaluation of the e-truck by answering the following questions. For each question check the box that best fits your rating.

We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Jean-Baptiste Gallo, (626) 744-5605 or jgallo@calstart.org.

First Name: _____

Last Name: _____

Occupation/Position: _____

Location: _____

Today's Date: _____

1) **Please provide a brief description of the route the EV is operating on:**

Average miles / Number of stops / Hours of operation / Type of customers / Drive to the airport / Other

2) **Performance**

Property of the e-truck compared to a similar conventional truck	**Much worse**	**Somewh at worse**	**Same**	**Better**	**Much better**
Initial launch from stand still	☐	☐	☐	☐	☐
Maneuverability at slow speeds	☐	☐	☐	☐	☐
Acceleration	☐	☐	☐	☐	☐
Shift quality of the transmission	☐	☐	☐	☐	☐
Pulling power with load	☐	☐	☐	☐	☐
Coasting / Deceleration	☐	☐	☐	☐	☐
Overall braking behavior	☐	☐	☐	☐	☐
Productivity (able to cover routes quicker)	☐	☐	☐	☐	☐

3) **Operation**

Property of the e-truck compared to a similar conventional truck	**Much worse**	**Somewh at worse**	**Same**	**Better**	**Much better**
Cold Start	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Inside noise level	☐	☐	☐	☐	☐
Outside noise level	☐	☐	☐	☐	☐
Issues with pedestrian traffic	☐	☐	☐	☐	☐
In-cab ergonomics (control, switches, access doors…)	☐	☐	☐	☐	☐

4) **Did you have any issues with electric range (ran out of battery, battery running low at the end of the shift…)?**

5) **Did you have any issues with charging (vehicle not charging when plugged in, vehicle discharged in the morning, vehicle not fully charged in the morning…)**

6) **Please provide an overall rating of the e-truck.**

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

Suggestions and Comments

7) Please provide suggestions or recommendations of performance areas that need improvement in the e-truck.

8) Please share any additional comments you have concerning the e-truck.

(Thank you for your participation!)

APPENDIX 4E:
Battery Electric Truck Fleet Manager Evaluation Survey

As part of the electric trucks (e-truck) deployment and testing period we would like to hear your input and evaluation of the e-truck. It will help us evaluate the performance of the e-truck and identify areas that need improvement. Please take 10 minutes to provide your evaluation of the e-truck by answering the following questions. For each question check the box that best fits your rating.

We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Jean-Baptiste Gallo, (626) 744-5605 or jgallo@calstart.org.

First Name: _____

Last Name: _____

Occupation/Position: _____

Today's Date: _____

1) General performance

Property of the e-truck compared to a similar conventional truck	**Much worse**	**Somewh at worse**	**Same**	**Better**	**Much better**
Driver Acceptance	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Availability for job assignments	☐	☐	☐	☐	☐
Productivity (able to cover routes quicker)	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Maintenance Issues	☐	☐	☐	☐	☐
Maintenance Costs	☐	☐	☐	☐	☐

2) Please provide an overall rating of the e-truck.

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

Suggestions and Comments

3) Please provide suggestions or recommendations of performance areas that need improvement in the e-truck.

4) Please share any additional comments you have concerning the e-truck.

(Thank you for your participation!)

APPENDIX 4F:
Battery Performance and State of Health Report

This Appendix discusses the battery health in the E-trucks that we evaluated. While the evaluation was not long enough to measure degradation of the battery the period of the testing, there are observations from the usage and testing that provide insights about the battery systems on the E-trucks. The batteries on all the three trucks are Li-ion type batteries with different energy storage capacity. The E-Cell has a 55.5 kWh battery, the eStar a 80 kWh battery, and the Smith electric has a 80 kWh battery. The battery packs are liquid cooled. The battery health was evaluated from several sources during the demonstration and testing:

1) Charging data and logs
2) Road test from at the Southern California Edison EV Test Center
3) Chassis dynamometer battery SOC data

The charging times for the trucks are related to the size of the batteries as well as to the charging rate. During the road testing a FCCC MT E-Cell was charged at a nominal voltage of 240V from 0 percent to 100 percent SOC. Typical charge duration was measured between 12 and 14 hours to achieve the bulk of the charge and over 17 hours to achieve a full charge. During the road testing, maximum charging current was recorded at 23.2 A (AC) and maximum grid charging power at 5.6 AC kW. Given the total vehicle range determined by the road testing (between 56.2 and 67.6 miles), we estimate that 1 hour of charging represents 4.0 to 4.8 miles of range

Navistar advertises that the eStar can recharge in approximately 8 hours. Although we were not able to directly verify that claim, the in-use data collected on the 4 Navistar eStars indicate that typical charge duration would be more than 8 hours to reach a full charge.

Smith Electric reported that the Newton Step Van needs 6 to 8 hours to reach a full charge at a continuous current of 75A. For this project, a Smith Electric Newton Step Van was tested on a chassis dynamometer. Both the facility electrical system and the EVSE used for this testing were limited in the grid current that could be used for charging. During the chassis dynamometer testing, maximum charging current was recorded at 17 A (DC) and maximum grid charging power at 6.7 kW. Therefore, the charging times recorded were longer than what one would expect at a customer site equipped with the recommended charging infrastructure. Typical charge duration from 0 percent to 100 percent SOC was measured at about 13 hours to achieve the bulk of the charge and 14 hours and 20 minutes to achieve a full charge. From the steady state range test conducted during the chassis dynamometer testing, the total battery capacity was measured at 89.64 AC kWh.

The eStar vehicles tested were a second generation model and had some improvements in the battery packaging. Use of lighter material (reinforced fiberglass) made the battery pack lighter by about 300 lbs. The other modification that occurred in second generation model was also the addition of a separate lead-acid battery to power the air conditioning system which leaves more of the energy in the traction battery intact. This was a good improvement as we heard from the

user fleet. We did not have data on the first generation of vehicles in order to document the specific effects this had on the overall efficiency of the vehicles

Finally, in terms of maintenance reports we did note record significant maintenance issues with respect to the batteries. We note that one battery pack had to be replaced on the E-cell vehicle in November 2011. In terms of overall health, the batteries functioned well on the E-trucks and did not report any overheating or power loss that sometimes is associated with hot weather. In the future it would be valuable to perform more detailed evaluation of the battery performance and durability testing over time.

APPENDIX 5A:
CalHEAT Truck Inventory by Class and Application

CalHEAT performed a California Truck Inventory Study[66] 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.[67] The vehicle classes included in the inventory are shown in Figure 1 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.

As CalHEAT's Roadmap was being developed, 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 as shown in Figure 1 below. The intent behind the formation of these 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 that which would be achieved by a Class 6 truck in similar use. However, in terms of how a truck is affected by a given technology 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.

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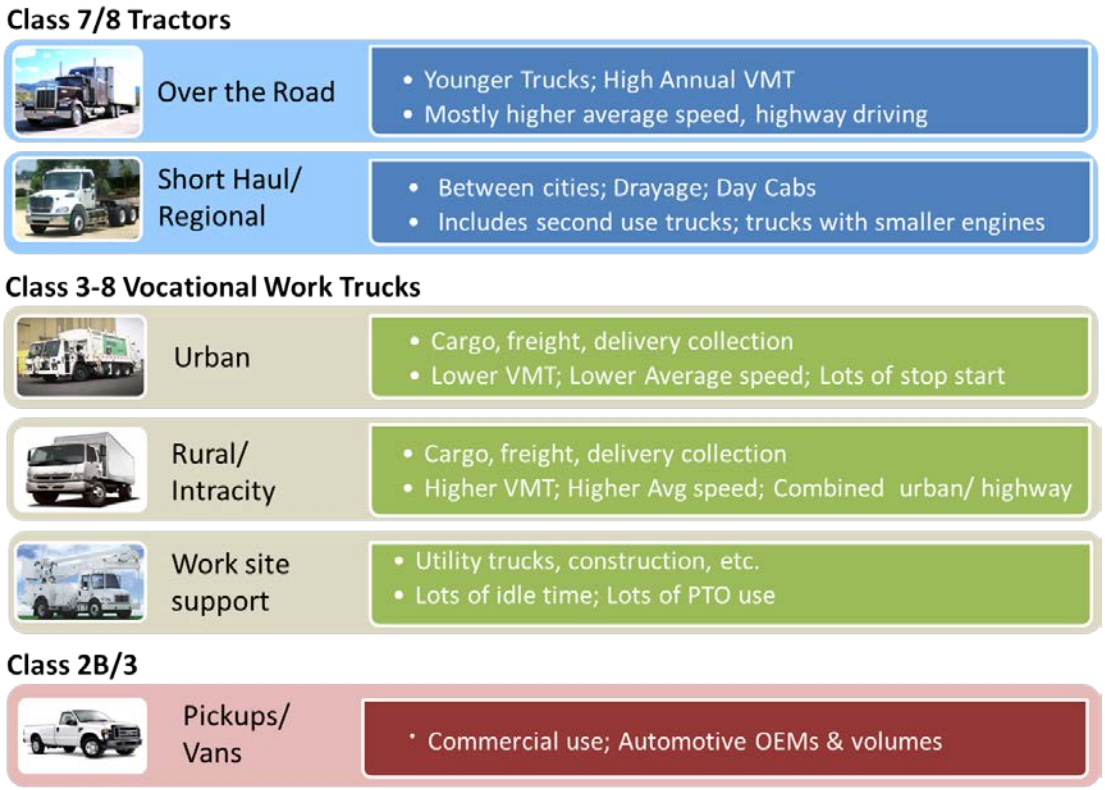
[66] Jennings, Geoff, and Brotherton, Tom. (CalHEAT). ***California Truck Inventory and Impact Study, June, 2012.*** http://www.calstart.org/Projects/CalHEAT/Presentations-and-Publications.aspx

[67] 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 1: Six Truck Categories Based on Technology Applicability



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

Source: California Hybrid, Efficient and Advanced Truck Research Center

Table 1: Truck Categories, 2010 Populations, and CO2 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%

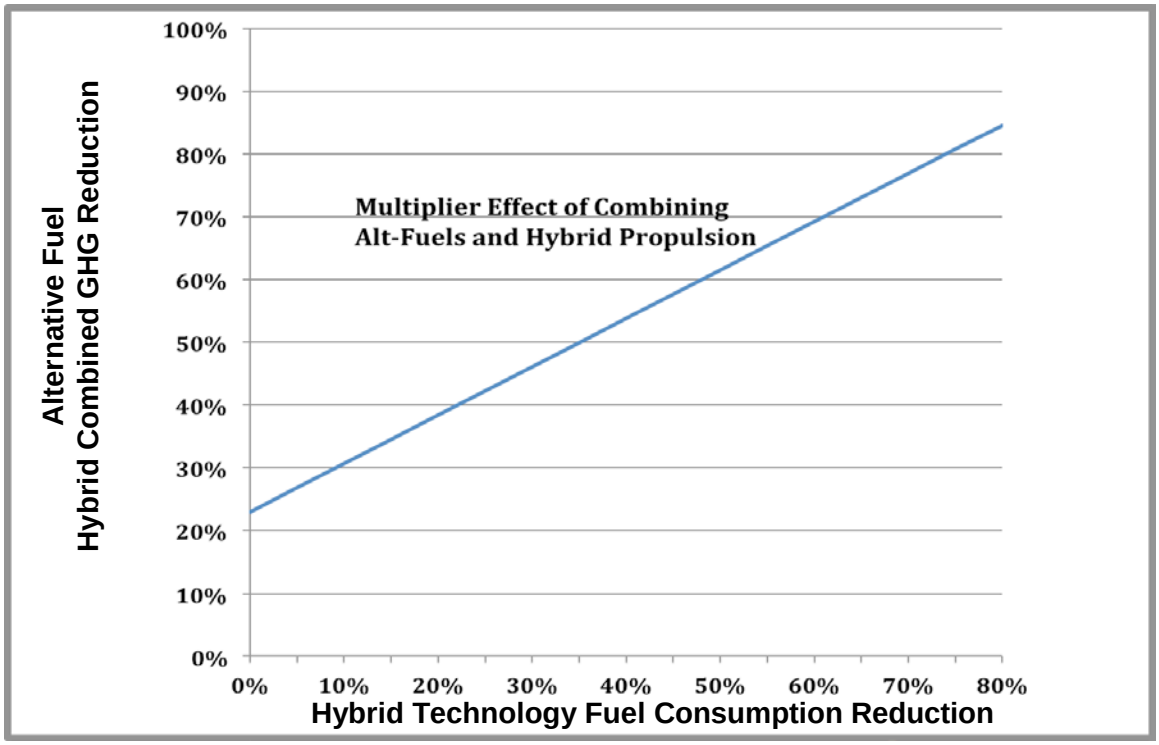
California truck population by weight class and application, along with average vehicle miles traveled, CO_2 equivalent emissions in MMT/year, the percentage of vehicles by category, and percentage contribution to total truck CO_2e emissions.

Source: California Hybrid, Efficient and Advanced Truck Research Center calculations

APPENDIX 5B:
Combined Benefits of Alternative Fuel and Hybrid Propulsion

The benefits of the alternative fuel-hybrid propulsion combination come from the reduction in WTW CO_2 emissions produced by the switch from diesel to NG fuel, the reduced fuel consumption of the hybrid drivetrain, and then the effect of putting the two together. Figure 1 below illustrates that multiplier effect by showing what happens when the GHG reductions that come with compressed natural gas are combined with the fuel consumption and GHG reductions resulting from use of hybrid technology. That is to say that a vehicle burning CNG, which reduces GHG 23 percent on its own (arrow), will emit 27 percent less GHG when combined with hybrid hydraulic technology that reduces fuel consumption by 5 percent, and up to roughly 54 percent when put together with hybrid technology that reduces fuel consumption by 40 percent. This figure visually illustrates this multiplier effect.

Figure 1: Alt-Fuel Hybrid Combined Effect for GHG Reduction



Source: California Hybrid, Efficient and Advanced Truck Research Center Interviews with Industry

The statistics on GHG emissions and the California truck population can be used to estimate the impact of NG hydraulic hybrid use on overall California truck emissions. For example, if 10 percent of Class 3-8 Urban trucks were equipped with NG hydraulic hybrids, the annual emissions of CO_2e per vehicle for all Class 3-8 trucks would be reduced by an average of 42 percent, down to 8.27 metric tons (MT).

Calculating this effect on the total 2010 Class 3-8 truck population shows that if 10 percent of Class 3-8 trucks adopted natural gas hydraulic hybrid technology, the overall annual emissions of CO_2e for the category would be about 3.456 million metric tons (MMT). That's a drop of 4.2 percent from the 2010 annual CO_2 equivalent of 3.607 MMT for that population. The point being that putting the two technologies together can have an impressive impact. If some of the barriers to adoption of these combined technologies can be overcome, the alt-fuel-hybrid system could play an important role in meeting 2020 and 2050 goals for California to reduce petroleum-based fuel consumption, and reduce carbon emissions.

APPENDIX 5C:
Assessment Model

Ricardo Inc, under consulting contract to CALSTART, used an Excel spreadsheet model to assess the impact of the combined effects of alternative fuels and hybrid technology in the CalHEAT truck categories (see Appendix 5A for details on the truck categories). This appendix documents the components of the model, the inputs and the concluding results of the analysis accomplished when the model was exercised.

Slide C-1 presents a schematic of the Assessment Model Overview. These three tables are shown in larger size in the following 3 slides. The bar chart includes estimates of three types of hybrid vehicle propulsion systems – hydraulic hybrid vehicle (HHV), plug-in hybrid electric vehicle (PHEV) and hybrid electric vehicle (HEV) using the various alternate fuels shown in the fuel table in the upper left of the chart. These fuel WTW GHG reductions are combined with the table in the lower left describing the GHG reduction resulting from the three hybrid vehicle types. The bar chart describes the combined effects for the Class 3-8 urban application only. Other combinations would generally be a smaller amount of improvement than represented by the C3-8 Urban truck category. The same spreadsheet technique with compatible tables was also compiled for criteria pollutants.

Slide C-2 focuses on the fuel input. The greatest reduction potential for a gasoline replacement is ethanol E85, made from CA Poplar, cellulose. The key Reference is Table A24 in the Tiax CEC report found in the bibliography slides C-11-C13 at the end of this appendix. The greatest reduction for replacing diesel fuel is DME. CNG made from landfill gas (shown as RNG-renewable natural gas in the charts above) offers the greatest amount of WTW GHG reduction. The baseline fuel for E85 is RFG gasoline. The baseline for comparison of all other fuels is ULSD diesel.

The primary source for the GHG, petroleum reduction and emissions criteria data come from the Tiax California Energy Commission (CEC) report entitled: "Full fuel cycle assessment: Well-to-wheels energy inputs, emissions and water impacts." Report number CEC-600-2007-004-REV, revised August 1, 2007.

It is interesting to note that the range of TTW improvements available from various fuels is greatly exceeded by the variation in WTT. Based on the amount of GHG created or absorbed during the fuel manufacturing process, the most attractive fuels based on GHG reduction are those that require little energy to create, or in fact absorbs GHG in the manufacturing process (such as the use of landfill gas to create renewable natural gas).

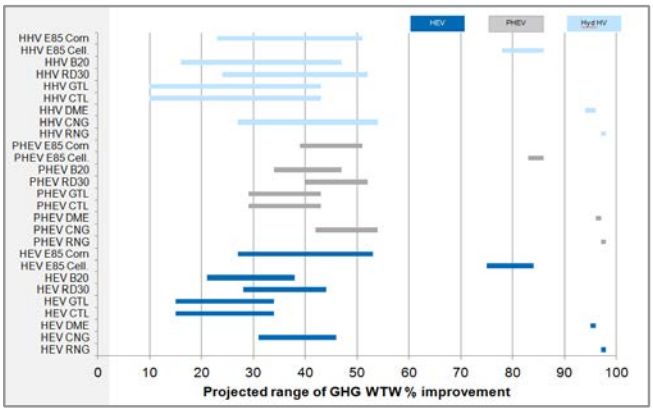
Slide C-3 documents the estimates for WTW GHG reduction taken from the CalHEAT Roadmap report prepared by Ricardo for CALSTART. The report is entitled "Support of CalHEAT Technology Assessment", and dated November 10, 2011. Ranges of GHG reduction are based on variability of technology, as well as range of actual fuel economy, CO2 and GHG reductions reported by various fleets and OEMs. It should be noted that a major cause of variability expressed in the wide range of some technologies is due to duty cycle variations,

specifically the amount of start/stop in the operating cycle. In fact, duty cycles that are entirely st stop-start, with little to no high speed or constant speed driving can achieve fuel economy improvement of 70 percent or more (HHV information from EPA).

Slide C-4 illustrates the combination of the benefits of GHG reduction from the three variants of hybrid vehicles and the various fuel types identified. The effect of various fuels is referenced from the Tiax CEC report noted. The effect of the vehicle types is taken from the CalHEAT Technology Assessment report prepared by Ricardo, Nov. 10, 2011. The DME fuel type shown references the DME sourced from CA Poplar. Although only one DME fuel is shown here, both DME types are listed on the summary table on Slide C-2. RNG estimate is based on renewable natural gas from landfill gas. RNG data was taken from report written by California EPA, Air Resources Board, 2009. Detailed California-Modified GREET Pathway for Compressed Natural Gas (CNG) from Landfill Gas. Version 2.1. February 28, 2009.

As a point of departure, Slide C-5 shows the Class and application of current production models that offer hybrid propulsion systems. Slide C-6 shows the same matrix that offer natural gas propulsion. Slide C-7 combines these two charts showing the overlap of hybrids and NG propulsion that exist in the market place. Some key combinations already exploit this overlap such as in the HD refuse hauler. Slides C8, C9 and C10 are the recommendations for important demonstration projects. The balance of the slides comprise the bibliography

Slide C 1


HEV
PHEV
Hyd HV
HHV E85 Corn
HHV E85 Cell.
HHV B20
HHV RD30
HHV GTL
HHV CTL
HHV DME
HHV CNG
HHV RNG
PHEV E85 Corn
PHEV E85 Cell.
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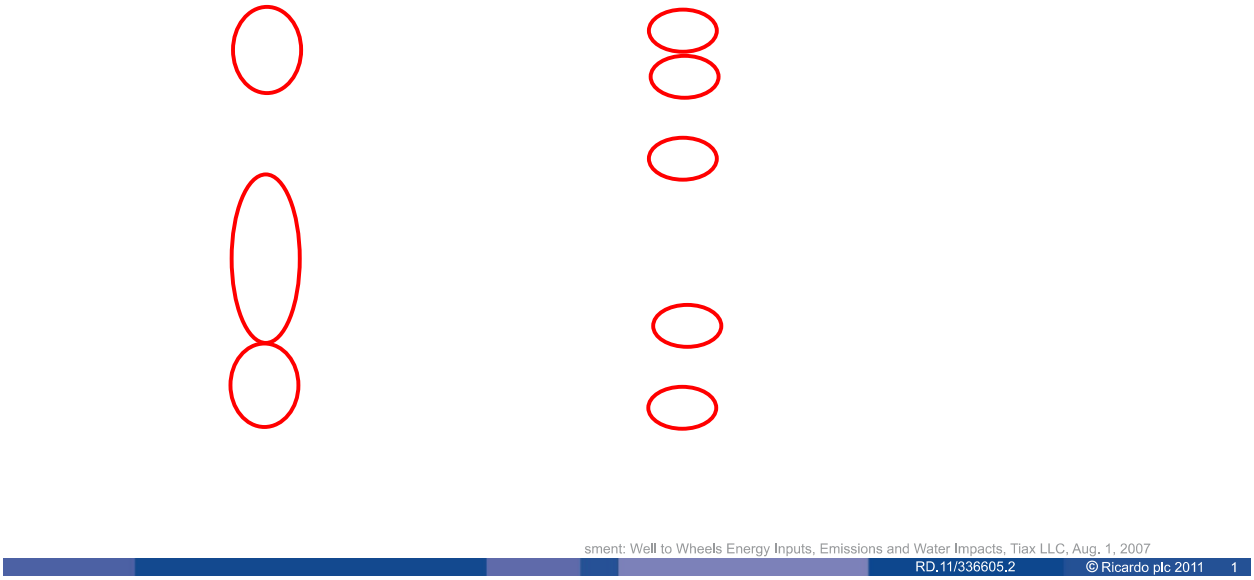
90
100
Projected range of GHG WTW % improvement

Slide C 2


sment: Well to Wheels Energy Inputs, Emissions and Water Impacts, Tiax LLC, Aug. 1, 2007
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Slide C 3

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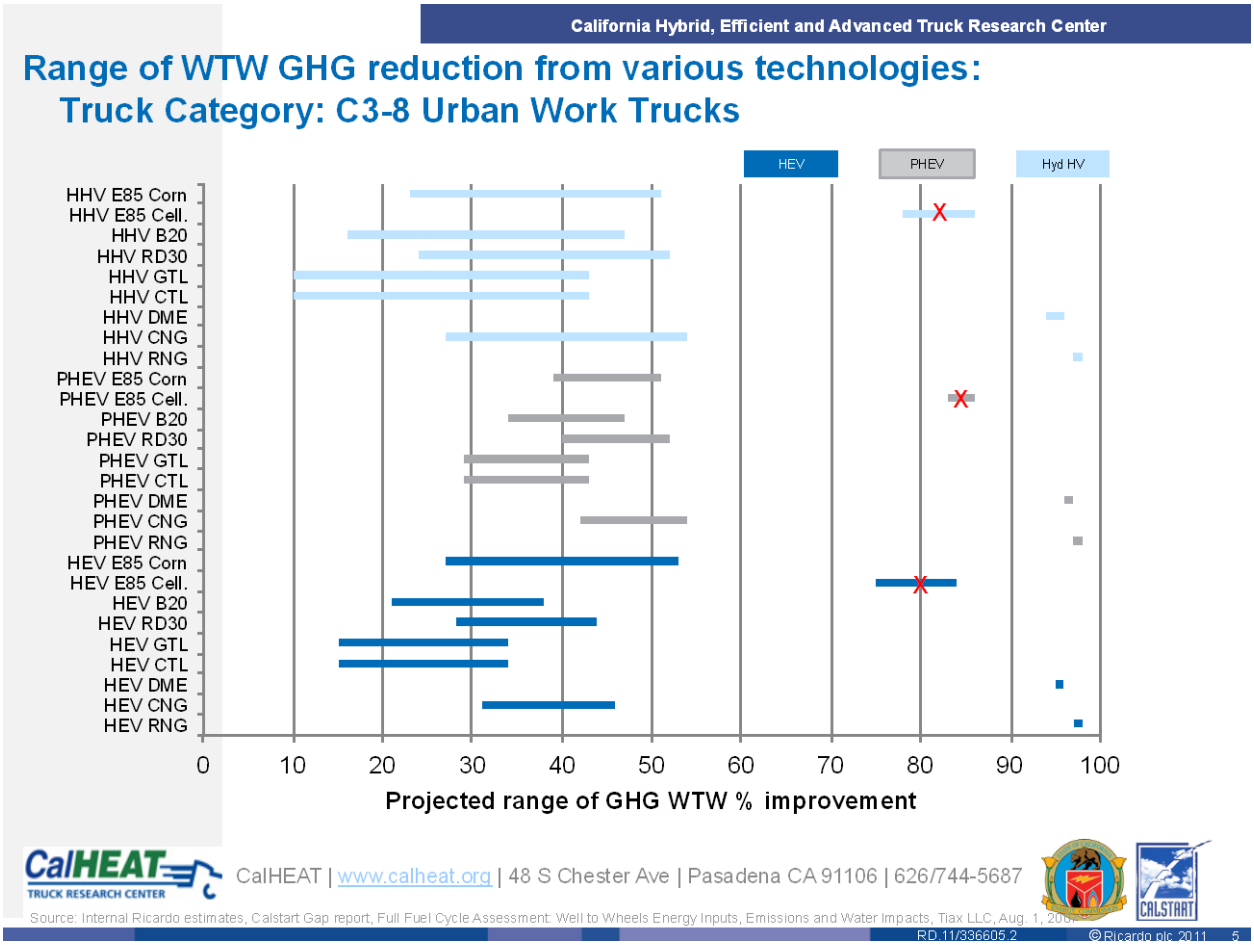
Slide C 4


California Hybrid, Efficient and Advanced Truck Research Center
Range of WTW GHG reduction from various technologies:
Truck Category: C3-8 Urban Work Trucks
HEV
PHEV
Hyd HV
HHV E85 Corn
HHV E85 Cell.
HHV B20
HHV RD30
HHV GTL
HHV CTL
HHV DME
HHV CNG
HHV RNG
PHEV E85 Corn
PHEV E85 Cell.
PHEV B20
PHEV RD30
PHEV GTL
PHEV CTL
PHEV DME
PHEV CNG
PHEV RNG
HEV E85 Corn
HEV E85 Cell.
HEV B20
HEV RD30
HEV GTL
HEV CTL
HEV DME
HEV CNG
HEV RNG
0
10
20
30
40
50
60
70
80
90
100
Projected range of GHG WTW % improvement
CalHEAT
TRUCK RESEARCH CENTER
CalHEAT | www.calheat.org | 48 S Chester Ave | Pasadena CA 91106 | 626/744-5687
CALSTART
Source: Internal Ricardo estimates, Calstart Gap report, Full Fuel Cycle Assessment: Well to Wheels Energy Inputs, Emissions and Water Impacts, Tiax LLC, Aug. 1, 200
RD.11/336605.2
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5

Slide C 5

Potential Pathways Forward

- OEMs Production Hybrid Offerings and Segment Population

OEMs Work Truck Category Population – Hybrid Models Available					
Truck Application	Truck Weight Class				
	4	5	6	7	8
Step Van	43,601	6,780	3,382	140	
Box Truck	26,093	10,466	31,262	12,427	745
Drayage		846	22,540	30,986	29,070
Beverage		14	125	1,336	569
Refuse Truck			78	141	5,468
Urban Work			146	612	5,638
Utility		11	1,252	1,660	145
Pick-Up	58,701	39,591	16,519		
PU/Utility	2,517	1,811	3		
Work Truck	2,786	15,509	61,283	53,708	33,348

Based on published data & OEM interviews

Slide C 6

Potential Pathways Forward 2

- OEMs Production NG Offerings and Segment Population

OEMs Work Truck Category Population – Natural Gas Models Available					
Truck Application	Truck Weight Class				
	4	5	6	7	8
Step Van	43,601	6,780	3,382	140	
Box Truck	26,093	10,466	31,262	12,427	745
Drayage		846	22,540	30,986	29,070
Beverage		14	125	1,336	569
Refuse Truck			78	141	5,468
Urban Work			146	612	5,638
Utility		11	1,252	1,660	145
Pick-Up	58,701	39,591	16,519		
PU/Utility	2,517	1,811	3		
Work Truck	2,786	15,509	61,283	53,708	33,348

Nased on published data & OEM interviews

Slide C 7

Potential Pathways Forward

- OEMs Production NG/Hybrid and Segment Population

OEMs Work Truck Category Population – Hybrid/NG Models Available					
Truck Application	Truck Weight Class				
	4	5	6	7	8
Step Van	43,601	6,780	3,382	140	
Box Truck	26,093	10,466	31,262	12,427	745
Drayage		846	22,540	30,986	29,070
Beverage		14	125	1,336	569
Refuse Truck			78	141	5,468
Urban Work			146	612	5,638
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Pick-Up	58,701	39,591	16,519		
PU/Utility	2,517	1,811	3		
Work Truck	2,786	15,509	61,283	53,708	33,348

Preliminary, based on published data & OEM interviews

Slide C 8

in the long run

Slide C 9

transportation fuel.

Slide C 10

Make a cost reduction (a series of steps) to make a business case

Slide C 11

s. October 3, 2011 DEER Conference

Slide C 12

, Sturman Industries, 2011. “Unlocking the Potential of Alternative Fuels for Transportation.” November 2011.

Slide C 13

Bibliography of technical resources (3/3)

26. Salomonsson, Per, Volvo Technology, 2011. "Alternative Fuels and an Update on the BioDME Project." F.O. Licht's World Ethanol and Biofuels Conference. November 10, 2011.
27. Vassiliadis, Marie, Volvo Truck, 2007. "Carbon Dioxide Emissions from Trucks Can be Halved by 2020." October 16, 2007. www.hybridcar.com

APPENDIX 5D:
Data Collection Plan and Interview Results

Since the alt-fuel hybrid propulsion systems are not naturally coming together in the market place, a set of questions were developed to engage industry to drive out and understand the opportunities and barriers to those systems. Slide D-1 highlights a series of questions that were asked of various organizations representing OEMs, fleets, and technology providers in order to get a range of input regarding the hybrid and alternate fuel technologies. The results of the data collection are summarized in the subsequent slides in this appendix.

Slide D-2 is a high-level list of interviewees from industry indicating their affiliation, name and position. The results, for the most part, are aggregated to focus on the results and not the individuals. That was not possible in all cases.

Slide D-3 summarizes the major themes captured from the various interviews and associated with labels that hint at the important themes or response categories. The more detailed responses by category are included in the subsequent slides. The slides are arranged so that the highlights of specific responses appear under the question asked by the interviewer. Slides D-4 through 15 document the aggregated responses associated with specific interview questions.

In addition to the structured interviews, Ricardo also captured information from studies and their own internal studies and discussions with specific OEMs about their interest in alt-fuel hybrids.

Slide D-16 summarizes some data surrounding biodiesel availability that is much better than other alternative fuel types in many areas. The easiest path to market entry of an alternate fuel into a hybrid fleet is to use the same B5 or B20 (or other fuel) that the majority of the diesel fleet is using. Where Biodiesel is commonly used in the conventional powertrain fleet, it can easily be introduced into the HEV or HHV fleet. It should be noted that a barrier to use of higher percentages of biofuel is the engine warranty. Typically fleets will not exceed the allowable amount of biofuel as stated in the engine product warranty, commonly 5 percent (B5), sometimes 20 percent (B20). The ability to use biodiesel in conventional engines with little or no changes to the engine configuration itself, is the likely cause indicated by this survey which shows that fleets preferred biodiesel to use of CNG, even if CNG is substantially less expensive than biodiesel, in this case 1/3 less expensive.

Slide D-17 is another view of biodiesel from outside survey data. Buyer preferences favor introducing biodiesel rather than either CNG or hybrid technology in the fleet. This is expected to change as petroleum fuel prices continue to rise, and as the volume of alternative fuel and hybrid power trains enter the market.

Slide D-18 summarizes the perspective of these 4 major OEMs who offer both CNG as well as hybrid technology, although they do not currently offer the combination of the two on one vehicle. It should be noted that some vehicle testing is going on with this combination of

technologies. However, the combined cost of the two technologies can be prohibitive currently. The fuel consumption is already reduced because of the hybrid technology, so the additional increment of fuel savings from the NG fuel has diminished impact relative to the lower fuel consumption resulting from the hybrid technology. This results in increasing the payback period twice; once from the added technology, and once more because of the reduced fuel consumption on which the additional payback period was based.

Slide D-19 summarizes the Barriers and Needs as found through review of the data. Likewise, the enablers are shown in Slide D-20.

Slide D 1

ks

- Class 3-8 Rural
- Class 3-8 Urban
- Class 3-8 Worksite
- Class 8 OTR
- Class 7-8 Urban

Drivelines:

- HEV
- PHEV
- Hydraulic Hybrid Vehicle (HHV)

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Slide D 2

Interviews were conducted with the following individuals to provide further industry input and perspective

ansfer, Office of Transportation and Air Quality

Slide D 3

perate on fuels that have
95% WTW GHG reduction: e.g. DME, GTL, cellulosic ethanol and renewable NG from landfill gas

ated?

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2. Why combine alternative fuels with hybrid powertrains?

a. What benefits are expected?

ed trucks with nearby fuel station.

2c. Why combine alternative fuels with hybrid powertrains? What are the market and technical barriers? (1/2)

art-up costs,

preferably > 50K units. (EPA)

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ns?

What are the market and technical barriers? (2/2)

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Slide D 8

hy combine alternative fuels with hybrid powertrains?

What are the market and technical enablers for each alt fuel / hybrid vehicle combination?

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Slide D 9

p encourage the combination of these technologies? (1/2)

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Slide D 10

Slide D 11

Reductions in GHG, petroleum consumption, criteria emissions

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Slide D 12

4. How large is the potential market for HV combined with alt fuel, by fuel type, and in which vehicle segments?

e scale. (EPA)

t availability of the alternate fuels are anticipated by 2020? 2050? (1/2)

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Slide D 14

ate fuels are anticipated by 2020? 2050? (2/2)

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Slide D 15

uels WITH hybrid technologies (PHEV, HEV, and HHV) are anticipated by 2020? 2050?

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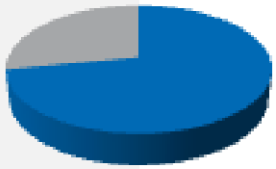
Slide D 16

California Hybrid, Efficient and Advanced Truck Research Center

Alternate fuels interest favors biodiesel over natural gas

Based on end-user research, biodiesel + hybrid is more likely than CNG alone or with hybrid



Source: Frost & Sullivan

- Biodiesel is the preferred alternative fuel option for use in HD vehicles in fleet, even at a higher price
- Industry feedback suggests fewer barriers to entry with biodiesel than natural gas as the alternative fuel of choice
- This trend may be effected by predicted continued increase in diesel prices, while CNG prices are expected to remain flat

CNG Advantages (+)	Biodiesel Advantages (+)
• CNG is less expensive than Diesel, produces lower emissions and is perceived to keep engine components cleaner • Hybrid NG trucks and busses have been seen in demonstration fleets, particularly where NG vehicles are in use	• Already used in many fleets • Most fleets using biodiesel can easily incorporate in their HEV diesel fleet without adding infrastructure • Most fleets using B20 and can easily mix with B5 or B10 during winter months
CNG Disadvantages (−)	**Biodiesel Disadvantages (−)**
• CNG is not as readily available in all regions as diesel, requiring some fleets to install their own fueling stations • Most often used in transit bus or delivery fleets requiring vehicles return to home base for refueling	• Lack of availability in some areas • Price premium of biodiesel vs. ULSD. This may change as price of diesel fuel continues to climb

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Source: Ricardo research, interviews, Frost and Sullivan Strategic Analysis of N. American and European Hybrid Truck, Bus and Van Market, May 2010

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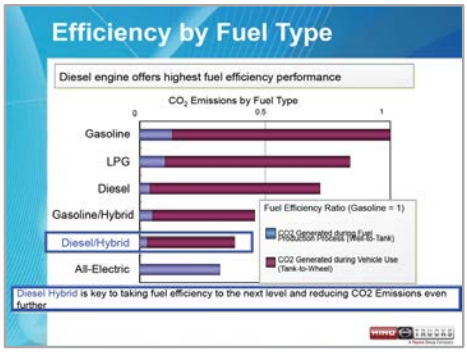
Slide D 17

g with a known quantity

Slide D 18


Efficiency by Fuel Type
Diesel engine offers highest fuel efficiency performance
CO_2 Emissions by Fuel Type
0
0.5
1
Gasoline
LPG
Diesel
Gasoline/Hybrid
Diesel/Hybrid
All-Electric
Fuel Efficiency Ratio (Gasoline = 1)
CO2 Generated during Vehicle Use (Tank-to-Wheel)
Diesel Hybrid is key to taking fuel efficiency to the next level and reducing CO2 Emissions even further

Slide D 19

ank system $30,000; low production volume; weight of system

– OEMs perception - these technologies compete R&D funds, incentives; 2010 invest

onformable low-pressure CNG storage with a hybrid system in a truck

- Stepping stone … CEC Storage tank development

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APPENDIX 5E:
Model Assessment Report

The initial Slide E-1 provides an overview of the Assessment Model shown in more detail in the Appendix 5C Assessment Model. The Assessment Model description illustrates the combined effects for the Class 3-8 urban application only. Other combinations would generally be a smaller amount of improvement than represented by the C3-8 urban truck category. However, this Appendix 5E provides results from the spreadsheet model aggressively applied across all truck categories and all alt-fuels. The baseline fuel for E85 is RFG gasoline. The baseline for comparison of all other fuels is ULSD diesel.

In Slide E-2, additional business and technology drivers are being introduced to influence the rate of technology development and deployment. New legislation resulting in more aggressive fuel economy standards in passenger cars and light and heavy commercial vehicles has a significant impact in the rate of technology introduction. In addition, concerns over energy independence and security are likely to result in mandates for use of renewable fuels. It is also anticipated that more aggressive fuel economy standards for commercial vehicles will drive further technology changes directed at engines, drive trains, as well as aerodynamics, rolling resistance, and vehicle communication (platooning, etc.). This slide is a portion of the roadmap that can influence the progress of alt-fuel hybrids and their penetration into the market place.

Slide E-3 describes the scenarios for apportioning the reductions in total CO_2 for the State of California to all the truck population being studied in this report. The baseline levels in 1990 are compared to the actual levels in 2008, and then are projected to the levels in 2050 if no major changes occur (Business-as-usual scenario) to reduce the CO_2 emissions. The goal set for 2050 is to reduce GHG to 80 percent below the level of 1990 is also shown, and serves as the target for the 3 scenarios that follow on the subsequent charts.

In Slide E-4 the chart in the upper left shows the targeted levels of CO_2 as an aggregate of California emissions through 2050. This serves to define the targets for the portion attributed to the truck population being examined in this report. Based on these targets, some assumptions were made in order to run a what-if analysis to project CO_2 levels in 2030. The scenario modeled on this slide compares the CO_2 levels based on the population of California trucks in fleets in 2008, totaling a CO_2 emissions of 35 million metric tons to what that number would be in 2030 if 60 percent of the truck fleet population was converted to hybrid propulsion and 60 percent of the fleet uses alternative fuels as described in the assessment model. The alt-fuels are sourced as shown in the box in the upper right. In this scenario, a 30 percent reduction of CO_2 could occur relative to the levels of CO_2 in the benchmark year 1990. Of course, this is a rather aggressive penetration of hybrid and alt-fuel technology but it shows the powerful impact that such a combination can have on the emissions.

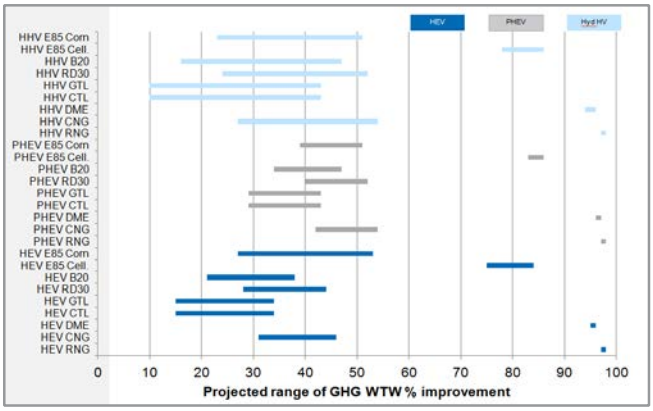
Slide E-5 is an even more aggressive case that assumes a what-if analysis to project CO_2 levels in 2030 if all the truck population used hybrid and alt-fuels. The scenario modeled on this slide

compares the CO_2 levels based on the population of vehicles in 2008, totaling a CO_2 emissions of 35 million metric tons to what that number would be in 2030 if the entire vehicle fleet was hybrid and the entire fleet uses alternative fuels as described above. In this scenario, a 57 percent reduction of CO_2 could occur relative to the levels of CO_2 in the benchmark year 1990.

Slide E-6 illustrates the most aggressive set of assumptions the what-if analysis to project CO_2 levels in 2050, relative to the goal of an 80percent reduction from 1990 levels. The scenario modeled on this slide compares the CO_2 levels based on the population of vehicles in 2030, totaling a CO_2 emissions of 13.5 million metric tons to what that number would be in 2050 if the entire vehicle fleet was hybrid and the entire fleet uses advanced alternative fuels with a projected GHG reduction of 95 percent as described above. In this scenario, an 80 percent reduction of CO_2 could occur relative to the levels of CO_2 in the benchmark year 1990. It requires wide availability of renewable advanced biofuels, which may require aggressive stimulus to make these fuels both affordable and available in sufficient quantities.

The following slides E7-E9 indicate the documentation used to develop estimated savings in GHG, establish industry trends, identify barriers and enabler, and to add greater depth to the understanding of industry priorities in the pursuit of future GHG reduction.

Slide E 1

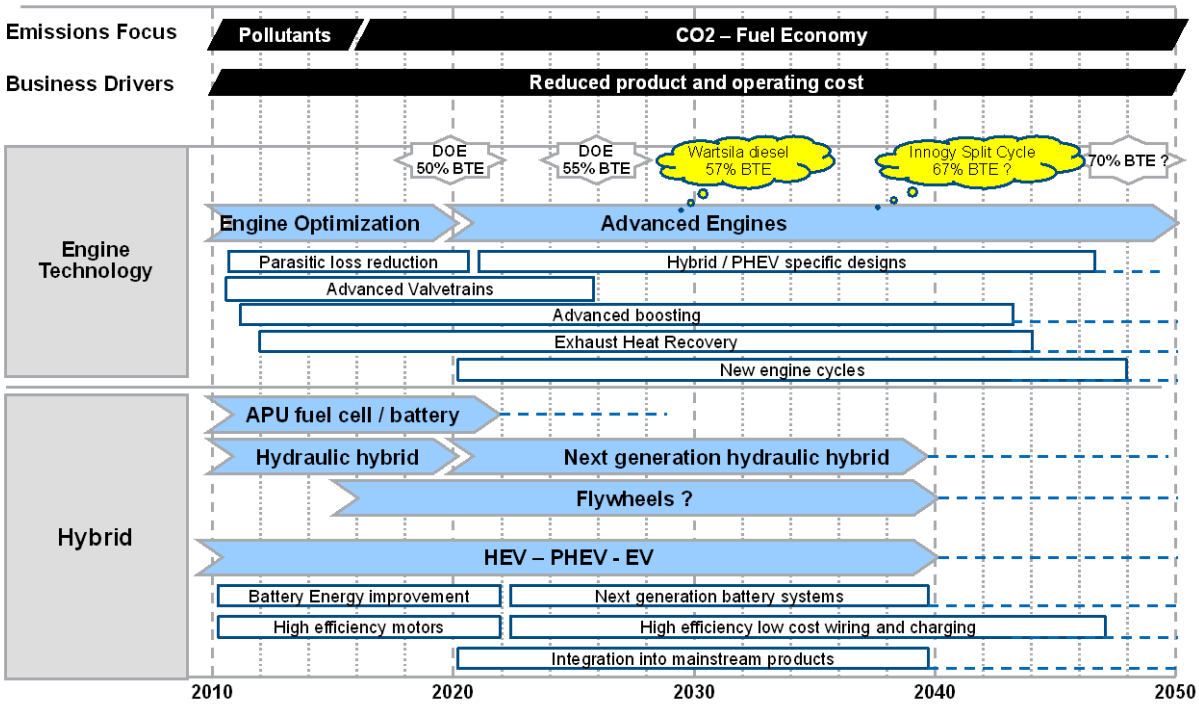


Slide E 2

Technology Roadmap

Engine technology is expected to advanced through 2050 in parallel with increasing synergy to hybrid powertrain solutions

Possible Roadmap for Commercial Vehicle Technology



Source: Ricardo Analysis, NESCAFF report, DOE Supertruck reports

Timeline and technology examples for illustration purposes

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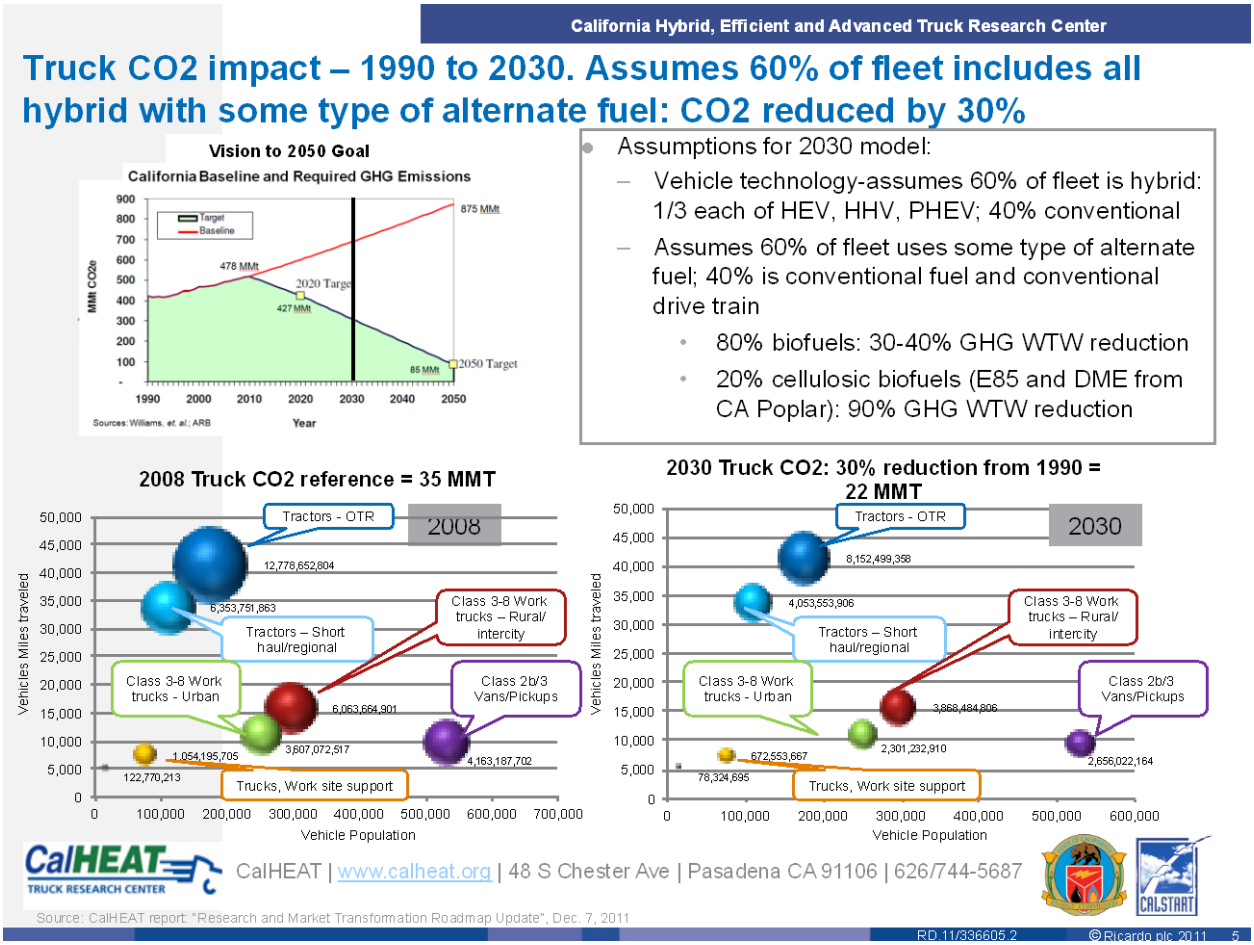
Slide E 3

bution from On
Highway Trucks

Slide E 4


California Hybrid, Efficient and Advanced Truck Research Center
Truck CO2 impact – 1990 to 2030. Assumes 60% of fleet includes all hybrid with some type of alternate fuel: CO2 reduced by 30%
Vision to 2050 Goal
California Baseline and Required GHG Emissions
Target
Baseline
MMt CO2e
478 MMt
427 MMt
2020 Target
875 MMt
85 MMt
2050 Target
Year
Sources: Williams, et. al.; ARB
Assumptions for 2030 model:
Vehicle technology-assumes 60% of fleet is hybrid: 1/3 each of HEV, HHV, PHEV; 40% conventional
Assumes 60% of fleet uses some type of alternate fuel; 40% is conventional fuel and conventional drive train
80% biofuels: 30-40% GHG WTW reduction
20% cellulosic biofuels (E85 and DME from CA Poplar): 90% GHG WTW reduction
2008 Truck CO2 reference = 35 MMT
2008
Tractors - OTR
12,778,852,804
6,353,751,863
Tractors – Short haul/regional
Class 3-8 Work trucks – Rural/ intercity
Class 3-8 Work trucks - Urban
6,063,664,901
Class 2b/3 Vans/Pickups
3,607,072,517
4,163,187,702
1,054,195,705
122,770,213
Trucks, Work site support
Vehicles Miles traveled
Vehicle Population
2030 Truck CO2: 30% reduction from 1990 = 22 MMT
2030
Tractors - OTR
8,152,499,358
4,053,553,906
Tractors – Short haul/regional
Class 3-8 Work trucks – Rural/ intercity
Class 3-8 Work trucks - Urban
3,868,484,806
Class 2b/3 Vans/Pickups
2,301,232,910
2,656,022,164
672,553,667
78,324,695
Trucks, Work site support
Vehicles Miles traveled
Vehicle Population
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CALSTART
Source: CalHEAT report: "Research and Market Transformation Roadmap Update", Dec. 7, 2011
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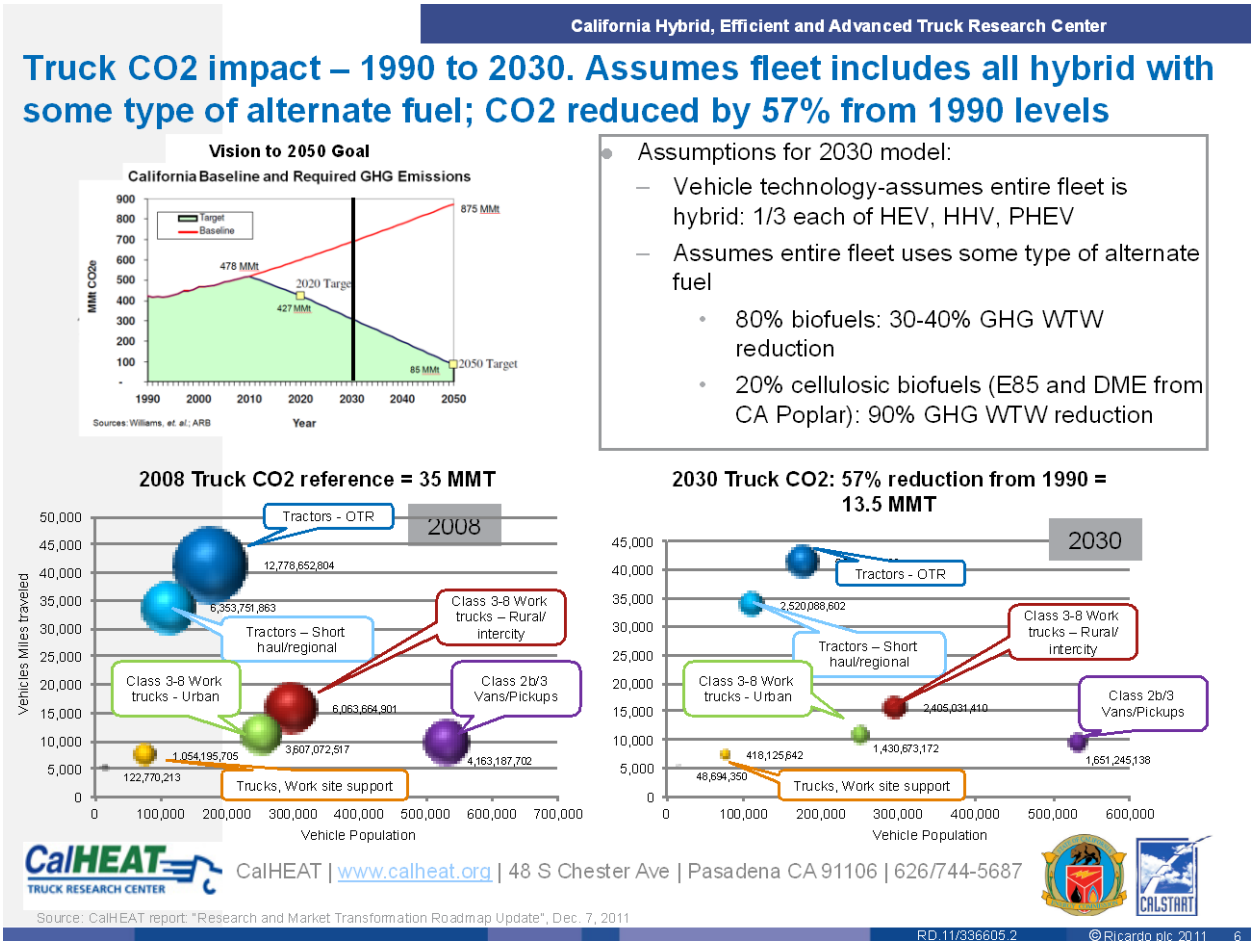
Slide E 5


California Hybrid, Efficient and Advanced Truck Research Center
Truck CO2 impact – 1990 to 2030. Assumes fleet includes all hybrid with some type of alternate fuel; CO2 reduced by 57% from 1990 levels
Vision to 2050 Goal
California Baseline and Required GHG Emissions
Target
Baseline
MMt CO2e
478 MMt
875 MMt
2020 Target
427 MMt
85 MMt
2050 Target
Year
Sources: Williams, et. al.; ARB
Assumptions for 2030 model:
Vehicle technology-assumes entire fleet is hybrid: 1/3 each of HEV, HHV, PHEV
Assumes entire fleet uses some type of alternate fuel
80% biofuels: 30-40% GHG WTW reduction
20% cellulosic biofuels (E85 and DME from CA Poplar): 90% GHG WTW reduction
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12,778,852,804
6,353,751,863
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Class 3-8 Work trucks - Urban
6,063,664,901
Class 2b/3 Vans/Pickups
3,607,072,517
1,054,195,705
4,163,187,702
122,770,213
Trucks, Work site support
Vehicles Miles traveled
Vehicle Population
2030 Truck CO2: 57% reduction from 1990 = 13.5 MMT
2030
Tractors - OTR
2,520,088,602
Tractors – Short haul/regional
Class 3-8 Work trucks – Rural/ intercity
Class 3-8 Work trucks - Urban
2,405,031,410
Class 2b/3 Vans/Pickups
1,430,673,172
418,125,642
1,651,245,138
48,694,350
Trucks, Work site support
Vehicle Population
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CALSTART
Source: CalHEAT report: "Research and Market Transformation Roadmap Update", Dec. 7, 2011
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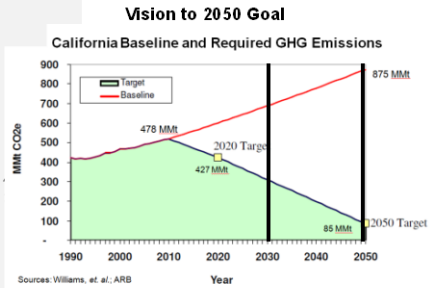
Slide E 6

California Hybrid, Efficient and Advanced Truck Research Center

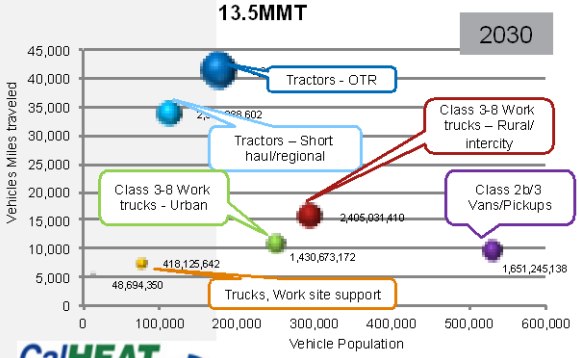
Truck CO2 impact – 2008 to 2030 and 2050. Fleet includes all hybrid and alternate fuel. 2050 CO2 reduced by 80% from 1990.



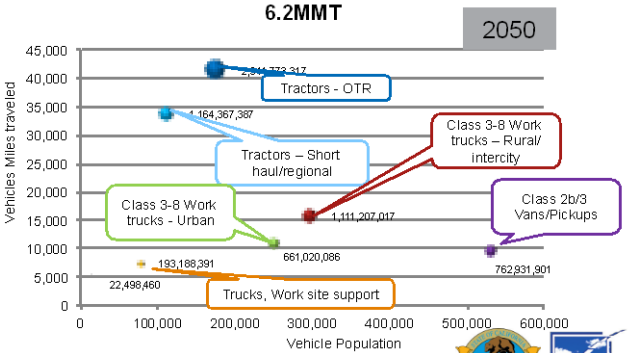
Truck CO2 Reduction Scenarios		
Year	CO2 (MMt)	% Change
1990	31.2	-
2008	35.0	+12%
2030	13.5	-57%
2050 Goal	6.2	-80%

Assumptions for 2050 model:
60% of alternate fuel used is from DME, RNG, CNG from CA poplar or E85 cellulosic material with ~95% GHG reduction

2030 Truck CO2: 57% less than 1990 = 13.5MMT



2050 Truck CO2: 80% less than 1990 = 6.2MMT



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Source: CalHEAT report: "Research and Market Transformation Roadmap Update", Dec. 7, 2011

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Slide E 7

s. October 3, 2011 DEER Conference

Slide E 8

, Sturman Industries, 2011. “Unlocking the Potential of Alternative Fuels for Transportation.” November 2011.

Slide E 9

ctober 16,

2007. www.hybridcar.com