Parallel-Series Multimode Compressed Natural Gas Plug-In Hybrid Electric Vehicle

Design, Optimization and Demonstration of an Intelligent Plug-In Hybrid Electric Vehicle Powertrain
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Finally, this project could not have succeeded without the hard work of Efficient Drivetrain’s own team members, including Kristal Ferchau, Galdino Ferretiz, Thomas Gibson, Mario Miranda, Dana Morton, Julio Razo, Mike Vang, Taylor Yu, and the brilliant and indefatigable Jean-Baptiste Gallo.
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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- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

The Parallel-Series Multimode CNG-PHEV, Design, Optimization and Demonstration of an Intelligent PHEV Powertrain project report is the final report for the Parallel-Series Multi-Mode Class 4 CNG-PHEV project (Grant Number PIR-13-013) conducted by Efficient Drivetrains, Inc. The information from this project contributes to Energy Research and Development Division’s Transportation Program.

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

Efficient Drivetrains, Inc. (EDI) designed, integrated, and optimized a plug-in hybrid electric vehicle (PHEV) drivetrain (the EDI PowerDrive™ system) with an existing United States Environmental Protection Agency/California Air Resources Board-approved General Motors 6.0-liter engine converted to compressed natural gas (CNG) by Greenkraft, Inc. EDI also identified duty cycles and applications for the proposed technology, including achieving 100 percent all-electric operations under certain drive cycles.

EDI optimized the EDI PowerDrive™ system design process, which included updates to reduce the system weight, rebalance vehicle weight distribution, reposition the CNG tank, improve performance, and tailor the system to the Greenkraft vehicle. The optimized engine and EDI PowerDrive™ system were then integrated into a 14,500-lb., Class 4, medium-duty truck provided by Greenkraft. The research team then validated, tested, and demonstrated the complete truck on road, during emissions testing and fleet operations testing. EDI’s cost projections for the system were estimated at $176,906 for the prototype vehicle; these costs are projected to drop to $34,460 by 2020 costs, assuming production of 5,000 units per year.

Dynamometer testing revealed a combined average fuel economy of 43.1 to 66.1 miles per gasoline gallon equivalent depending on test cycle, while on-road testing showed carbon dioxide emissions reductions of about 51 percent compared to a conventional CNG vehicle on a rural/intercity route, and about 48 percent on an urban route. The project’s outreach efforts culminated in a voice-of-customer event, where fleet vehicle managers were given the opportunity to test drive and provide feedback on the completed vehicle.

Keywords: Parallel-series multimode, plug-in hybrid electric vehicle, PHEV, compressed natural gas, CNG, Efficient Drivetrains, Inc., EDI, PowerDrive.

Please use the following citation for this report:

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EXECUTIVE SUMMARY

Introduction
Medium- and heavy-duty vehicles play a critical role in supporting California's economy; yet, they also produce significant quantities of criteria pollutant and greenhouse gas (GHG) emissions, and according to the California Energy Commission, account for 16 percent of the state's petroleum consumption. Advanced technologies such as plug-in hybrid electric vehicles (PHEV) have been identified as two key pathways to reduce these negative impacts. These alternative fuels also transition the state away from diesel- and gasoline-powered vehicles. Combining the two solutions into one vehicle can present significant advantages not fully explored, especially in medium-duty vehicle applications. A natural gas PHEV truck would offer most of the benefits of zero-emission, all-electric vehicles, with the added advantage of an extended range fueled by compressed natural gas (CNG) or renewable natural gas.

Efficient Drivetrains, Inc. (EDI) in Milpitas (Santa Clara County) is a rapidly growing, advanced transportation technology leader and innovator in high-efficiency plug-in-hybrid and full electric powertrain systems for commercial vehicles. EDI’s PowerDrive™ system, showcased in this project in a parallel-series multimode CNG-PHEV drivetrain system, is an advanced suite of drivetrain solutions spanning light-, medium-, and heavy-duty applications. The system can intelligently and automatically adapt to operate either as only an electric vehicle (EV) for neighborhood driving, as a series-hybrid optimized for stop and go city traffic conditions, or as an efficient parallel-hybrid optimized for highway driving conditions.

Project Purpose
This project team addressed the lack of sufficient real-world, operational data about CNG-PHEVs. EDI had already identified integration, incremental cost, and vehicle weight as the issues most critically requiring research, development, and demonstration to support the continued development and commercialization of a medium-duty CNG-PHEV drivetrain option for California fleets. The project team also identified duty cycles and applications for CNG-PHEV systems that would provide the greatest benefit to fleet operators by optimizing zero-emission operations and range.

The team looked at the design, integration, and optimization of EDI PowerDrive™ system with an existing Environmental Protection Agency (EPA)/California Air Resources Board-approved (CARB) General Motors (GM) 6.0-liter (L) engine converted to CNG by Greenkraft, Inc. The optimized engine and EDI PowerDrive™ system were then integrated into a medium-duty truck provided by Greenkraft. The complete truck was then validated, tested, and demonstrated on road, in real-world fleet operations and in ride-and-drive demonstrations with select fleets, supporting development of potential sales targets when commercialized.
**Project Process**

The EDI team visited Greenkraft in October 2014 to inspect the base model truck and take measurements for the design of the complete integrated system. Greenkraft also provided EDI with computer assisted design schematics of the base CNG vehicle’s chassis and fuel delivery system.

In January 2015, Greenkraft delivered a 2014 Class 4 G1 truck with a CNG-powered GM/Greenkraft 6.0L V8 engine at EDI’s Vehicle Integration & Support Center in Dixon (Solano County), California. EDI prepared the base vehicle to integrate the EDI PowerDrive™ CNG-PHEV drivetrain system by removing the original transmission and modifying the rear axle, driveline, and electrical harness to support installation of the proposed equipment.

Fabrication and assembly was completed over five months and included installing the EDI PowerDrive™ and all associated components, as well as integrating the battery packs, high-voltage and low-voltage components, and cooling system. EDI completed the wiring and electrical connection, including harnesses with high- and low-voltage cabling. EDI also updated vehicle software (including vehicle data collection, controller area network preparation, and hybrid logic design) and completed integrating the EDI PowerDrive™ and vehicle accessories.

**Project Results**

The team expects the prototype EDI PowerDrive™ system cost will decrease substantially as a result of streamlining and optimization of the manufacturing processes, economies of scale with volume purchases, and falling battery prices. The estimated 2020 cost at 5,000 units per year) is $34,460 with an anticipated payback period of 4.5 years.

The complete truck was validated, tested on a chassis dynamometer, and demonstrated under normal driving conditions for on-road during emissions and real-world fleet testing. Chassis dynamometer testing revealed a combined average fuel economy of 43.1 to 66.1 miles per GGE depending on test cycle, while on-road testing showed reduced carbon dioxide (CO₂) emissions of roughly 51 percent compared to a conventional CNG vehicle on a rural/intercity route, and about 48 percent on an urban route. The team also identified reductions in criteria air pollutant emissions, including up to 89 percent less carbon monoxide (CO) emissions, and up to 70 percent of particulate matter (PM) emissions. Oxides of nitrogen (NOₓ) emissions also decreased by 16 percent on an urban test route but increased by 43 percent during testing on a rural/intercity route. The emissions of CO, NOₓ, PM, and hydrocarbon (HC) measured for both vehicles were low in absolute terms, so that the percentage differences have limited significance for air quality. The increases in NOₓ emissions with the rural/intercity route were attributed to infrequent “spikes” in pollutant concentrations, which generally coincided with vehicle acceleration, and engine restarting. For the next phase of this program, EDI will focus on better integration of the EDI PowerDrive™ and the Greenkraft CNG engine and better calibration of the whole integrated system which is expected to lead to dramatic improvements in performance and emission reductions.

The project’s outreach efforts culminated in a **voice-of-customer** event, where 39 persons, including 18 fleet managers who all served as technical advisory committee members, test...
drove and provided feedback on the completed vehicle. The event significantly increased the project team's exposure to potential customers and highlighted strong fleet interest in alternative vehicle technologies. Feedback from the technical advisory committee also identified product support, purchase price, and diversity of vehicle platforms as critical areas for product improvement.

The project team attended several industry events and technology forums to raise awareness of the project, recruit attendees for the voice-of-customer event, and gather preliminary feedback on the Class 4 CNG-PHEV truck and the EDI PowerDrive™ technology. These events also helped the project team to reach fleet managers who were not able to attend the voice-of-customer event: MEMA SoCal Meeting (July, 2015), EPRI Technical Advisor Meeting (September, 2015), North American Natural Gas Vehicle Conference & Expo (September 2015), High-efficiency Truck Users Forum (HTUF) National Technical Session (September 2015) and the Northern California Clean Technology Forum (October 2015).

**Benefits to California**

The project produced numerous direct and indirect benefits toward fully commercializing EDI's PowerDrive™ system. Integrating the EDI PowerDrive™ into a Greenkraft medium-duty truck and voice-of-customer event resulted in a roadmap to achieve emissions certification as well as having very positive driver feedback. Moreover, working with equipment suppliers, industry partners, fleets and regulators provides benefits to the customer as the product becomes tailored to the customer’s needs and less costly when commercialized.

The on-road testing provided information about the product that could be useful in production models of the PowerDrive™ and improved EDI's standing and knowledge in the industry. Established relationships from this project with original equipment manufacturers and other industry partners will directly support commercialization by integrating PowerDrive in more trucks. Also, strengthening the supply chain will help reduce the manufacturing cost as the prototype cost was high, but EDI has developed a reasonable cost reduction analysis, illustrating a path to an 80 percent cost reduction during commercial scale production.

This project has strengthened EDI's commitment to technology development and manufacturing in California. Benefits of the public-private partnership between EDI and California, including rapid acceleration of new vehicle technologies, in-state manufacturing, and technology development in California. EDI estimates about 25 future jobs in California, ultimately reaching 200 in-state jobs, including high-quality positions in engineering, sales, management, and manufacturing, with additional indirect benefits to in-state employment. In July 2018, following the completion of this project, Cummins announced acquisition of Efficient Drivetrains, recognizing the company’s talented workforce and transportation electrification expertise. The acquisition is expected to accelerate deployment and adoption of the PowerDrive™ system demonstrated in this project.
CHAPTER 1: Introduction

1.1 Efficient Drivetrains, Inc.
EDI was founded in April 2006 as a research and development partnership with the University of California, Davis (UCD) Hybrid Electric Vehicle Center. As part of the partnership, EDI negotiated an exclusive licensing agreement for the UCD’s entire PHEV patent portfolio. Building upon this portfolio, EDI has developed a suite of unique, effective, and highly efficient PHEV and EV drivetrain systems and controls. Further, the company has licensed portions of its extensive patent portfolio to major vehicle and vehicle technology producers, including Ford, Toyota, and Siemens.

With the growth in United States and global demand for EDI products, EDI recently expanded its California manufacturing presence with a new, 30,000 square-foot facility—the EDI Advanced Vehicle Manufacturing Facility (AVM)—located in an industrial park in Milpitas (Santa Clara County). This facility will ultimately support production increases up to approximately 6,000 PHEV and EV drivetrains per year. The EDI AVM is expected to be operational by the end of 2017 and ready to manufacture EDI PowerDrive™ drivetrains systems to integrate into medium- and heavy-duty truck platforms.

EDI has been particularly successful in leveraging its patents into road tests and vehicle demonstrations, while continuing to develop solid relationships with major fleet managers in California and across the country. To date, EDI has produced and demonstrated the broadest portfolio of industry-first technology offerings. This project represents a meaningful step forward in EDI’s commercialization and product development processes.

1.2 Project Overview: Purpose, Goals, and Objectives
Medium- and heavy-duty vehicles are essential to California’s economy; yet, they also produce significant quantities of criteria pollutant and GHG emissions and account for 16 percent of the state’s petroleum consumption.¹ Low-carbon fuels such as natural gas, and advanced technologies, such as PHEVs, have been identified as two key pathways to reduce these negative impacts and transition the state away from diesel- and gasoline-powered vehicles. Combining the two solutions into one vehicle can present significant advantages that have not been fully explored, especially in medium-duty vehicles. A natural gas PHEV truck would offer most of the benefits of zero-emission, all-electric vehicles, with the added advantage of an extended range fueled by clean burning natural gas. Commercially available hybridization technologies have not historically included a cost-competitive option for fleets that operate CNG-powered

medium- and heavy-duty vehicles. This project explored the lack of sufficient real-world, operational data about CNG-PHEVs. EDI had identified integration, incremental cost, and vehicle weight as the issues most critically requiring research development and demonstration to support developing and commercializing a medium-duty CNG-PHEV option for California fleets. The project team also identified duty cycles and applications for CNG-PHEV systems that would provide the greatest benefit to medium-duty fleet operators through optimizing zero-emission operations and range.

This project team designed, integrated, and optimized an EDI PowerDrive™ system with an existing Environmental Protection Agency (EPA)/California Air Resources Board (CARB)-approved GM 6.0L engine converted to CNG by Greenkraft, Inc. The optimized engine and EDI PowerDrive™ system were then integrated into a medium-duty truck provided by Greenkraft. The truck was then validated, tested, and demonstrated on road, in real-world fleet operations and in ride-and-drive demonstrations with select fleets.

1.3 Statement of Work Summary

1.3.1 Goals and Objectives

The goals of this project were to:

- Develop and optimize a CNG-PHEV system suitable for medium-duty vehicle applications; and
- Determine which duty cycles and applications for medium-duty CNG-PHEV systems promise the greatest benefits, including possible elimination of using CNG and achieving 100-percent all-electric operations in certain cycles.

The objectives of this project were to:

- Successfully integrate and optimize an existing Greenkraft CNG-powered engine in a Class 4 medium-duty Greenkraft truck with the intelligent EDI PowerDrive™;
- Meet or exceed CARB medium/heavy-duty on-road emission certification requirements for 2016;
- Test and validate the integrated CNG-PHEV truck under normal operating conditions;
- Achieve approximately 29 percent thermal efficiency improvements compared to the baseline CNG engine;
- Effectively triple the miles per GGE of the baseline CNG-powered Greenkraft truck from approximately 9 miles per GGE to 27;
- Define the duty cycles under which the proposed CNG-PHEV can achieve 100 percent all-electric operations, and to eliminate using CNG;
- Perform short demonstrations of the proposed CNG-PHEV with various regional fleets.

1.4 Tasks and Key Deliverables

The project was completed through seven tasks, including these deliverables.

Task 1: General Project Tasks
- Project schedules, list of match funds, match funds letter, subcontracts, Technical Advisory Committee (TAC) commitments, TAC meeting summaries, Critical Project Review (CPR) reports, progress determinations, final meeting agreement summary, schedule for completing closeout activities, draft and final written products, progress reports, invoices, final report outline, final report.

Task 2: Contract Execution
- Demonstration site contract; Measurement and Verification Contract

Task 3: Prototype Design
- CAD schematics and specifications; equipment and materials list; design drawings; CPR report

Task 4: Prototype Assembly and Integration
- Chassis Dynamometer Test Plan; Draft Chassis Dynamometer Test Results; Final Chassis Dynamometer Test Results; Final Design Drawings

Task 5: Validation
- Validation test plan; fleet test plan; draft validation test report; final validation test report; draft fleet test report; final fleet test report; draft third party verification report; final third-party validation report

Task 6: Evaluation of Project Benefits
- Kick-off meeting benefits questionnaire; mid-term benefits questionnaire; final meeting benefits questionnaire

Task 7: Technology / Knowledge Transfer Activities
- Draft initial fact sheet; final initial fact sheet; draft final project fact sheet; final project fact sheet; draft technology / knowledge transfer plan; final technology / knowledge transfer plan; presentation materials

Task 8: Product Readiness Plan
- Draft production readiness plan; final production readiness plan
CHAPTER 2:
Prototype Design

This chapter summarizes the design approach taken by EDI to electrify an existing Greenkraft CNG-powered medium-duty truck. It also summarizes the findings and outcomes of the prototype design process.

2.1 Greenkraft Base Vehicle

The base vehicle was a Greenkraft, G1, medium-duty commercial truck rated at a 14,500-lb. GVWR and outfitted with an EPA/CARB-approved GM 6.0L engine converted to CNG by Greenkraft. The base vehicle also integrates a Greenkraft CNG fuel delivery system, which includes a 30-GGE CNG tank with regulator, fuel filter, and CNG fuel rail / injectors. Specifications and other key features are shown in Table 1.

Table 1: Greenkraft G1 Base Truck Specifications

<table>
<thead>
<tr>
<th>Category</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Year</td>
<td>2014</td>
</tr>
<tr>
<td>Chassis Manufacturer</td>
<td>Greenkraft</td>
</tr>
<tr>
<td>GVWR</td>
<td>14,500 lb. (Class 4)</td>
</tr>
<tr>
<td>Engine Model</td>
<td>GM / Greenkraft LC8 6L V8</td>
</tr>
<tr>
<td>Engine Peak Power</td>
<td>323 hp (241 kW) @ 4600 RPM</td>
</tr>
<tr>
<td>Engine Peak Torque</td>
<td>373 ft.-lb. (506 Nm) @ 4400 RPM</td>
</tr>
<tr>
<td>Fuel System</td>
<td>CNG / 30-GGE fuel tank</td>
</tr>
<tr>
<td>Exhaust System</td>
<td>Three Way Catalyst</td>
</tr>
<tr>
<td>Tires</td>
<td>215 / 75 R-17.5</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>150 in.</td>
</tr>
<tr>
<td>Transmission Model / Type</td>
<td>GM Hydramatic 6L90 / Six speed automatic</td>
</tr>
<tr>
<td>Suspension Type</td>
<td>Spring Suspension</td>
</tr>
<tr>
<td>Brake Type</td>
<td>Air Brakes</td>
</tr>
<tr>
<td>Cab Placement</td>
<td>Cab Forward Design</td>
</tr>
</tbody>
</table>

Source: Greenkraft, 2015.

2 Greenkraft’s executive order for this engine family can be found at: CARB Executive Order A-398-0013-1
https://www.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2015/greenkraft_hdoe_a3980013r1_6d0_0d20_cng.pdf
2.2 EDI Technology Overview

EDI’s PowerDrive™ drivetrain products include a suite of advanced drivetrain solutions spanning light, medium, and heavy-duty applications (Figure 1). The intelligent EDI PowerDrive™ system is a compact, lightweight, high-efficiency four-mode, series-parallel, PHEV drivetrain that integrates two electric motors into the drivetrain of a downsized Internal Combustion Engine (ICE). This advanced series-parallel PHEV system can deliver all of the benefits of parallel and series hybrid electric vehicle systems, with an impressive improvement in fuel economy compared with standard hybrid electric vehicle systems. While driving, the EDI PowerDrive™ automatically switches among its four driving modes to intelligently adapt to driving conditions.

**Figure 1: Four Modes of EDI PowerDrive™ Operation**

- **EV Mode**: the electric motor #1 (EM1) operates the vehicle in only EV mode, using energy stored in the on-board battery, for neighborhood driving or all-electric driving or both up to approximately 40 miles.
- **EV+ Mode**: operates similar to the EV mode but with additional power by integrating both electric motors (EM1 and EM2) to provide additional torque optimal for hill climbing and added acceleration.
- **Parallel Mode**: the ICE provides power to the vehicle drive, while EM1 maintains the battery state of charge and EM2 provides additional power, optimal for highway and continuous high-speed driving.
- **Series Mode**: EM2 provides power to drive the wheels, while the ICE and EM1 maintain the battery state of charge, optimal for stop and go city traffic conditions and low-speed driving.
EDI’s technology and design have several advantages; EDI’s PowerDrive™ system design focuses on reducing complexity, weight, and cost. The technology is adaptable to a unique inline form, allowing the drivetrain to be integrated into any light, medium, or heavy-duty application or vehicle design. Specifically, the proposed drivetrain integrates all motors and clutches while fitting within the space of the conventional transmission supplied with the base vehicle (Figure 2).

**Figure 2: EDI PowerDrive™ Schematic**

This results in an expedited time to market and minimizes development costs. These benefits have been well received by vehicle fleets, culminating in demonstrations with utility fleets such as Pacific Gas and Electric (Figure 3). EDI’s technology, as installed in these vehicles, provides significant benefits not available with conventional vehicles. For example, these demonstration work trucks incorporate EDI PowerDrive™ technology into a standard Ford F-550 base vehicle. These new PHEV work trucks have 30 miles of all-electric range and enough battery capacity to operate vehicle accessories for up to 10 hours a day without idling the base diesel engine. The system can also provide a mobile, grid-synchronizable power source from the truck’s battery or engine acting as a generator.

**Figure 3: PG&E Demonstration Work Trucks Incorporating the EDI PowerDrive™ Technology**
2.3 Vehicle Design Process

The EDI team visited Greenkraft in October 2014 to inspect the base model truck and take all necessary measurements for the design of the complete integrated system. Greenkraft also provided EDI with computer assisted design (CAD) schematics of the base CNG vehicle’s chassis and fuel delivery system. During this process, EDI discovered that less documentation was available for the base vehicle than originally anticipated. As a result, some vehicle-specific design elements—such as bolt patterns, exact wire routing, connector installation, and electrical component placement—were moved to the vehicle build phase, rather than designed ahead of time.

Using the available specifications and drawings, EDI completed an engineering evaluation of the process required to adapt and integrate the EDI PowerDrive™ system into the Greenkraft chassis and engine. Figure 4 and Figure 5 show the vehicle component layout selected after completing this rigorous engineering evaluation with the CNG fuel tank behind the cab and the battery packs between the front and rear wheels. EDI also incorporated design features to support further advances in compact assembly and reduced weight, exceeding EDI’s existing system.

![Figure 4: Vehicle Component Layout](source: EDI)
2.4 Vehicle Specifications

EDI developed the following vehicle specifications for the completed vehicle based on the design process (Table 2 and Table 3).

Table 2: Proposed Class 4 CNG-PHEV Truck Specifications

<table>
<thead>
<tr>
<th>Category</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
</tr>
<tr>
<td>GVWR</td>
<td>14,500 lb. (Class 4)</td>
</tr>
<tr>
<td>Curb Weight</td>
<td>9,100 lb.</td>
</tr>
<tr>
<td>Chassis Configuration</td>
<td>4 x 2 (rear wheel drive)</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>GM / Greenkraft LC8 6L V8</td>
</tr>
<tr>
<td>Peak Power</td>
<td>323 hp (241 kW) @ 4600 RPM</td>
</tr>
<tr>
<td>Peak Torque</td>
<td>373 ft.-lb. (506 Nm) @ 4400 RPM</td>
</tr>
<tr>
<td>Fuel System</td>
<td>CNG / 30-GGE fuel tank</td>
</tr>
<tr>
<td>Exhaust System</td>
<td>Three-Way Catalyst</td>
</tr>
<tr>
<td>Emission Certification Year</td>
<td>2015</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
</tr>
<tr>
<td>Tires</td>
<td>225 / 70R 19.5</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>150 in.</td>
</tr>
<tr>
<td>Length / Width / Height</td>
<td>275 in. / 78 in. / 87 in.</td>
</tr>
<tr>
<td><strong>Basic Performance</strong></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3: Proposed Class 4 CNG-PHEV Truck Battery Specifications

<table>
<thead>
<tr>
<th>Battery System</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry</td>
<td>Prismatic Li-Ion</td>
</tr>
<tr>
<td>Max / Min Battery Voltage</td>
<td>737 V / 450 V</td>
</tr>
<tr>
<td>Peak Power</td>
<td>400 kW / 680 VDC / 650 A</td>
</tr>
<tr>
<td>Capacity</td>
<td>40 kWh</td>
</tr>
<tr>
<td>Charger</td>
<td>SAE J1772 / Level 2</td>
</tr>
<tr>
<td>Charging Time</td>
<td>6-12 hours (depending on AC source)</td>
</tr>
</tbody>
</table>

Source: EDI

### 2.5 EDI PowerDrive™ Cost Projection

Parts and material sourcing lists were developed based on interim design and vehicle specifications (Table 4). For the initial build of the prototype, many parts were purchased in single quantity; as a result, costs were high. EDI anticipates that costs would be reduced considerably for a fully commercialized product.

<table>
<thead>
<tr>
<th>EDI PowerDrive™ Equipment Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype</td>
<td>$176,906</td>
</tr>
<tr>
<td>Current Costs: 50 units</td>
<td>$86,254</td>
</tr>
<tr>
<td>Current Costs: 5,000 units</td>
<td>$39,716</td>
</tr>
<tr>
<td>2020 Costs: 5,000 units</td>
<td>$34,460</td>
</tr>
</tbody>
</table>

Source: EDI

The total cost for the equipment of the prototype EDI PowerDrive™ system included in the project was $176,906. However, based on anticipated optimizing the manufacturing processes at EDI’s Advanced Vehicle Manufacturing Facility in Milpitas (Santa Clara County), economies of scale with volume purchases, and falling battery prices, EDI estimates that 2020 incremental costs at 5,000 units per year would be $34,460 for a fully commercial EDI PowerDrive™ system.
not including the base model truck. At this cost, fleets could anticipate a 4.5 years payback period with 2020 projected fuel prices.\textsuperscript{3}

\textsuperscript{3} Assumes 100 miles/day for 250 days/year. Conventional diesel truck fuel economy is assumed to be 8 MPG and the CNG-PHEV truck fuel economy is assumed to be 11.2 MPG in hybrid mode. All-electric range is assumed to be 40 miles and the EV mode efficiency 0.8 AC kWh/mile. Diesel ($3.70/gallon), CNG ($2.28/DGE) and electricity ($0.10/kWh) fuel prices are based on projections using the U.S. EIA Short-Term Energy Outlook for July 2016 and U.S. EIA Annual Energy Outlook 2015.
CHAPTER 3: Prototype Assembly and Integration

This chapter reviews the prototype assembly and integration tasks that were completed under Task 4 of the approved scope of work. All activities were completed on time and within the proposed schedule for the project.

3.1 Prototype Build Process

In January 2015, Greenkraft delivered a 2014 Class 4 G1 truck with a CNG-powered GM / Greenkraft 6.0L V8 engine at EDI’s Vehicle Integration & Support Center in Dixon (Solano County) (Figure 6). EDI prepared the base vehicle for integration of the EDI PowerDrive™ system by removing the original transmission and modifying the rear axle (Figure 7), driveline, and electrical harness to support installation of the proposed equipment.

Figure 6: As-Built Greenkraft Truck at EDI’s Vehicle Integration & Support Center in Dixon (Solano County), January, 2015

![As-Built Greenkraft Truck](image)

Source: EDI.

Fabrication and assembly was completed over five months. The process included installation of the EDI PowerDrive™ system and all associated components, as well as integration of the battery packs, high-voltage and low-voltage components, and cooling system. EDI then completed wiring and electrical connection, including harnesses along with high- and low-voltage cabling (Figure 8). EDI also updated vehicle software (including vehicle data collection, Controller Area Network (CAN) preparation, and hybrid logic design) and completed EDI PowerDrive™ integration and vehicle accessories integration (Figure 9).

During the fabrication process, EDI identified deficiencies in the system’s electric motors. These deficiencies were quickly repaired by the motor vendor, fully resolving the issue, but were responsible for a 2-month schedule delay for the overall integration process. Other issues
centered on minor challenges with the base vehicle systems. These issues were identified and resolved by EDI without any additional impact to the project schedule.

**Figure 7: Modification of the Rear Axle (Left) and Fabrication / Installation of the Battery System Frame (Right)**

Source: EDI.

**Figure 8: Component Integration and High and Low Voltage Wiring (Left) and Final Battery System Installation (Right)**

Source: EDI.
3.2 Final Product

The completed CNG-PHEV truck (Figures 10-12) met the specifications identified, and incorporated all systems and components as proposed. These systems and components include the electric drive; high-voltage battery pack; hybrid control unit (HCU); high-voltage power distribution unit (PDU), DC/DC converter (600V to 12 / 24V), low-voltage fuse/relay/distribution unit, on-board charger; and driver display. Key vehicle electrification accessories include an electric power steering, electric HVAC, and an electronic braking system. These systems are managed by EDI’s power control software, which manages all drivetrain and battery system functions during operation, and also provides diagnostics, fault management, and communication functions with vehicle operators and with external networks.
Vehicle operation was designed for ease of operator use. Basically, the vehicle operator drives the CNG-PHEV like a conventional diesel or gasoline truck. The vehicle automatically and intelligently switches from EV, EV+, Series and Parallel modes as necessary, with no interaction or initiation required by the operator. A driver interface display provides a detailed summary of system status. The driver can also opt to take full manual control over vehicle operating modes.
3.3 Final Design Drawings

To accommodate the flatbed required for the fleet test (Section 4.2), EDI updated the CNG-PHEV truck design and produced final drawings. Key updates included changes to accommodate installation of a flatbed onto the vehicle chassis; repositioning of the CNG tank from behind the cab to the left side of the vehicle frame, as well as shifting Battery Pack 2 from the left side of the vehicle frame to the rear of the vehicle; repositioning of the charger, rear air tank, and radiator; repositioning of the rear bumper by 4 inches; improving the weight distribution and balancing; and re-plumbing of all CNG lines and filler valve located on the left side of vehicle (Figure 13).

EDI then modified the CNG-PHEV truck according to the final design drawing updates, and also arranged for installing a flatbed with stake options and wood paneling onto the vehicle. Taillights were also integrated into the flatbed design (Figure 14).
CHAPTER 4: Validation and Testing

This chapter reviews the validation tests that were completed in support of the project. These activities were completed under Task 5 of the approved Scope of Work.

4.1 Chassis Dynamometer Testing

EDI commissioned chassis dynamometer testing at the Santa Ana, California facility of a Greenkraft subsidiary, California Environmental Engineering, LLC (CEE). Testing was completed on CEE’s heavy-duty dynamometer, which is designed to handle a range of vehicles and vehicle loads under typical on-road driving conditions. The system includes a 48-inch, electric AC chassis dynamometer with dual, direct-connected, 300-HP motors attached to each roll set. The dynamometer applies appropriate loads to the test vehicle to simulate factors, such as roadway friction and wind resistance, which the vehicle would experience under typical driving conditions. During testing, a driver accelerated and decelerated the vehicle, following a series of driving traces, while the vehicle was chained to the dynamometer.

In October 2015, the completed, Class 4 CNG-PHEV truck was tested over three standardized drive cycles (Table 5), as well as two constant-speed cycles, at a total vehicle test weight of 9,500 lb.:

- Urban Dynamometer Driving Schedule – Heavy Duty (UDDS-HD)
- Highway Fuel Economy Test (HWFET)
- Heavy Heavy-Duty Diesel Truck – Transient (HHDDT-Transient)
- Constant 30 MPH
- Constant 60 MPH
- Acceleration tests

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>UDDS-HD</th>
<th>HWFET</th>
<th>HHDDT-Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Driving Speed</td>
<td>28.2 mph</td>
<td>48.6 mph</td>
<td>18.2 mph</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>58.0 mph</td>
<td>59.9 mph</td>
<td>47.5 mph</td>
</tr>
<tr>
<td>Total Running Time</td>
<td>1060 sec.</td>
<td>765 sec.</td>
<td>668 sec.</td>
</tr>
<tr>
<td>Percentage Idle</td>
<td>33.3%</td>
<td>0.8%</td>
<td>15.6%</td>
</tr>
<tr>
<td>Total Distance</td>
<td>5.6 miles</td>
<td>10.3 miles</td>
<td>2.9 miles</td>
</tr>
<tr>
<td>Stops per Mile</td>
<td>2.52</td>
<td>0.10</td>
<td>1.40</td>
</tr>
<tr>
<td>Kinetic Intensity</td>
<td>0.60826</td>
<td>0.21912</td>
<td>1.37650</td>
</tr>
</tbody>
</table>

Source: EDI
Testing was completed over five days, allowing for complete recharging of the vehicle’s battery in between testing cycles. Multiple standardized drive cycle tests were completed as shown in Table 6.

**Table 6: Chassis Dynamometer Test Plan**

<table>
<thead>
<tr>
<th>Test Day</th>
<th>Test Cycle</th>
<th>Description</th>
<th>Speed Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Day 1</td>
<td>Constant 30 MPH</td>
<td>Charge battery to full, run vehicle at a constant 30 MPH speed in EV mode for 10 min</td>
<td><img src="image1.png" alt="Speed Profile" /></td>
</tr>
<tr>
<td>Test Day 1</td>
<td>Constant 60 MPH</td>
<td>Charge battery to full, run vehicle at a constant 60 MPH speed in EV mode for 10 min</td>
<td><img src="image2.png" alt="Speed Profile" /></td>
</tr>
<tr>
<td>Test Day 2</td>
<td>UDDS</td>
<td>Charge battery to full, run vehicle on UDDS cycle in EV mode until engine comes on</td>
<td><img src="image3.png" alt="Speed Profile" /></td>
</tr>
<tr>
<td>Test Day 2</td>
<td>UDDS</td>
<td>Run vehicle on 3 UDDS cycles in hybrid mode, starting with engine cold and let warm up to operating temperature</td>
<td><img src="image4.png" alt="Speed Profile" /></td>
</tr>
<tr>
<td>Test Day</td>
<td>Test Cycle</td>
<td>Description</td>
<td>Speed Profile</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Test Day 3</td>
<td>HHDDT-Transient</td>
<td>Charge battery to full, run vehicle on HHDDT-Transient cycle in EV mode until engine comes on</td>
<td></td>
</tr>
<tr>
<td>Test Day 3</td>
<td>HHDDT-Transient</td>
<td>Run vehicle on 3 HHDDT-Transient cycles in hybrid mode, starting with engine cold and let warm up to operating temperature</td>
<td></td>
</tr>
<tr>
<td>Test Day 4</td>
<td>HWFET</td>
<td>Charge battery to full, run vehicle on HWFET cycle in EV mode until engine comes on</td>
<td></td>
</tr>
<tr>
<td>Test Day 4</td>
<td>HWFET</td>
<td>Run vehicle on 3 HWFET cycles in hybrid mode, starting with engine cold and let warm up to operating temperature</td>
<td></td>
</tr>
</tbody>
</table>
The chassis dynamometer testing generated data on vehicle acceleration, powertrain efficiency, EV range, and fuel economy. As shown in Table 7, powertrain efficiency ranged from 0.39 DC kWh/mile (Constant 30 MPH) to 0.61 DC kWh/mile (Constant 60 MPH), with standardized test cycles falling within this range. These powertrain efficiencies translated into maximum EV ranges of 48.2 miles (Constant 60 mph) to 75.4 miles (Constant 30 mph) (Table 7: EV Range Test Results).

<table>
<thead>
<tr>
<th>Test Cycle*</th>
<th>Powertrain Efficiency</th>
<th>Maximum EV Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant 30 MPH</td>
<td>0.39 DC kWh/mile</td>
<td>75.4 miles</td>
</tr>
<tr>
<td>Constant 60 MPH</td>
<td>0.61 DC kWh/mile</td>
<td>48.2 miles</td>
</tr>
<tr>
<td>UDDS</td>
<td>0.57 DC kWh/mile</td>
<td>51.6 miles</td>
</tr>
<tr>
<td>HWFET</td>
<td>0.53 DC kWh/mile</td>
<td>56.0 miles</td>
</tr>
<tr>
<td>HHDDT-Transient</td>
<td>0.51 DC kWh/mile</td>
<td>57.2 miles</td>
</tr>
</tbody>
</table>

* All test cycles performed at 9,500 lb. test weight

Source: EDI

Acceleration test results indicate more than adequate performance for a typical Class 4 truck (Table 8).

<table>
<thead>
<tr>
<th>Test Cycle*</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 60 MPH</td>
<td>14.6 seconds</td>
</tr>
<tr>
<td>0 to 50 MPH</td>
<td>10.3 seconds</td>
</tr>
<tr>
<td>40 to 60 MPH</td>
<td>7.3 seconds</td>
</tr>
</tbody>
</table>

* All test cycles performed at 9,500 lb. test weight

Source: EDI
Charge sustaining mode happens after the battery has reached its minimum state of charge and the engine is started. In charge sustaining mode, the Class 4 CNG-PHEV truck operates as a hybrid electric truck. As shown in Table 9, charge sustaining average fuel economy ranged from 14.8 miles per GGE (HWFET test cycle) to 23.8 miles per GGE (HHDDT-Transient test cycle).

**Table 9: Charge Sustaining Fuel Economy Test Results**

<table>
<thead>
<tr>
<th>Test Cycle*</th>
<th>Charge Sustaining Average Fuel Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDDS</td>
<td>15.3 miles per GGE</td>
</tr>
<tr>
<td>HWFET</td>
<td>14.8 miles per GGE</td>
</tr>
<tr>
<td>HHDDT-Transient</td>
<td>23.8 miles per GGE</td>
</tr>
</tbody>
</table>

* All test cycles performed at 9,500 lb. test weight

Source: EDI

For a PHEV, the combined operation includes charge depleting (EV mode) and charge sustaining (hybrid mode). For this test, the team calculated the combined average fuel economy on an 80-mile route. As Table 10 shows, the combined average fuel economy ranged from 43.1 miles per GGE (UDDS test cycle) to 66.1 miles per GGE (HHDDT-Transient test cycle).

**Table 10: Combined Fuel Economy Test Results**

<table>
<thead>
<tr>
<th>Test Cycle*</th>
<th>Combined Average Fuel Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDDS</td>
<td>43.1 miles per GGE</td>
</tr>
<tr>
<td>HWFET</td>
<td>49.3 miles per GGE</td>
</tr>
<tr>
<td>HHDDT-Transient</td>
<td>66.1 miles per GGE</td>
</tr>
</tbody>
</table>

* All test cycles performed at 9,500 lb. test weight

Source: EDI

Actual on-road electric vehicle range and overall fuel economy will vary widely with driving conditions, based on variable real-world drive cycles and use of vehicle accessories. The values presented are representative of the specific drive cycles and driving conditions identified, and were derived from testing completed in a controlled environment using standardized drive cycles. These results should not be used to predict electric range and overall fuel economy under different driving conditions. EDI recommends that further testing be completed to analyze all factors that influence actual electric range and overall fuel economy.

### 4.2 On-Road Emissions Testing

Spurred by increasingly stringent national, state, and regional emissions requirements, on-road emissions performance is a critical aspect of technology development for the EDI CNG-PHEV truck. To this end, EDI and CALSTART retained Engine, Fuel, and Emissions Engineering, Inc. (EE&FE) to measure on-road pollutant emissions from the prototype Class 4 CNG-PHEV truck. EE&FE conducted emissions measurements for the vehicle as it followed two predetermined test routes, designed to simulate typical rural/intercity driving and urban delivery operation.
Measurements, including emissions of CO$_2$, CO, NO$_x$, PM, and total hydrocarbons (THC) were performed in real time and using a EF&EE's Ride-Along Vehicle Emission Measurement (RAVEM) system. A charge depleting performance test was also conducted to assess battery-only operation of the CNG-PHEV truck.
4.2.1 Testing Vehicles, Parameters, Routes, and Methods

Tests were carried out on the prototype Class 4 CNG-PHEV truck and a conventional natural gas-powered truck based on the same Greenkraft platform, as summarized in Table 11.

The two vehicles were somewhat different from each other: the Class 4 CNG-PHEV truck was not fitted with a box or cab roof fairing, leading to different aerodynamic profiles that could potentially affect fuel consumption and emissions levels, especially at high speeds. This table also highlights differences in GVWR, gas tank size, chassis model year, and tires.

**Table 11: Project and Baseline Vehicles for On-Road Emissions Testing**

<table>
<thead>
<tr>
<th></th>
<th>EDI CNG-PHEV Truck</th>
<th>Conventional Greenkraft CNG Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis Manufacturer and Model Year</td>
<td>Greenkraft, 2014</td>
<td>Greenkraft, 2013</td>
</tr>
<tr>
<td>GVWR</td>
<td>14,500 (Class 4)</td>
<td>17,950 (Class 5)</td>
</tr>
<tr>
<td>Curb Weight</td>
<td>9,100 lb.</td>
<td>7,360 lb.</td>
</tr>
<tr>
<td>Engine Model</td>
<td>GM / Greenkraft LC8 6L V8</td>
<td></td>
</tr>
<tr>
<td>Fuel System</td>
<td>Natural Gas 30-GGE fuel tank</td>
<td>Natural Gas 60-GGE fuel tanks</td>
</tr>
<tr>
<td>Exhaust System</td>
<td>Three-Way Catalyst</td>
<td></td>
</tr>
<tr>
<td>Tires</td>
<td>215 / 75 R-17.5</td>
<td>225 / 70 R-19.5</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>150 in.</td>
<td></td>
</tr>
<tr>
<td>Transmission Make</td>
<td>EDI</td>
<td>GM</td>
</tr>
<tr>
<td>Model / Type</td>
<td>Dual clutch / dual motor</td>
<td>Hydramatic 6L90, 6-speed</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>40 kWh (rated)</td>
<td>N/A</td>
</tr>
<tr>
<td>Testing Weight With Box / Loaded</td>
<td>12,820 lb.</td>
<td>11,080 lb.</td>
</tr>
</tbody>
</table>

Source: EDI, Greenkraft

The trucks were loaded differently to simulate payload transport and to adjust vehicle curb weight to reflect actual conditions. An intermediate bulk container was attached to the CNG-PHEV truck and filled with water to simulate box weight, payload, and other accessories. The same container was secured in the box van body of the conventional CNG truck, but filled to a lower level to simulate payload only. The additional weight of the hybrid system on the CNG-
PHEV truck was not compensated for during testing of the conventional CNG truck. Both vehicles were tested with a 1,240 lb. payload plus the weight of two operators and emissions testing equipment.

Testing was conducted on two predefined routes designed to represent real-world operating conditions for a delivery vehicle (Table 12 and Figure 15). The Rural/Intercity route represents freeway driving operation with high speeds and few stops, while the Urban route represents city driving operation with low speeds and frequent stops. To ensure robust data, at least four tests for each vehicle were conducted for each route.

**Table 12: Driving Route Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>Rural / Intercity Route</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Driving Speed</strong></td>
<td>45.1 mph</td>
<td>18.4 mph</td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
<td>61.5 mph</td>
<td>40.8 mph</td>
</tr>
<tr>
<td><strong>Total Running Time</strong></td>
<td>2,057 sec.</td>
<td>2,803 sec.</td>
</tr>
<tr>
<td><strong>Percentage Idle</strong></td>
<td>4.4%</td>
<td>20.5%</td>
</tr>
<tr>
<td><strong>Total Distance</strong></td>
<td>24.7 miles</td>
<td>11.4 miles</td>
</tr>
<tr>
<td><strong>Number of Stops</strong></td>
<td>6</td>
<td>28</td>
</tr>
<tr>
<td><strong>Starting Elevation</strong></td>
<td>58 ft.</td>
<td>58 ft.</td>
</tr>
<tr>
<td><strong>Highest Elevation</strong></td>
<td>105 ft.</td>
<td>72 ft.</td>
</tr>
<tr>
<td><strong>Closest Test Cycle</strong></td>
<td>HHDDT Cruise</td>
<td>CSHRV</td>
</tr>
</tbody>
</table>

Source: EDI

**Figure 15: Maps of the Rural / Intercity (left) and Urban (right) Test Routes**

Source: EDI
Emissions measurements were collected from the exhaust using EF&EE’s portable emissions measurements system, RAVEM. This system uses constant-volume sampling and a proportional partial-flow sampling system in a compact device (Figure 16). Electric power to operate the RAVEM system was supplied using a small gasoline-engine generator. Corrections for analyzer drift and charge correction for the hybrid vehicle were applied to test results, as applicable.

Figure 16: RAVEM System Installed on the Prototype CNG / PHEV (left) and the Conventional CNG Truck (right)

Source: EDI

4.2.2 Test Results: Charge Depleting Performance

All-electric mode performance for the CNG-PHEV truck was assessed for both Rural/Intercity and Urban driving routes. The Urban driving route, with more accelerations and decelerations, is a more intensive route and the energy consumption was higher overall than for the Rural/Intercity route. The increased number of decelerations, however, in the Urban route allowed the vehicle to recapture 9 percent more energy during braking. The all-electric range was measured at 34.6 miles for the Rural/Intercity route, and 33.5 miles for the Urban route (Table 13)

<table>
<thead>
<tr>
<th></th>
<th>Rural / Intercity Route</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Energy Consumption</td>
<td>0.86 DC kWh/mi</td>
<td>0.90 DC kWh/mi</td>
</tr>
<tr>
<td>Regenerative Braking Recapture Rate</td>
<td>7%</td>
<td>16%</td>
</tr>
<tr>
<td>All-Electric Range</td>
<td>34.6 mi. (measured)</td>
<td>33.5 mi. (calculated)</td>
</tr>
</tbody>
</table>

Source: EDI

The EDI PowerDrive™ system was able to provide significant engine off operation. In the Rural/Intercity route, 4 percent of the miles and 13 percent of the time were driven with the engine off and 4 percent of the time spent at zero speed was done with the engine off. In the Urban route, 29 percent of the miles and 31 percent of the time were driven with the engine off
and 18 percent of the time spent at zero speed was done with the engine off. Figure 17 details the engine off operation of the Prototype CNG / PHEV.

Figure 17: Summary of Engine Off Operation for the Prototype CNG-PHEV Truck

The CNG-PHEV truck was charged after the Rural/Intercity route testing to characterize its charging profile (Table 14). The maximum charging power was equal to 5.3 kW. The bulk charge duration for a charge from 36 percent to 100 percent took about five hours; total charge took 5 hours and 13 minutes. Total alternating current (AC) charging energy was 26.9 kWh and total DC charging energy was 24.4 kWh. The average charging efficiency from AC to direct current (DC) was calculated as 91 percent, meaning that for one AC kWh sent to the vehicle, the battery receives 0.91 DC kWh. A continuous power draw of about 477 W was measured after the charge was completed, until the vehicle was unplugged.

Table 14: Summary of Charging Performance Characteristics

<table>
<thead>
<tr>
<th>At 15A Charging Current</th>
<th>Charge Starting</th>
<th>Bulk Charging</th>
<th>Total Charging End</th>
<th>Vehicle Unplugged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Time (hh:mm:ss)</td>
<td>00:00:00</td>
<td>5:03:22</td>
<td>5:13:00</td>
<td>14:37:48</td>
</tr>
<tr>
<td>AC Energy Charged</td>
<td>0.00</td>
<td>26.24</td>
<td>26.88</td>
<td>31.37</td>
</tr>
<tr>
<td>DC Energy Charged</td>
<td>0.00</td>
<td>23.85</td>
<td>24.40</td>
<td>24.40</td>
</tr>
</tbody>
</table>

Source: EDI
4.2.3 Test Results: Emissions Performance

Emissions were measured over several test runs for each route: the conventional CNG truck did four runs of the Rural/Intercity and Urban routes, the CNG-PHEV truck did six runs (two in EV mode and four in hybrid mode) of the Rural/Intercity and Urban routes. To facilitate vehicle comparison, emission test results for the CNG-PHEV truck were combined into a blended mode operation, which combines all-electric (charge-depleting) and hybrid (charge sustaining) modes of operation. This provides data more representative of the way a fleet would operate the CNG-PHEV. As shown in Table 15, the CNG-PHEV was found to reduce CO₂ emissions by approximately 51 percent in comparison to the conventional CNG truck on the Rural/Intercity route, and by 48 percent on the Urban route. Emissions of CO and PM also decreased substantially.

NOₓ emissions also decreased by 16 percent on the Urban test route, but increased by 43 percent during testing on the Rural/Intercity route. The emissions of CO, NOₓ, PM, and HC measured for both vehicles were low in absolute terms, so that the percentage differences have limited significance for air quality. The identified increases in NOₓ emissions along the Rural/Intercity route were attributed to infrequent “spikes” in pollutant concentrations, which generally coincided with vehicle acceleration, and with the engine restarting.

Table 15: Emissions Test Summary on an 80-Mile Route

<table>
<thead>
<tr>
<th>Category</th>
<th>CO₂</th>
<th>CO</th>
<th>NOₓ</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rural / Intercity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype CNG / PHEV</td>
<td>350.01</td>
<td>0.50</td>
<td>0.14</td>
<td>0.00</td>
</tr>
<tr>
<td>Conventional CNG</td>
<td>719.09</td>
<td>2.05</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>% Difference v. Conventional CNG</td>
<td>-51.3%</td>
<td>-75.7%</td>
<td>+43.4%</td>
<td>-69.7%</td>
</tr>
<tr>
<td><strong>Urban</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype CNG / PHEV</td>
<td>442.32</td>
<td>0.35</td>
<td>0.20</td>
<td>0.01</td>
</tr>
<tr>
<td>Conventional CNG</td>
<td>852.53</td>
<td>3.16</td>
<td>0.24</td>
<td>0.01</td>
</tr>
<tr>
<td>% Difference v. Conventional CNG</td>
<td>-48.1%</td>
<td>-89.0%</td>
<td>-16.0%</td>
<td>-41.9%</td>
</tr>
</tbody>
</table>

Source: EDI

Emissions results gained during the testing process are an important step toward establishing a baseline for the behavior of the EDI PowerDrive™ system when combined with an internal combustion engine. For the next phase of this program, EDI will focus on better integration of the EDI PowerDrive™ and the Greenkraft CNG engine, and better calibration of the whole integrated system. The team expects this integrated system to lead to dramatic improvements in performance and emission reductions (Chapter 7 for additional details).
4.3 Fleet Testing

In addition to the ride and drive activities completed during the voice-of-customer process (Chapter 5), EDI also completed an in-depth fleet test designed to evaluate truck performance under real-world fleet conditions.

4.3.1 Fleet Test Company and Fleet Description

EDI selected JP Fence Co. to complete fleet testing. JP Fence Co. is a San Jose based company that serves residential and commercial customers. The company’s main business line is the supply and installation of steel fencing, hand railings, and gates. JP Fence Co.’s projects typically require vehicles that have a large cargo area to transport materials to sub-contractors and to end customers/work sites. Finished products can be large, necessitating a flatbed truck. The company’s existing vehicle duty cycles include use under city and highway driving conditions with frequent stops at job sites, and for equipment and material pick-up.

JP Fence Co.’s fleet comprises five vehicles including two GMC C5500 flatbed trucks and three Class 3 pickup trucks. During the fleet test, the Class 4 CNG-PHEV truck replaced a GMC C5500 flatbed truck.

4.3.2 Fleet Test Area

JP Fence Co. primarily operates in the southern portions of the San Francisco Bay Area, roughly from San Mateo and Union City in the north, to the southern portions of San Jose and Morgan Hill in the south (Figure 18).

Figure 18: Fleet Test Company (JP Fence Co.) Operational Range

Source: EDI.
While most driving is done within 30 miles of San Jose, where JP Fence is based, vehicles often travel to different locations in one day and must be able to drive up to 250 miles per day. This makes it an ideal application for a plug-in hybrid vehicle, capable of providing zero-emission operation most of the time and range-extended hybrid operation when business requires it.

### 4.3.3 Fleet Test Objectives and Data Collection

Fleet testing evaluated vehicle performance under real-world operating conditions. The team evaluated a variety of factors, including fuel economy, all-electric range, overall vehicle performance, and driver and fleet operator experience. EDI collected data points shown in Table 16.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles Driven</td>
<td>Vehicle Data Logger</td>
</tr>
<tr>
<td>Number of Charges</td>
<td>Vehicle Data Logger</td>
</tr>
<tr>
<td>Miles Driven in EV Mode</td>
<td>Vehicle Data Logger</td>
</tr>
<tr>
<td>Miles Driven in Hybrid Mode</td>
<td>Vehicle Data Logger</td>
</tr>
<tr>
<td>Average Fuel Economy</td>
<td>Calculated from Vehicle Data Logger and Fuel Consumption</td>
</tr>
<tr>
<td>Fleet Test Operator Feedback</td>
<td>Daily Driver Logs and Operator Survey</td>
</tr>
</tbody>
</table>

Source: EDI

### 4.3.4 Fleet Test Process

The fleet test was completed over a period of four weeks. During this time, JP Fence Co. integrated the test vehicle into its normal daily service / operations (Figure 19). There were no driving restrictions imposed on the vehicle operators, in order to most accurately capture real-world use conditions.
EDI delivered the complete Class 4 PHEV-CNG truck for testing to JP Fence Co. on June 1, 2016, and supplied a wall-mounted EV charger to charge the truck. JP Fence Co. maintained an ongoing record of fuel consumed using a vehicle log, and copies of all fuel receipts. The test vehicle was plugged to the charger whenever available. After completing a four-week test period on June 29, 2016, JP Fence Co. returned the vehicle and provided EDI with fuel records and the fleet survey.

4.3.5 Fleet Test Results

During the demonstration, the Class 4 PHEV-CNG truck was used during regular work and construction activities, including transporting fencing materials to construction sites, delivering supplies to the office, and carrying toolboxes and machinery to various customer sites. No mechanical, electrical, software, CNG fueling system or EV charger issues were reported with the truck during the test period. Measured results were positive and highlight viability and success of prototype vehicle performance (Table 17).

Results shown that the Class 4 CNG-PHEV truck improved fuel economy by more than 176 percent, in comparison to the average fuel economy of a Class 4 truck (ranging from 7 to 12 mpg, average 9.5 mpg)\(^4\) Additionally, the truck improved fuel economy by 40 percent in hybrid mode, in comparison to the average fuel economy of a Class 4 truck.

Table 17: Fleet Test Results

<table>
<thead>
<tr>
<th>Evaluation Category</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of Evaluation</td>
<td>June 1 to June 29, 2016</td>
</tr>
<tr>
<td>Total Miles Driven</td>
<td>294.5 miles</td>
</tr>
<tr>
<td>Total Miles Driven in EV Mode</td>
<td>144.8 miles</td>
</tr>
<tr>
<td>Total Miles Driven in Hybrid Mode</td>
<td>149.7 miles</td>
</tr>
<tr>
<td>Total CNG Consumed</td>
<td>11.23 GGE</td>
</tr>
<tr>
<td>Average Combined Fuel Economy</td>
<td>26.2 miles per GGE</td>
</tr>
<tr>
<td>Average Fuel Economy in Hybrid Mode</td>
<td>13.3 miles per GGE</td>
</tr>
</tbody>
</table>

Source: EDI.

Fleet feedback was positive. Compiled results from the driving logs and operator surveys indicated that JP Fence Co. was very satisfied with the vehicle’s overall performance, and reported that the test vehicle performed as well as the conventional truck that it replaced, with the added benefit of greatly improved fuel economy. Charging the vehicle was reported to be a simple process that did not adversely impact business operation. Survey responses further indicated that:

- JP Fence Co. expressed a high interest in adding CNG-powered plug-in hybrid electric trucks, such as the test vehicle, to its fleet;
- JP Fence Co. was most concerned about warranty, service and support, the viability of EDI and Greenkraft, and the potentially high purchase price of a commercial version of the test vehicle. This concern echoed response from other fleets during the voice-of-customer process (Chapter 5);
- JP Fence Co. was also concerned about the availability of natural gas fueling infrastructure, and noted that a diesel or gasoline option for this truck would be more interesting. This concern also echoed response from some other fleets during the voice-of-customer process (Chapter 5);
- The availability of incentive funding and a reduced vehicle cost would help convince JP Fence Co. to purchase a Class 4 CNG-PHEV truck;
- While JP Fence Co. expressed great interest in advanced technologies, the no-compromise PHEV solution was preferred to other options that limit range like all-electric trucks, or that have increased complexity and/or limited refueling options like fuel cell trucks.

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5 Gasoline Gallon Equivalent
CHAPTER 5: Technology/Knowledge Transfer Activities

This chapter summarizes the technology and knowledge transfer activities, including the voice-of-customer event, that were completed under Task 6 of Scope of Work.

5.1 Technology and Knowledge Transfer Overview

EDI completed technology and knowledge transfer activities to help make knowledge gained, experimental results, and lessons learned available to the public and key decision makers. Technology and knowledge transfer activities included activities by project partner CALSTART. These activities included direct customer outreach and demonstration, as well as publication and public release of project documentation.

Based on prior CALSTART and EDI experience, the project team chose direct business-to-business (B2B) communications as a primary means of reaching out to potential future vehicle purchasers. The project team attended industry events and conferences, provided show floor displays and poster sessions, and organized a direct voice-of-customer event. These activities were supplemented with targeted emails and phone calls with fleet managers, state and regional regulators and other industry stakeholders.

The project team’s target audience for technology outreach aligns with the truck’s anticipated users: fleet operators seeking a Class 4/5 vehicle with either a box or bed installed for use in light hauling applications. Target industries include urban delivery, trades (plumbing, HVAC, electricians), small business (food delivery, equipment), and city and county fleets interested in reducing GHG and criteria air pollutant emissions, as well as utilities, given their role as electricity providers and natural gas fuel suppliers.

EDI also explored policy development goals as a facet of project outreach. These goals focus on increasing awareness among regulators of natural gas PHEV trucks to raise awareness, helping to accelerate CARB emissions certification, and support incentive funding (HVIP6) for the trucks developed under this project.

5.2 Project Fact Sheets

Two project fact sheets were created to describe the project. These sheets focused on the Class 4 CNG-PHEV truck and the benefits of the EDI PowerDrive™ technology (Figures 20 and 21). These fact sheets were used during discussions with interested fleets and provided to each attendee at the voice-of-customer event.

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6 The California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) was launched in 2009 to accelerate purchase of cleaner, more efficient trucks in California. The program provides vouchers to partially offset purchase of such vehicles.
Figure 20: Initial Project Fact Sheet

**EDI CNG-PHEV Class 4 MD Green Kraft Truck**

**Project Overview**
EDI and Green Kraft, Inc. have developed an innovative Class 4 CNG-PHEV truck that will provide a significant reduction in total cost of ownership, reduce emissions, and improve safety. The vehicle is designed to meet the needs of urban and regional delivery applications, delivering both cost savings and environmental benefits.

**Why It’s Important**
The Class 4 CNG-PHEV truck is designed to meet the needs of urban and regional delivery applications, delivering both cost savings and environmental benefits. The vehicle is powered by a CNG-PHEV system that provides a range of up to 300 miles, allowing for efficient and sustainable delivery operations.

**Key Features**
- **Electric Range**: 300 miles
- **CNG Range**: 300 miles
- **Total Range**: Over 700 miles
- **Reduction in CO2 Emissions**: Significant reduction compared to traditional diesel vehicles

**Powertrain**
- **PHEV System**: Integrated into the vehicle’s drivetrain, providing a hybrid electric power source for optimal performance.
- **CNG Fuel System**: Compressed natural gas stored in high-pressure tanks, providing a sustainable and clean energy source.

**Operational Benefits**
- **Cost Savings**: Reduced fuel costs and maintenance savings
- **Environmental Benefits**: Reduced emissions and improved air quality
- **Safety Enhancements**: Advanced safety features, including real-time monitoring and automatic emergency braking systems.

**Conclusion**
EDI and Green Kraft’s Class 4 CNG-PHEV truck offers a promising solution for delivery operations, combining the best of electric and natural gas technologies to provide a cost-effective and environmentally friendly alternative to traditional diesel vehicles.

Source: EDI.

Figure 21: Final Project Fact Sheet

**Let’s Go with Class 4 PHEV CNG Truck**

**Meet the Growing Demand**
Aerospace national, state, and local regulations to reduce emissions are spurring significant investments in low and zero-emission technologies. To meet these stringent requirements, there are demanding new options to reduce their day-to-day performance impacts. Also, in order to reduce emissions, allowing for all-electric or diesel-electric operation and vehicle access to the electric grid, the state of the truck configuration options has been limited.

**Demonstration Truck Performance & Features**
- **Demonstrated 80% of all electric operating range**: Potential for up to 400 miles
- **Expected 30% on gasoline equivalent (GGE)**, an advancement in CNG Green Kraft trucks above NA30%
- **Ability to drive 300 miles of electric operation, without any compromised range gas coupling under certain conditions**
- **Fully recharge the battery pack from empty to about 7 hours**
- **Benefits include cleaner air, quiet operations, and reduced emissions**
- **Benefits the demand of cleaner air solution, electric and gasoline markets**
- **Uses California’s advanced technology and infrastructure grants for clean-gas vehicles from the state**

Source: EDI.
5.3 Website and Media Mentions

To publicize the voice-of-customer event, and to increase awareness of these hybrid trucks and the EDI PowerDrive™ system generally, EDI prepared a media release describing the project and the Class 4 CNG-PHEV truck on October 6, 20157. Numerous trade websites picked up the communications around the truck, project, and technology. A small sample is shown in Figures 22-24.

Figure 22: Fleets and Fuels Reprint (Excerpt)

EDI & Greenkraft Unveil CNG Plug-In

October 6, 2015 in CNG, Electric Drive, Hybrids, New Products, NOVs by Rich Piellisch | No Comments

Class 4 Truck Said to Be a ‘First-of-its-Kind Market-Disruptive Vehicle’

Efficient Drivetrains, Inc. has unveiled a compressed natural gas-fueled plug-in hybrid electric Class 4 logistics truck it says was “made possible by EDI’s innovative drivetrain technology and vehicle control software.”

EDI and Greenkraft unveiled their CNG-fueled, plug-in hybrid electric truck at a Calstart event with Southern California Gas in Downey today.


Natural gas plug-in hybrid Class 4 logistics truck with EDI drive system
6 October 2015

Hybrid and electric drivetrain provider Efficient Drivetrains, Inc. (EDI), in partnership with Greenkraft, CALSTART and the California Energy Commission, has designed and optimized a compressed natural gas and plug-in hybrid electric Class-4 logistics truck. The truck is being officially unveiled at a voice of the customer event hosted by CALSTART at the Southern California Gas Energy Resource Center today.

The CNG PHEV truck has an all-electric range of 40 miles (64 km). EDI’s technology effectively tripled the miles per gasoline gallon equivalent (GGE) of the baseline 14,500-pound CNG-powered truck from approximately 9 miles per GGE to 27.

The EDI Power Drive’s lightweight, modular, inline form allows easy optimization for a wide range of vehicle types with minimal changes to the original vehicle chassis and frame, making rapid conversions and market introductions possible.

CALSTART developed the Voice of the Customer (VOC) event for EDI, with funding from the Southern California Gas Company. Designed to give the manufacturer and supplier guidance on the powertrain concept, the VOC event and ride and drive will provide user input.

Efficient Drivetrains, Inc. Technology Featured in First-of-Its-Kind CNG-PHEV Class-4 Truck

MILPITA, Calif.--(BUSINESS WIRE)--

Efficient Drivetrains, Inc. (EDI), a global leader in advanced high-efficiency zero emissions hybrid and electric drivetrain solutions, today announced a compressed natural gas and plug-in hybrid electric Class-4 logistics truck made possible by EDI’s innovative drivetrain technology and vehicle control software.

This Smart News Release features multimedia. View the full release here: http://www.businesswire.com/news/home/20151005005836/en/

The first-of-its-kind market-disruptive vehicle will help fleets switch from petroleum-based liquid fuels to domestically available, cleaner-burning natural gas and electricity. The truck will be officially unveiled at a voice of the customer event hosted by CALSTART at the Southern California Gas Energy Resource Center on October 6.

CALSTART developed the Voice of the Customer (VOC) event for EDI, with funding from the Southern California Gas Company. Designed to give the manufacturer and supplier guidance on the powertrain concept, the VOC event and ride and drive will provide crucial user input. Before the vehicle’s unveiling, CALSTART surveyed more than 30 fleets and developed the event’s highly interactive agenda. After the event, CALSTART will manage on-road emissions and fuel economy testing of the truck. Additionally, the organization will issue follow-up user surveys to solicit helpful feedback, further accelerating the commercialization process.

News Highlights:

• EDI, in partnership with Greenkraft, CALSTART and the California Energy Commission, designed and optimized an intelligent plug-in hybrid electric


5.4 Other Industry Outreach

The project team attended several industry events and technology forums to raise awareness of the project, recruit attendees for the voice-of-customer event, and gather preliminary feedback on the Class 4 CNG-PHEV truck and the EDI PowerDrive™ technology. These events also helped
the project team to reach fleet managers who were not able to attend the voice-of-customer event.

- **MEMA SoCal Meeting (July, 2015)**
  CALSTART, on behalf of EDI, presented to the Municipal Equipment Maintenance Association (MEMA)/Southern California Local Chapter (http://www.memafleet.org/) at the Orange County Sanitation District in Fountain Valley, California. MEMA provides fleet managers of county, city, and other local fleets with a forum for the free exchange of experience, technical knowledge, ideas, and opinions with the aim of enhancing the delivery of public services. Many of the city and county fleets present at this meeting also chose to attend the voice-of-customer event as a result of this meeting.

- **EPRI Technical Advisory Committee Meeting (September, 2015)**
  CALSTART, on behalf of EDI, presented at the Commercial and Industrial Electric Transportation Industry Advisory Council in Long Beach, California. Attendees included representatives from Alabama Power, Southern Company, PG&E, Toyota Industrial Equipment, Alaska Airlines, Southwest Airlines, TransPower, AeroVironment, Lockheed Martin, John Deere, the Port of Long Beach, the Port of Seattle, the CARB and the South Coast Air Quality Management District. The concept for the Class 4 CNG-PHEV truck was well received by the audience and had explicit support from a representative of PG&E, who was pleased with the EDI PowerDrive™ system, and that using a CNG-PHEV brought many advantages.

- **North American Natural Gas Vehicle Conference & Expo (September 2015)**
  CALSTART, on behalf of EDI, attended the conference in Denver, Colorado and reached out to several fleets and industry stakeholders (U.S. Department of Energy, Cummins Westport, Landi Renzo, Frito-Lay, Natural Gas Vehicles for America). While people expressed interest in the technology, most thought it would be difficult to make the business case for it in a climate of low diesel and gasoline prices.

- **High-efficiency Truck Users Forum (HTUF) National Technical Session (September 2015)**
  EDI participated in a panel presentation on advanced drivetrains integration and optimization along with representatives from Achates Power, AVL and Lightning Hybrids. HTUF is an ongoing program between CALSTART and the U.S. Army. The 2015 national meeting was held September 29-30 in Sterling Heights, Michigan and gathered a wide range of clean transportation professionals, with a focus on military applications and electrified vehicles and components. While the military does not use CNG as a fuel for its vehicles, the EDI PowerDrive™ system was well received.
5.5 Voice-of-Customer Event

5.5.1 Event Goals
Connecting fleet customers with the most appropriate advanced vehicle technology can be
difficult, due to varying needs, concerns, and purchase cycles. The voice-of-customer program,
led by CALSTART, helped to filter out sales talk and clear up confusion about how advanced
vehicle technologies work for fleets. The voice-of-customer process expects to provide unbiased
guidance to help connect fleet users and managers directly with vehicle makers. The voice-of-
customer event helped to provide EDI with a window into fleet markets for advanced medium-
duty CNG-PHEV trucks, while also exposing fleet representatives to EDI’s technology and
business model. CALSTART has found that these programs help to identify technical-,
perception-, and commercialization-related issues early in the commercialization process,
ultimately helping to speed commercialization.

5.5.2 Activities Leading to the Event
To identify a target audience/attendees list for the voice-of-customer event, CALSTART initiated
discussions with fleet managers, including those who had participated in previous voice-of-
customer events. CALSTART developed and sent a survey to a list of North American fleet
managers and followed up with the listees to collect survey responses and confirm event
participation. In total, CALSTART received surveys from 43 fleet managers from cities, counties,
and utilities in northern, central, and southern California, universities, truck rental companies,
a local port, a waste hauler, a regional construction contractor, other private companies with
vehicle fleets, and other cities outside of California (Figure 25.).

5.5.3 Event Overview and Attendance
With funding from Southern California Gas Company (SoCalGas), CALSTART held the event on
October 6, 2015 at the SoCalGas Energy Resource Center in Downey, California. The event was
the capstone of the technology transfer plan and included a session of regulators and other
industry stakeholders (Technical Advisory Committee) followed by a session for Fleet Operators
(Primary Users), and a Ride & Drive event.
At the event, a series of presenters provided information about EDI’s technology, the project, its application to fleet vehicles, and technology benefits to fleet operators.

- **Allison Smith (Energy and Environmental Affairs Manager, Southern California Gas Company)**: Welcome and introduction to the event.
- **Joerg Ferchau (CEO, EDI)**: High level overview of EDI.
- **Leonhard Fahreddin (Director of Operations, EDI)**: Product presentation including truck technical background, performance, serviceability, and durability.
- **Frank Ziegler (Director of Sales and Marketing, Alternative Fuels Trucks, Greenkraft, Inc.)**: Product presentation including truck technical background, performance, serviceability, and durability.
- **Jean-Baptiste Gallo (Senior Project Engineer, CALSTART)**: Fuel economy and emissions analysis and Q&A session.
- **Efrain Ornelas (Fleet Engineer, Pacific Gas & Electric Company)**: Fleet perspective and business case for EDI PowerDrive™ systems.
- **Allen Nielsen (Director of Business Development, Ryder System, Inc.)**: Fleet perspective and business case for CNG and LNG trucks.
After speaker presentations, a Q&A session was provided, and a government and industry round-table discussion took place, covering next steps for commercializing the vehicle. Later, participants were given the opportunity to test-drive the vehicle. Voice-of-customer participants were also surveyed to better understand their likelihood of purchasing the vehicles, and to identify key concerns and considerations that might hinder their purchase.

In total, 39 persons, including 18 fleet managers, attended the event (Figure 26) and photos from the events are shown in (Figure 27). Attendees included representatives from:

- Eight California cities and counties.
- Corporate fleets, including Enterprise, Frito-Lay, Penske, Ryder, and UPS.
- Utilities including Pacific Gas and Electric, SoCalGas, and Southern California Edison.
- South Coast Air Quality Management District, San Joaquin Valley Air Pollution Control District, California Energy Commission, and California Air Resources Board.
- Greenkraft, and Quantum Technologies.

**Figure 26: Event Attendees**
5.5.4 Post-Event Activities

After the event, CALSTART followed up with all participants to complete a post-survey report to help identify and illustrate the before-and-after impact of the event.

5.5.5 Event Outcomes

**Increased Exposure.** The event substantially increased exposure for EDI and Greenkraft: only 45 percent of attendees were familiar with EDI and Greenkraft before the event.

**Fleet Operators Are Looking to Adopt Advanced Technology Vehicles.** Surveys completed at the event reveal good news about fleet operators and their desire to incorporate hybrid and advanced vehicles into their fleets: most participants strongly favor it. However, the using CNG appears to be a hurdle for fleets that do not have easy access to CNG refueling infrastructure, and there was a lower interest in vehicles that were explicitly powered by CNG (Figure 28).
Product Support is Key. The need for adequate warranty, service, and support was identified by 95 percent of respondents as a highly important area of needed improvement (Figure 29).

This concern underscores a problem common at this early stage in the industry. Participant concerns included:

“We have had a lot of failures with vendors who folded and can't support the products.”

“We have trucks that we can't get parts for.”

“As a government fleet, it's really about who will stand behind the product in the long term.”
Product Support Solutions. During the fleet roundtable, several potential solutions were discussed regarding the need for strong warranty, service, and support. These included:

- Using truck leasing programs to reduce risk exposure.
- Maintenance-friendly designs that will be serviceable over the long term
- In-house training for maintenance shops.
- Need for a dealer network with plenty of spare parts.
- Longer warranties with a buy-back agreement.
- Opportunities to troubleshoot proprietary computer software if needed.

Fleet managers also identified real-world testing and validation, and the opinion of other fleets as being important to early adoption of these vehicle technologies and systems.

Leasing Opportunities. Leasing was also discussed in greater detail, including potential for working with a national truck leasing provider (Ryder, Penske or Enterprise). Some of these companies maintain existing fleets of natural gas vehicles, and/or have maintenance personnel who could be trained to service the proposed vehicles as centralized service providers. Financing or leasing options may also be able to reduce or eliminate incremental cost issues and enable the economic benefits of lower fuel consumption to be realized starting on the first day of use.

Group Purchase and Trials. Other options discussed to help move these vehicles toward adoption and acceptance by fleets included development of group purchases across California or other states, to support county or city fleets; and trial period programs including short term (3-day vehicle loaner program) and extended (such as two weeks, months, months, or 1 year). There is an existing 3-day free natural gas truck (conventional drive technology) loaner program that is already in the Sacramento area, through Ryder that may serve as an example.8

Purchase Price and Incentives. Vehicle cost is a central concern for fleet managers (Figure 30), however, incentives may play a key role in allowing markets to develop until economies of scale can fully mitigate the higher initial costs of advanced technology vehicles. Fleets are willing to pay a premium for advanced vehicles, between $5,000 and $35,000 above the conventional vehicle purchase price. However, the advanced vehicles must show a return on investment, with simple payback periods generally in the 2 to 4 year timeframes. Commercialization incentives and grants will be necessary for a reasonable return on investment period.

More Vehicle Platforms. Availability of other vehicle platforms or vehicle size class/weight class or both was also an important factor that could help compel fleets to purchase an advanced vehicle.

EDI and Greenkraft Manufacturer Status. Surveys also revealed that most attendees viewed the pilot vehicle as a retrofit or conversion, and did not clearly understand Greenkraft’s status as a full scale OEM. Many commenters indicated that large OEMs are preferred to take up the technology. Greenkraft specifically was not viewed as a major competitor in the space, despite its manufacturing purchase license, strong experience, dealer agreements, service stations, large spare parts inventory, and engine certification experience. Similarly, many participants viewed EDI as a small startup and related it to previous small companies that had failed (Figure 31). Participant comments included:

“Why wouldn’t you buy a Hino? They are an established company.”

“We feel like the risk is lower with the Big 3 OEMs”

“It takes a lot to know a new vendor.”

“Other manufacturers that we have confidence in might get the nod first.”
### Figure 31: Voice-of-Customer Survey Responses: Areas of Concern

<table>
<thead>
<tr>
<th>Survey Question</th>
<th>Score (100 max, 0 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please rate the importance to you of each of the following possible</td>
<td></td>
</tr>
<tr>
<td>Concern about EDI and/or Greenkraft Viability</td>
<td>77</td>
</tr>
<tr>
<td>Purchase Price</td>
<td>75</td>
</tr>
<tr>
<td>User / Driver Acceptance</td>
<td>74</td>
</tr>
<tr>
<td>ARB Hybrid Certification</td>
<td>72</td>
</tr>
<tr>
<td>Battery Replacement Costs</td>
<td>71</td>
</tr>
<tr>
<td>Infrastructure Costs</td>
<td>60</td>
</tr>
<tr>
<td>Concern over Reality of Technology</td>
<td>51</td>
</tr>
<tr>
<td>Availability of Natural Gas Fueling Infrastructure</td>
<td>51</td>
</tr>
<tr>
<td>Resale Value Uncertainty</td>
<td>49</td>
</tr>
<tr>
<td>Lack of Understanding of Business Case</td>
<td>46</td>
</tr>
</tbody>
</table>

Source: CALSTART.
CHAPTER 6:  
Production Readiness Plan

This chapter summarizes the production readiness plan completed by EDI for the technology and knowledge transfer activities that were completed under Task 7 of the project. This effort determined the steps that will lead to the manufacturing and commercializing the technologies developed under this project.

6.1 Path to Commercialization

Technology research and development represents only a fraction of the overall cost and time necessary to bring a product to market. An effective path to commercialization is required, in addition to a well-developed technology, to achieve market development. Following a process established by the National Renewable Energy Laboratory (NREL) to assess the technology readiness levels (TRL) for fuel cell electric bus commercialization (Figure 32), EDI has developed a reasonable and achievable path to commercialization, designed to transition product development from early technology research and development to market entry and full commercialization.

Figure 32: NREL Advanced Technology Vehicle Commercialization Process

EDI’s has engaged the State, other public funders, and private capital investors to support its commercialization process. The company’s partnership with the State has involved several advanced transportation funding programs to help bring EDI’s technologies to market:

- EDI was founded in 2006 and began operation in 2007 with a small government loan from the State of California.
- The present project (agreement number: PIR-13-013), funded by the California Energy Commission, achieved TRL 6 by building a prototype Class 4 CNG-PHEV truck and

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testing it in actual fleet operation.

- The next project (agreement number: C-32542-A), funded by the San Joaquin Valley Air Pollution Control District, will achieve TRL 7 by carrying out a full-scale demonstration and reliability testing of one Class 4 CNG-PHEV truck for a period of at least one year.
- The EDI Advanced Vehicle Technology Manufacturing Facility project (agreement number: ARV-14-047), funded by the California Energy Commission, will help achieve TRL 8 and 9 by developing, setting-up, commissioning, and operating a manufacturing facility capable of producing and testing EDI’s drivetrain and powertrain components for HEVs, PHEVs, and EVs, as well as installing the components into vehicles.

### 6.2 Commercialization Phases

EDI’s proposed path to commercializing the CNG-PHEV truck will proceed over four phases and will include five tollgates or checkpoints to assess performance and confirm next steps for development. The four phases with applicable tollgates, and proposed commercialization timeline, are summarized (Figure 33).

![Figure 33: CNG-PHEV Truck Commercialization Timeline](source: EDI)
Tollgate 0: Energy Commission Funding of PON-13-506 Proposal

EDI’s proposal for the project presented in this report was accepted by Energy Commission in May 2014.

Tollgate 1: SJVAPCD Funding of TAP-14-01 Proposal

EDI’s proposal for the follow-up project was accepted by SJVAPCD in March 2015. This will support Phase 2 of the commercialization process.

Phase 1: Development and Demonstration of Prototype Class 4 CNG-PHEV Truck (this project)

In this commercialization phase, EDI designed, optimized and demonstrated an intelligent plug-in hybrid electric vehicle powertrain and battery pack with up to 40 miles of all-electric range integrated with a 6.0-liter CNG engine suitable for medium and heavy-duty trucks.

Tollgate 2: Successful Completion of Phase 1

Phase 1 was judged to be successful for the following reasons: (1) Preliminary analysis shows cost can be reduced to make a viable business case for fleets; (2) voice-of-customer event was well-attended and successful; (3) Fleet testing showed very encouraging results; (4) Emissions testing revealed some issues that were deemed rectifiable; and (5) Phase 2 project was funded by SJVAPCD.

Development and Demonstration of Pre-Production Class 4 CNG-PHEV Truck (SJVAPCD Project)

This project will support continued development of the CNG-PHEV truck, developing a pre-commercial version of the truck built in Phase 1, targeting reductions in manufacturing and equipment costs, design improvements to support commercialization, an extended demonstration period, and continued progress toward emissions certification.

Tollgate 3: Successful Completion of Phase 2

Phase 2 will be judged to be successful if the following are met: (1) Demonstrate reduced costs from Phase 1 to Phase 2; (2) Completion of 12-month demonstration / real world operation; (3) Emissions testing results that show significant improvement in NOx emissions in comparison to Phase 1; and (4) Positive feedback from fleet partner and other industry stakeholders.

Phase 3: Build-Out of Manufacturing and Support Facilities

EDI’s recent expansion of its California-located manufacturing capability includes a new, 30,000 square foot facility in Milpitas (Santa Clara County), California (the EDI AVM). This facility will ultimately support production increases up to about 6,000 PHEV and EV drivetrains per year. The EDI AVM is expected to be operational by the end of 2017, and ready to manufacture EDI PowerDrive™ units (PD4000, PD6000 and PD8000) to integrate into Class 4 CNG trucks and other medium- and heavy-duty truck platforms. EDI will also continue to build out its Vehicle Integration and Support Center in Dixon (Solano County), for faster vehicle integration and field support.
Tollgate 4: Completion of EDI Advanced Vehicle Manufacturing Facility
Successful completion of the EDI AVM in Quarter 4 of 2017 or Quarter 1 of 2018.

Tollgate 5: EPA / ARB Emissions Compliance Achieved
EDI PowerDrive™ technology will achieve emissions compliance / certification by Quarter 1 or Quarter 2 of 2018.

Phase 4: Commercialization and Production Ramp-Up
Phase 4 will begin after all tollgates are completed, focusing on product sales and production ramp-up. During this stage, EDI will expand existing relationships with vehicle builders (Final Stage Vehicle Manufacturers) such as Greenkraft and First Priority GreenFleet. EDI will also establish strategic relationships with other vehicle builders and large medium- and heavy-duty truck OEMs, to include the EDI PowerDrive™ into their new vehicle build offerings. Lastly, EDI will strengthen its supply chain for key components of the EDI PowerDrive™ to reduce manufacturing time and costs.

6.3 Critical Barriers and Resolutions
During the commercialization process completed to date, EDI has identified several critical barriers, with strategies and plans to move past these barriers.

6.3.1 Meeting Target Cost
System incremental cost was identified during the voice-of-customer event, and during other contact with fleets, as a critical barrier to the massive adoption of advanced vehicle technologies such as the EDI PowerDrive™ system. EDI has identified a clear path that targets a unit production cost of $34,460 by 2020 (80 percent cost reduction in comparison to Phase 1 prototype; see Table 4). This will be achieved through:

- Technology refinement during Phase 1 and Phase 2 projects.
- Improvement in the cost-effective procurement of parts and materials.
- Economies of scale using commonalities within the EDI product line.
- Anticipated continued reduction in battery costs as use of plug-in hybrid vehicles grows worldwide (Table 18).
Table 18: Anticipated Battery Price Reductions Through 2030

<table>
<thead>
<tr>
<th></th>
<th>CE-Delft(^{10})</th>
<th>ICF(^{11})</th>
<th>SEI(^{12})</th>
<th>Frost &amp; Sullivan(^{13})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2015</strong></td>
<td>$600/kWh</td>
<td>$500 - $800/kWh</td>
<td>$400 - $600/kWh</td>
<td>$450 - $500/kWh</td>
</tr>
<tr>
<td><strong>2020</strong></td>
<td>$320/kWh</td>
<td>$350 - $650/kWh</td>
<td>$200 - $450/kWh</td>
<td>$375 - $425/kWh</td>
</tr>
<tr>
<td><strong>2030</strong></td>
<td>$215/kWh</td>
<td>$300 - $600/kWh</td>
<td>$150 - $300/kWh</td>
<td>$330 - $380/kWh</td>
</tr>
</tbody>
</table>

Source: EDI.

6.3.2 Driver and Fleet Acceptance

Driver and fleet acceptance efforts will target critical areas of concern identified during the voice-of-customer event. EDI will:

- Investigate potential future partnerships with rental companies such as Ryder, Enterprise, or Penske, to support extended fleet trials and rental programs.
- Explore offering vehicle leasing options to reduce incremental cost for the fleet.
- Measure performance and reliability during extended fleet demonstration and publicly disseminate results.
- Refine EDI PowerDrive™ system design for reliability and maintenance
- Define warranty or service guarantees and packages or both, consistent with industry standards.
- Partner with large established OEMs to use their dealership and maintenance support network and decrease risks to fleets.
- Educate fleet managers on EDI, its vehicle partners and the EDI PowerDrive™ technology.

6.3.3 Supply Challenges

EDI anticipates that supply challenges could cause delays in delivery of orders to customers during early commercialization. Until routine and tested supply lines are established, equipment lead time from equipment manufacturers could be subject to disruption by larger orders from other companies and other well-established equipment purchasers. Until supplier networks are well established, EDI will work closely with battery, motor, and other key EDI PowerDrive™ suppliers to handle all manufacturing needs, reduce lead times for delivery, and reduce costs. EDI will:


• Collaborate with battery suppliers to standardize batteries within the EDI product line and order larger quantities to increase purchasing power
• EDI will work with multiple battery cell manufacturers and process the final system assembly

### 6.3.4 Emissions Certification

As discussed in Chapter 4, on-road emissions testing identified elevated NOx emissions, attributed to infrequent “spikes” in pollutant concentrations, which generally coincided with vehicle acceleration, and with the engine restarting. EDI also identified improvement targets for recapture of braking energy, all-electric vehicle range, and further fuel economy improvement in hybrid mode. Emissions results gained during the testing process established a baseline for the behavior of the EDI PowerDrive™ system in combination with an internal combustion engine.

To more actively and effectively pursue emissions certification, EDI has initiated an emissions program that will support better integration of the EDI PowerDrive™ and the Greenkraft CNG engine and better calibration of the whole integrated system. This EDI program is expected to lead to dramatic improvements in performance and emission reductions. Key facets of this program are summarized in Table 19, EDI has already identified several opportunities for improvement and has established a process to reach emissions certification within the next 18 months.

**Table 19: EDI Emissions Program to Support Emissions Certification**

<table>
<thead>
<tr>
<th>Improvement Areas</th>
<th>Emissions Program Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braking Energy Recapture Optimization</td>
<td>• Continuing on-road testing of development vehicles and monitoring of emissions for multiple engine types – CNG, diesel, gasoline</td>
</tr>
<tr>
<td>All-Electric Range Improvement</td>
<td>• Purchase emission measurement equipment to facilitate testing, calibration and validation</td>
</tr>
<tr>
<td>CO₂ Emissions Reduction Improvements</td>
<td>• Increase development capabilities by adding dynamometer systems to EDI development facility in order to expand durability testing, emissions optimization and energy management of control software</td>
</tr>
<tr>
<td>NOx Emissions Improvements</td>
<td>• Improve control and energy management strategies: reduce engine cold starts to only one start-up after end of all-electric operation range; and monitor engine and exhaust system to establish optimal balance of engine use reduction</td>
</tr>
<tr>
<td></td>
<td>• Evaluate and deploy exhaust system and engine preheating to reduce the negative impacts of engine cold starts</td>
</tr>
</tbody>
</table>

Source:

Following the successful completion of this emissions program, EDI will register with applicable organizations for 50-state emissions certification, and Federal Motor Vehicle Safety Standards (FMVSS) compliance. For emissions certification, EDI will complete this process according to the following steps:
• Register with applicable agencies; notify of intent and initiate discussions with their representatives.
• Design a product test plan for development vehicles; review internally.
• Submit development product test plan to EPA/CARB.
• Create an emissions test plan.
• Create an on-board diagnostic test plan.
• Create a post-certification data collection and reporting plan, and other applicable test plans.
• Obtain test lab cost estimates and coordinate test lab availability.
• Create emissions application.
• Create diagnostic application.
• Analyze, document, and submit final test results to EPA/CARB.
CHAPTER 7:
Lessons Learned and Evaluation of Project Benefits

This chapter summarizes critical lessons learned during the project and evaluates benefits of the project.

7.1 Lessons Learned

EDI successfully completed prototype design including vehicle specifications, cost projections, assembled the EDI PowerDrive™ with integration into a Class 4 CNG truck and completed final design drawings. Testing and validation of the Class 4 CNG-PHEV truck was successfully carried out during chassis dynamometer testing, on-road emissions testing, and fleet testing. Lastly, EDI and its project partners completed substantial technology/knowledge transfer and outreach; and identified a reasonable, path to commercialization. The project successfully met these objectives:

- Successfully integrated and optimized a Class-4 Greenkraft CNG truck with the EDI PowerDrive™ system (Chapter 3).
- Successfully tested and validated the CNG-PHEV truck under normal operating conditions (Chapter 4).
- Achieved 26.2 miles per GGE average combined fuel economy, based on fleet testing, very nearly tripling base vehicle fuel economy of approximately 9 miles per GGE (Chapter 4).
- Successfully identified the driving and operating conditions under which the Class 4 CNG-PHEV truck can achieve all-electric operations and entirely eliminate CNG use (Chapter 4).
- Successfully performed short demonstrations of the CNG-PHEV at a voice-of-customer event (Chapter 5).

In addition to highlighting successes, lessons learned and areas of improvement identified during this project center on better integrating the EDI PowerDrive™ and the Greenkraft CNG engine and better calibrating the entire integrated system. Although the Class 4 CNG-PHEV truck did not meet CARB medium- and heavy-duty on-road emissions certification requirements for 2016, the project helped create a roadmap to achieve 50-state emissions certification within the next 18 months (Section 6.3.4).

7.2 Project Performance and Benefits

Overall, the project provided an array of direct and indirect benefits towards fully commercializing EDI’s PowerDrive™ system. These include:

- Truck Integration and Assembly:
- Successful integration of the EDI PowerDrive™ into a Greenkraft medium-duty truck.
- Experience gained in working with Greenkraft and their product.
- Experience gained in working with equipment suppliers.

**Vehicle Testing and Certification Progress:**
- Fleet testing results were strongly positive, including positive operator feedback.
- On-road emissions testing was encouraging and highlighted issue with elevated NOx, allowing future resolution through an emissions program.
- Created roadmap to achieve emission certification.

**Vehicle Commercialization Process:**
- Achieved Technology Readiness Level TRL 6.
- Prototype cost was high, but EDI has developed a reasonable cost reduction analysis, illustrating a path to an 80 percent cost reduction during commercial scale production.
- Greatly improved EDI’s standing and knowledge in the industry with the voice-of-customer event.
- Gained valuable insight from fleets and regulators, to allow future tailoring of a fleet-oriented product that meets the needs of fleet users.
- Established relationships with OEMs and other industry partners that will directly support commercialization.

- Identified key points of concern for potential fleet purchasers of the vehicle, through the voice-of-customer event.

### 7.2.1 Benefits of Public-Private Partnership

State funding, especially for smaller companies without R&D budgets as large OEMs, supports strong public-private partnerships that can help to rapidly accelerate advanced vehicle technology adoption, in-state manufacturing, and technology development in California, while helping to meet state statutory goals for emissions reduction and transportation electrification. Effective public-private partnerships can also provide rapid returns on state investment. For example, EDI was started by a small business loan from the state, which EDI has repaid. EDI’s small size affords it nimbleness compared to larger vehicle OEMs with longer product planning horizons; smaller technology providers like EDI can quickly bring advanced technology solutions to market. Small companies such as EDI are also able to react more flexibly and efficiently to develop value chains and business models that satisfy customer needs, including in niche markets. Continued support for growing businesses directly benefits California by promoting development of a strong transportation electrification ecosystem that can best help the state meet its emissions reduction goals and create high-quality manufacturing and engineering jobs.
7.2.2 EDI's Commitment to California

EDI maintains a strong commitment to California. In 2007, Professor Andrew Frank’s patent portfolio at UC Davis was exclusively licensed to EDI, which commercializes the patent portfolio and keeps paying royalties back to the University. Since then, the company has secured several grants from California agencies to continue its R&D and commercialization process. EDI also has a good track record with attracting foreign capital to California from private investors, and has been successful in developing strong relationships with foreign companies. These developments promise to enhance future progress toward global market development, further supporting manufacturing and R&D efforts in California.

In addition, EDI maintains strong ties with in-state industry and fleet leaders, such as PG&E, with which EDI has partnered to develop the “Game Changer” a 4WD, Class 5 PHEV work truck capable providing a mobile, grid-synchronizable power source from the truck’s battery or engine acting as a generator.

Thus, EDI's commercialization process will directly benefit the state economically and support California’s position as a national and global leader in developing advanced, low-emissions vehicle technologies and systems.

7.2.3 Jobs Benefits and Economic Growth

In the short term, EDI anticipates creating about 25 jobs at its growing Advanced Vehicle Manufacturing Facility in Milpitas (Santa Clara County). This figure is expected to grow to 200 California jobs in the long term, including high-quality positions in engineering, sales, management, and manufacturing. In addition, EDI will continue to build out its Vehicle Integration and Support Center in Dixon (Solano County), to provide faster vehicle integration and field support.

EDI will also work with local machine shops and specialty manufacturing companies to support its own buildout. In this manner, EDI's continued presence in California will help to expand the local automotive manufacturing community. Overall, it is estimated that EDI's growth will ultimately support an additional 500 jobs with suppliers and service vendors supporting EDI's manufacturing process.
## ACROYNMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMEP</td>
<td>Brake mean effective pressure</td>
</tr>
<tr>
<td>BTE</td>
<td>Brake thermal efficiency</td>
</tr>
<tr>
<td>CARB</td>
<td>California Air Resources Board</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>COVIMEP</td>
<td>Coefficient of variation of indicated mean effective pressure</td>
</tr>
<tr>
<td>CR</td>
<td>Compression ratio</td>
</tr>
<tr>
<td>DGE</td>
<td>Diesel gallon equivalent</td>
</tr>
<tr>
<td>DOHC</td>
<td>Dual overhead cam</td>
</tr>
<tr>
<td>EPIC</td>
<td>Electric Program Investment Charge</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>GGE</td>
<td>Gasoline gallon equivalent</td>
</tr>
<tr>
<td>GTI</td>
<td>Gas Technology Institute</td>
</tr>
<tr>
<td>HESI</td>
<td>High efficiency spark ignition engine</td>
</tr>
<tr>
<td>LNVIMEP</td>
<td>Lowest normalized value of the indicated mean effective pressure</td>
</tr>
<tr>
<td>mJ</td>
<td>Millijoules</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrogen Oxides</td>
</tr>
<tr>
<td>P</td>
<td>Port fuel injection</td>
</tr>
<tr>
<td>psig</td>
<td>Pounds per square inch</td>
</tr>
<tr>
<td>SET</td>
<td>Supplemental emissions test cycle - 13-mode engine characterization</td>
</tr>
<tr>
<td>TCI</td>
<td>Transistor coil ignition</td>
</tr>
<tr>
<td>VNT</td>
<td>Variable nozzle turbocharger</td>
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</table>