CALIFORNIA ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Retrofit Diesel Class 7 & 8 Work Trucks with a Plug-in Hybrid Electric Vehicle Powertrain System

Prepared for: California Energy Commission

Prepared by: Electric Power Research Institute

Gavin Newsom, Governor

December 2020 | CEC-600-2020-052

California Energy Commission

Mark Kosowski
Primary Author(s)

Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, California 94304-1338

Agreement Number: ARV-11-013

Aida Escala
Commission Agreement Manager

Elizabeth John
Office Manager
ADVANCED FUELS AND VEHICLE TECHNOLOGIES OFFICE

Hannon Rasool
Deputy Director
FUELS AND TRANSPORTATION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The Electric Power Research Institute prepared this report for the California Energy Commission in cooperation with the Odyne engineering team.

Many thanks go to John Petras, Todd McAndrews, Bill Mammen, and Matt Jarmuz from Odyne for their diligence and hard work in making this program a success.

Many thanks to Jamie Dunckley and Dan Bowermaster from Electric Power Research Institute for their support in the analysis.

This report describes the project sponsored by Electric Power Research Institute, the California Energy Commission, and Odyne Systems, Inc.

PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-10-603 to provide funding opportunities for Advanced Medium-and Heavy-Duty Vehicle Technologies Pre-Commercial Demonstrations. In response to PON-10-603, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards March 8, 2012 and the agreement was executed as ARV-11-013 on July 7, 2012.

ABSTRACT

Diesel powered work trucks consume substantial amounts of fuel and emit excess emissions of criteria pollutants and greenhouse gases (GHGs) in California fleets. Fleets have been hesitant to retrofit existing trucks to plug-in hybrids because of the high incremental cost and lack of familiarity with a relatively new technology. The principal goal of the "Gen 2 Advanced Technology Plug-In Hybrid Electric" project was to retrofit and demonstrate five Odyne pre-commercial work trucks in California in a variety of applications in the South Coast Air Basin and the Sacramento Valley Air Basin. A database was established of real-world operating experience, fuel savings and emission reductions to serve as a basis for fine-tuning and launching wide-scale commercialization. Following completion of the project, Odyne planned to establish a California retrofit facility.

The project objectives were to: (1) manufacture five retrofit plug-in hybrid electric kits and ship to California; (2) retrofit and install plug-in hybrid electric systems on five existing customer work trucks at the California assembly site; (3) demonstrate advanced diesel plug-in hybrid electric work trucks in several applications, in the South Coast Air Basin and Sacramento Valley Air Basin, evaluating truck performance and collecting data on fuel consumption, mileage, operations / duty cycle, repair, maintenance and other parameters; (4) quantify emissions and fuel benefits; and (5) assess customer feedback.

This program has accomplished the following:

- Produced and deployed five retrofitted Class 7 and 8 Plug-in Hybrid Electric trucks from Odyne Systems, Inc. in the Sacramento and South Coast air basins.
- Demonstrated the operating performance, fuel savings, and emissions reductions of Plug-In Hybrid Electric Vehicle work trucks in different applications.
- Established a database of real-world operating experience which will serve as basis for fine-tuning, launching, and wide-scale commercialization.
- Demonstrated the technical and market feasibility of the prototype technology in preparation for a full-scale commercial rollout of Odyne's retrofit Plug-in Hybrid Electric services.

Keywords: Plug-in Hybrid, Retrofit, Medium Duty, Emissions

Please use this citation for this report:

Kosowski, Mark. Electric Power Research Institute. 2020 *Retrofit Diesel Class 7 & 8 Work Trucks with a Plug-in Hybrid Electric Vehicle Powertrain System.* California Energy Commission. Publication Number: CEC-600-2020-052.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

The principal goal of this project was to retrofit and demonstrate five Odyne pre-commercial "Gen 2 Advanced Technology Plug-in Hybrid Electric" work trucks in a variety of applications. Odyne has built more than 150 trucks with their Plug-In Hybrid system but from a bare chassis. This program began with existing trucks that were already in use and had the aerial device or the digger derrick already installed.

The plan was for all trucks to be modified in Ontario, California by Valley Power. Odyne was to engineer and deliver all the hybrid components from its plant in Waukesha, Wisconsin to Valley Power. Valley Power would then retrofit the trucks in California. Odyne engineers would test the trucks to ensure the trucks were validated. Finally, the trucks would be delivered to the owners – City of Sacramento, Southern California Edison, and San Diego Gas & Electric (SDG&E). It was later determined that the Final Stage Manufacturers such as Altec and Terex needed to remove some of their equipment from the build prior to Valley Power completing the work.

The build process was modified so that the trucks would first go to the final stage manufacturers where they would remove the critical equipment. The trucks were then moved to Valley Power for retrofitting. Odyne completed testing of the system. Once that was accomplished, the trucks were moved back to the manufacturers to put the equipment back in place. Finally, the trucks were shipped back to original customers to be sent to the field. The process change caused delays than originally planned. Emissions testing was conducted with positive results. Data on charging habits and use of battery power have been collected.

Two work trucks from the City of Sacramento, two from San Diego Gas & Electric, and one from Southern California Edison were converted. Using the fuel and emissions test results from the dynamometer testing and the average use case, the University of California, Riverside's Center for Environmental Research and Technology concluded that the Odyne system reduces full-day fuel use by 50 percent or more, reduces greenhouse gas emissions by 50 percent or more, and reduces Nitrogen Oxide (NOx) emissions by 80 percent or more, compared to their diesel counterparts.

CHAPTER 1: Program

The program included building five retrofit trucks that are listed in Figures 1 and 2. These trucks were taken out of their respective utilities fleet to be retrofit. These trucks have been used as work trucks for years and this program allowed these trucks to be retrofit to hybrid trucks.

Figure 1: Truck Information #1

Customer	Truck Type	Class	Chassis Manufacturer	Final Stage Manufacturer	Engine Type & Displacement
City of Sacramento #1	Aerial Bucket	7	International	Terex	MaxxForce DT 7.6L 210HP
City of Sacramento #2	Aerial Bucket	7	International	Terex	MaxxForce DT 7.6L 210HP
San Diego Gas & Electric #1	Aerial Bucket	8	International	Terex	MaxxForce DT 7.6L 285HP
San Diego Gas & Electric #2	Digger Derrick	8	International	Terex	MaxxForce DT 7.6L 285HP
Southern California Edison	Aerial Bucket	7	Freightliner	Altec	Cummins ISB 6.7L 250HP

Source: Electric Power Research Institute

Figure 2: Truck Information #2

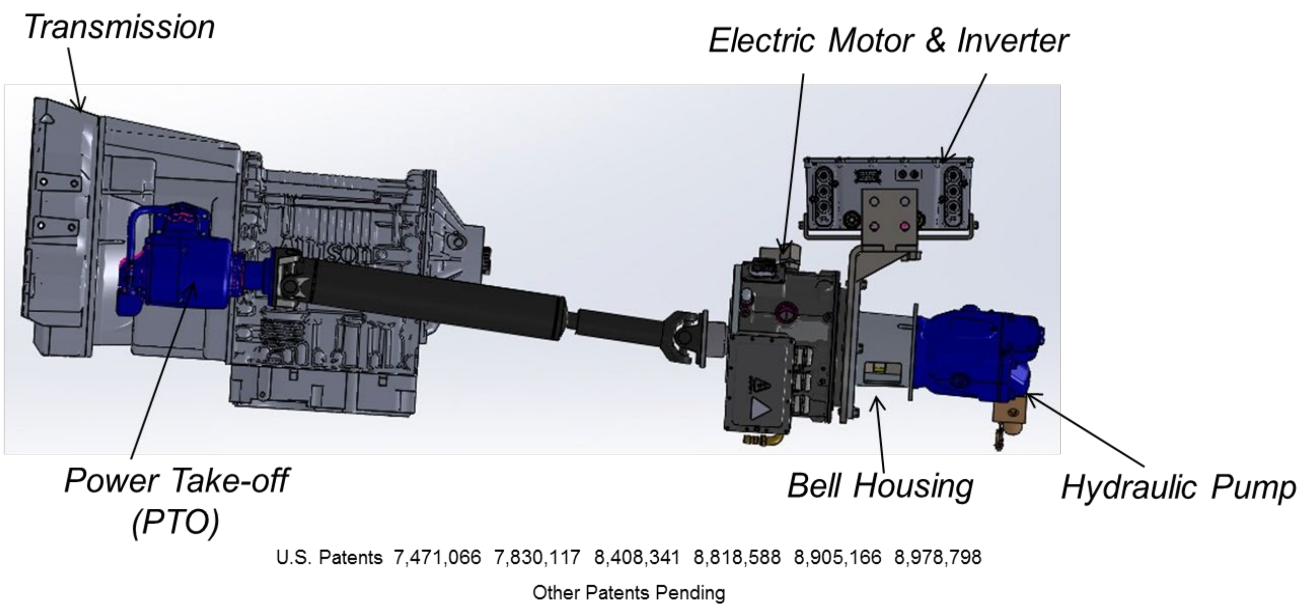
Customer	Model Year	VIN	Plate Number	Retrofit Start	Retrofit Completion	Delivery to Customer
City of Sacramento #1	2008	1HTMMAAN09H130576	CA 1314561	6/22/2015	8/21/2015	10/22/2015
City of Sacramento #2	2008	1HTMMAAN29H130577	CA 1314562	9/14/2015	11/13/2015	2/4/2016
San Diego Gas & Electric #1	2008	1HTWDAARX9J120867	CA 8T56430	5/11/2015	7/10/2015	8/27/2015
San Diego Gas & Electric #2	2008	1HTWDAAR19J125195	CA 8T56429	10/26/2015	12/28/2015	3/7/2016
Southern California Edison	2012	1FVACXDT9EHFT2453	IN 2219666	8/3/2015	10/2/2015	3/9/2016

Source: Electric Power Research Institute

CHAPTER 2:
Odyne System Design

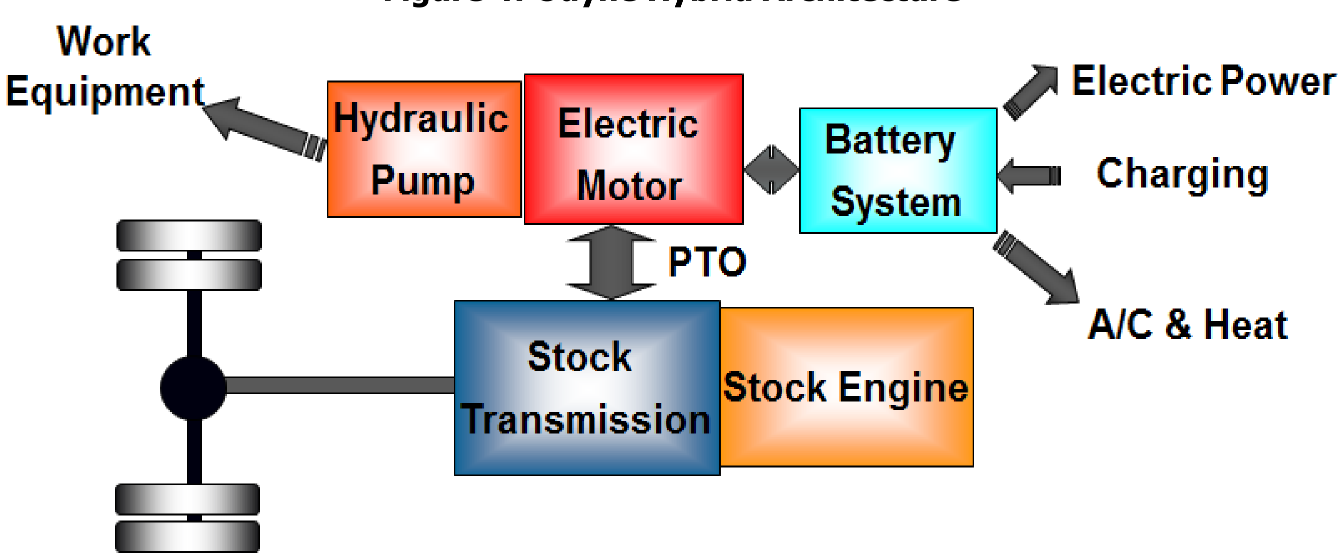
The Odyne hybrid system is a simple, parallel hybrid system that allows the torque of the electric motor to augment the torque output of the diesel engine, thus saving fuel. The motor speed is synchronized with the engine speed through the power take-off (PTO) unit. The traction motor drives the PTO, adding torque to the rear axle, or converts torque from the PTO into power to charge the hybrid batteries (see Figures 3 and 4). Six patents have been granted, and other patents are pending.

Figure 3: Odyne Powertrain Configuration



Source: Electric Power Research Institute

Figure 4: Odyne Hybrid Architecture



Source: Electric Power Research Institute

The motor can also drive the hydraulic pump that controls the aerial device. A clutch in the PTO allows the motor to drive the hydraulic pump for the aerial device. If the clutch is closed, the diesel engine torque drives the pump and concurrently charges the hybrid batteries through the traction motor.

The advantages of the electrically-driven hydraulic pump are reduction in sound level at the job site, improved fuel consumption, and reduced emissions. The diesel engine need not idle during the hydraulic pump control. The pump is activated only when the operator provides the control to move the hydraulics. This feature saves energy when the aerial device is being used.

The Odyne parallel hybrid solution provides a redundant system for the operator to minimize any downtime. If the motor or part of the system breaks, the truck can still be used in its conventional way. It provides the ability to retrofit existing trucks in the field and allows for low validation and capital equipment costs.

The Odyne system requires no modifications to the original manufacturer drivetrain. The hybrid system is simply an added system. It is a simplified system with integration with the PTO. The system uses the compatible SAE J1939 "Recommended Practice—Serial Control and Communications Heavy Duty Truck Network" truck controller-area network (CAN) communications.

The Odyne operational modes are driving mode, stationary mode, and charge mode, as follows:

Drive Mode The launch assist and regenerative braking operate automatically in a charge-depleting condition during normal drive when state of charge (SOC) is greater than 5 percent. The truck enters a charge-sustaining condition when SOC is between 5 percent and 0 percent. Drive mode is automatically disabled during an anti-lock braking system event, and it can be manually disabled by a cab switch.

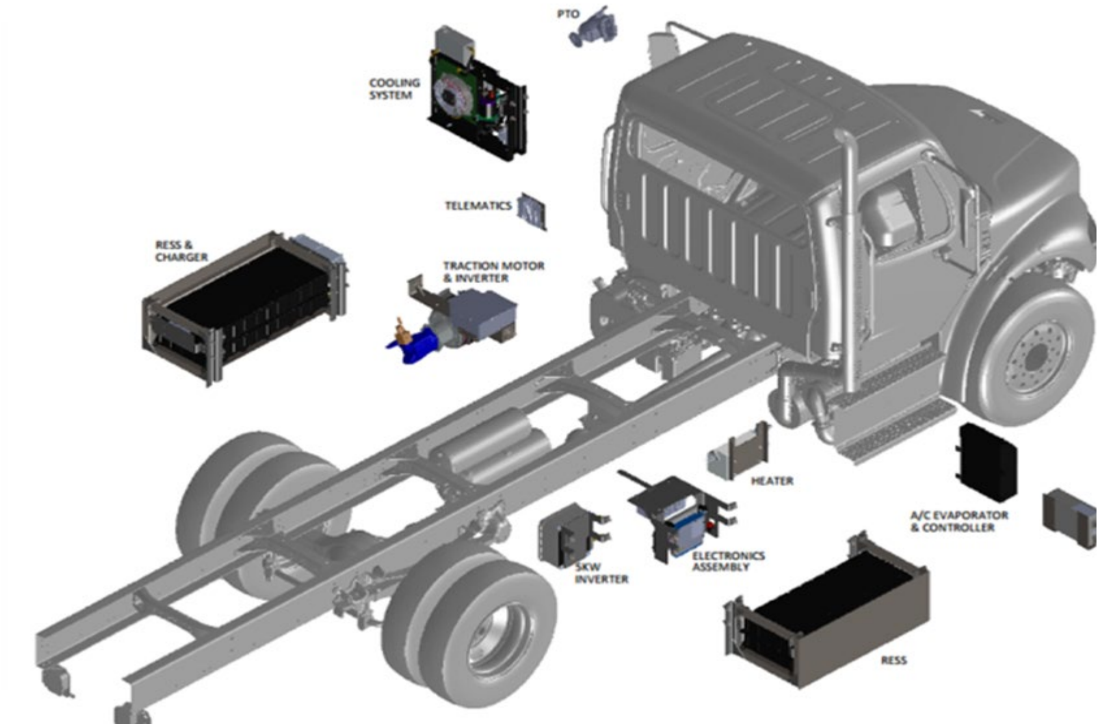
Stationary Mode Stationary mode—also called electric power takeoff operation—provides engine-off mechanical power through the hybrid motor/battery to run hydraulic or pneumatic equipment. It also provides electric power for equipment or heating and air conditioning through 12 V and 120/240 V inverters. During the stationary mode when the state of charge (SOC) is low, an engine charge occurs. The engine charge is capable of field charging the battery using the truck internal combustion engine/hybrid motor. The system provides automatic engine start and power transfer at 5 percent SOC, and it maintains all work functions while charging from 5 percent to 30 percent SOC. When the SOC reaches 30 percent, the engine is automatically shut down and reverts to full-electric operation. This is done for efficiency and to allow the engine to shut down for noise reasons.

Charge Mode

Charge mode is the state in which the truck is attached to the grid through the electric vehicle supply equipment (EVSE) and power flows to the truck through the onboard charger to the batteries.

In the standard configuration, the truck has two battery packs, one on each side of the chassis rails, and the cooling system is mounted at the rear of the cab on the driver's side. The inverter and motor are mounted between the rails, and the smart charging system is mounted to the charger, near the left side battery (see Figure 5). Some trucks may have slightly different configurations due to chassis or application packaging constraints.

Figure 5: Odyne Chassis Assembly



Source: Electric Power Research Institute

The Odyne system also provided a 3.0-kilowatt charging system to charge the batteries. The charging connector and interface are compliant with "SAE Surface Truck Recommended Practice J1772, SAE Electric Vehicle Conductive Charge Coupler." Each truck was also provided with a 120-V Level 1 EVSE (cord set).

The trucks are provided with a 6- kilowatt, 120/240-volt, pure sinusoidal 60-Hertz export power. Each truck had its own export power interface that was provided by the final stage manufacturer. The Odyne system specifications are listed in Appendix A.

CHAPTER 3: Tasks and Schedules

Project Tasks

1. Install Electric Power Research Institute telematics units on baseline vehicles
    - Completed by Valley Power
2. Odyne Project Coordination
    - Generate Statement of Work
    - Coordinate retrofit activities with facilities
3. Initial body rework and integration
    - Completed by aerial device service centers
4. Hybrid system installation
    - Completed by Valley Power
5. Final body rework and integration
    - Completed by aerial device service centers

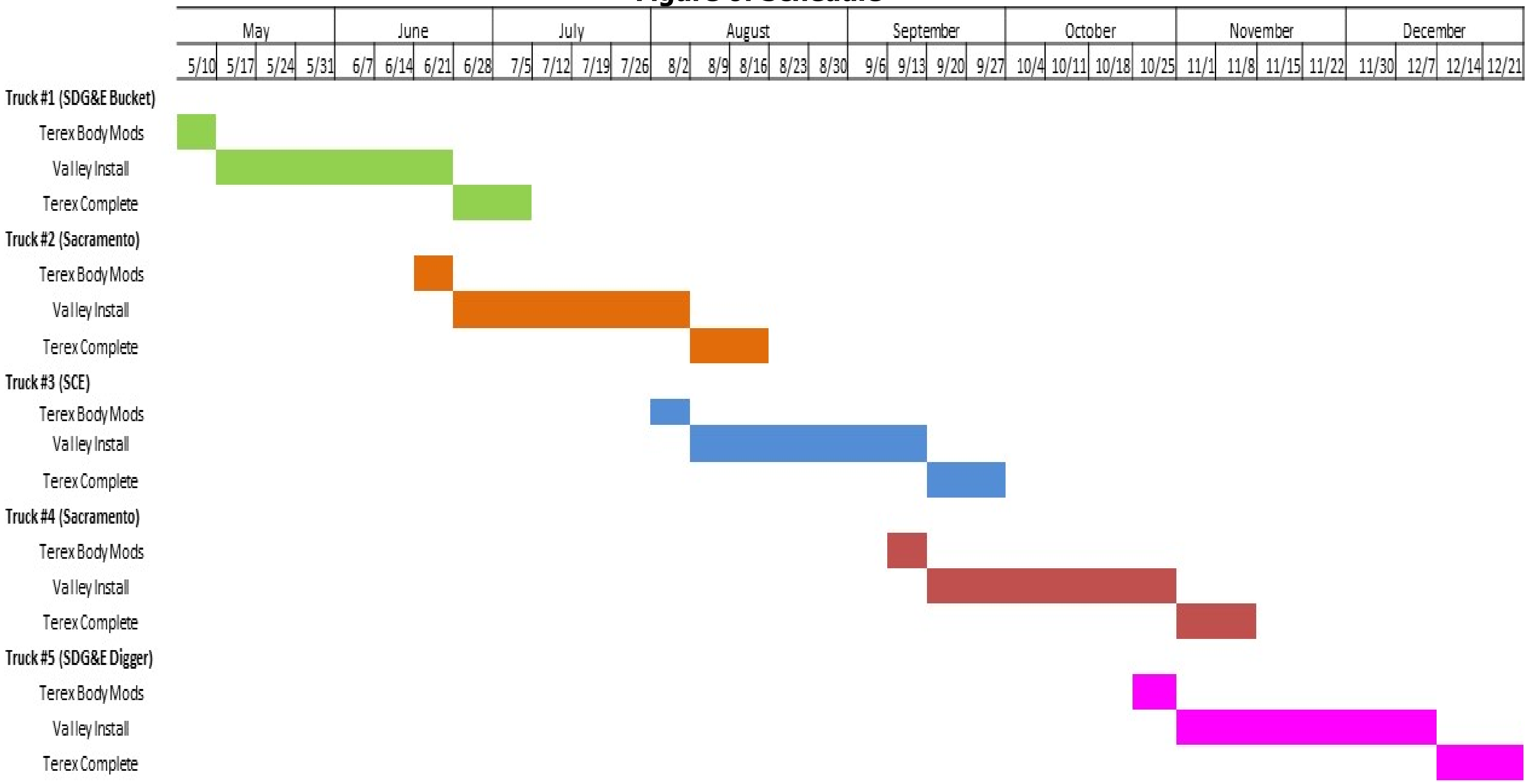
Odyne Project Tasks

- Obtain truck documentation
- Meet with Valley Power and aerial device service centers at truck locations to discuss retrofit process, equipment locations and integration
- Determine changes needed to aerial devices for on-demand setup
- Generate work instructions
- Order long lead time components
- Obtain quotes and timing estimates from aerial equipment manufacturers
- Create hybrid chassis layout drawings
- Identify new parts
- Generate and release bill of materials for parts ordering
- Ship kits to Valley Power

Schedules

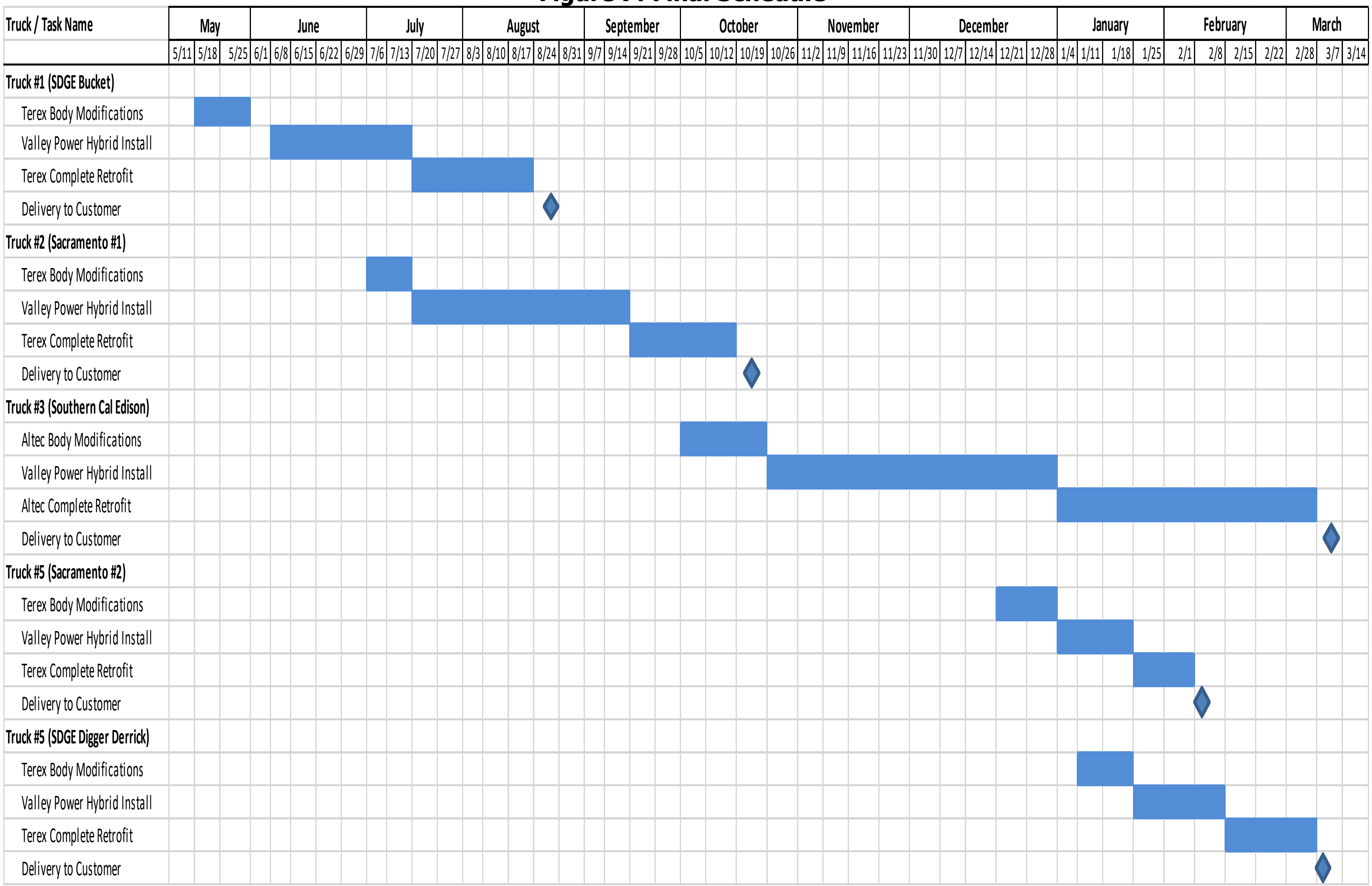
The schedules for the program changed several times. The original schedule is shown in Figure 6. The schedule was made to minimize down time to the customers. Valley Power was not resourced to work on multiple vehicles concurrently. Work on SDG&E and Sacramento trucks was staggered to avoid having more than one truck out of service at a time. The final schedule is shown in Figure 7.

Figure 6: Schedule



Source: Electric Power Research Institute

Figure 7: Final Schedule



Source: Electric Power Research Institute

Causes of Delays

There were various reasons that caused schedule delays:

1. Integration challenges at aerial device service centers due to lack of technical expertise. Terex Services relied heavily on Odyne's previous knowledge of hydraulic and electrical integration rather than working with internal Engineering resources.
2. Resource constraints at aerial device service centers and Valley Power. Typically, one technician was assigned to complete retrofit tasks.
3. An Odyne technician was initially required on-site for functional testing and inspections at Valley Power. Valley Power technicians were later trained and were able to complete testing with just telephone support.
4. Old electrical and hydraulic schematics were not always available.
5. Hand-off delays to and from Valley Power.
    a. Transportation delays due to availability of drivers.
    b. Technicians are not always immediately available after hand-off.
6. Customers did not promptly make the vehicles available as requested due to field operational needs:
    a. City of Sacramento vehicle #2 hand-off was delayed due to engine issue on vehicle #1.
    b. SDG&E digger derrick hand-off was delayed by customer due to training need.
7. Southern California Edison's request for fiber optics requirement was added after the retrofit process had begun:
    a. It took Altec several weeks to determine feasibility and provide cost estimate.
    b. Long lead time for parts.
    c. Fiber optics had not been previously retrofitted at the Pomona service facility.

CHAPTER 4: Cost of Retrofits and Benefits

There are many Class 6 to 8 trucks in fleets today that could be retrofitted to a plug-in hybrid status. The cost to do this is currently about $30,000 above the cost of the base hardware and assembling it on a new chassis prior to the final stage manufacturer completing the body work. There are additional costs in removing and moving the truck from its base status. This does not include the cost to the fleet with an out of commission truck for several months during the retrofit.

Odyne is a leader in hybrid drive systems for medium- and heavy-duty vehicles. Odyne's advanced plug-in hybrid technology enables trucks over 14,000 pounds gross weight vehicle rating to have substantially lower fuel consumption, lower emissions, quieter job site operations, and reduced operating and maintenance costs. Odyne has been actively developing and testing new and retrofit prototypes of plug-in hybrid electric work trucks throughout the United States. The company will sell its unique modular hybrid system for new and retrofit applications directly to truck manufacturers and through a global distribution and service network.

Odyne's advanced Plug-In Hybrid Electric Vehicle work trucks will help California achieve its energy and air quality goals, and help fleets realize lower fuel and maintenance costs, due to:

- Night-time charging of batteries, using off-peak electrical grid energy. Batteries discharge during day use, with less diesel/gasoline fuel use while driving, and no diesel/gasoline fuel use during battery operation of hydraulics and climate controls at work site.
- Incremental emissions benefits via plugging into California's grid, due to renewable energy, low carbon fuels policies. Up to 100 percent idle reduction (battery powered).
- Improved vehicle acceleration and fuel economy via launch assist using electric traction motor.
- Reduced diesel/gasoline fuel consumption, through energy efficient regenerative braking as well as battery-powered operation of truck-mounted equipment and climate controls.
- Reduced emissions of GHGs and criteria pollutants vs. conventional diesel vehicle.
- Quiet worksite operation which is highly beneficial in residential neighborhoods or at night.
- Lower maintenance costs due to less engine idle time and reduced brake wear.
- Reduced installation time due to power take-off interface: redundant power for auxiliary components.
- Non-intrusive, since original drive train is not modified and interfaces with vehicle power train system; no changes to original manufactured transmission or engine certification; CARB compliant as a regular truck.

- Fuel neutral hybrid system that can be adapted to alternative fuel engines.
- Designed to facilitate rapid scale to high volume vs. highly integrated designs requiring changes to the transmission or other power train components.
- Flexibility- can be installed as retrofit (in-use truck), or new (during final stage manufacturing).
- Reduced emissions inhaled by workers in closed spaces such as tunnels.

CHAPTER 5:
Description and Pictures of Retrofitted Trucks

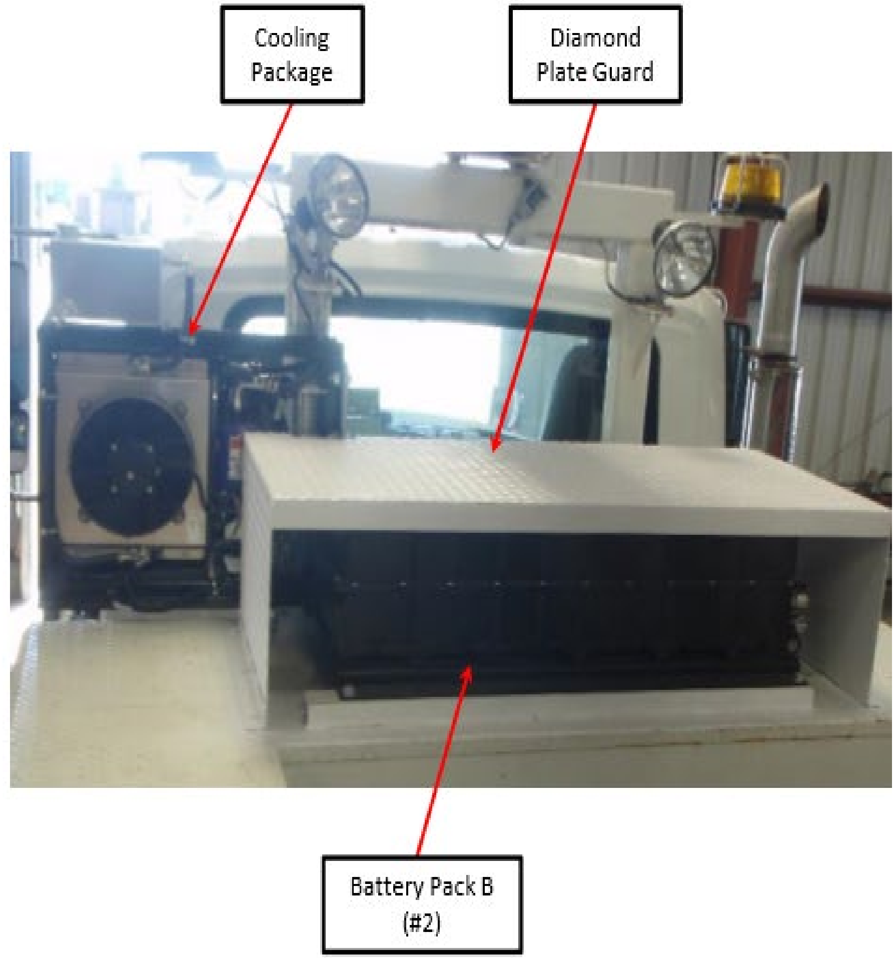
San Diego Gas and Electric Aerial Truck

SDG&E provided two trucks- one aerial device truck and one digger derrick. The pictures below show the hardware that was added to the truck. See figures 8 to 11 below.

Figure 8: SDG&E Aerial Truck

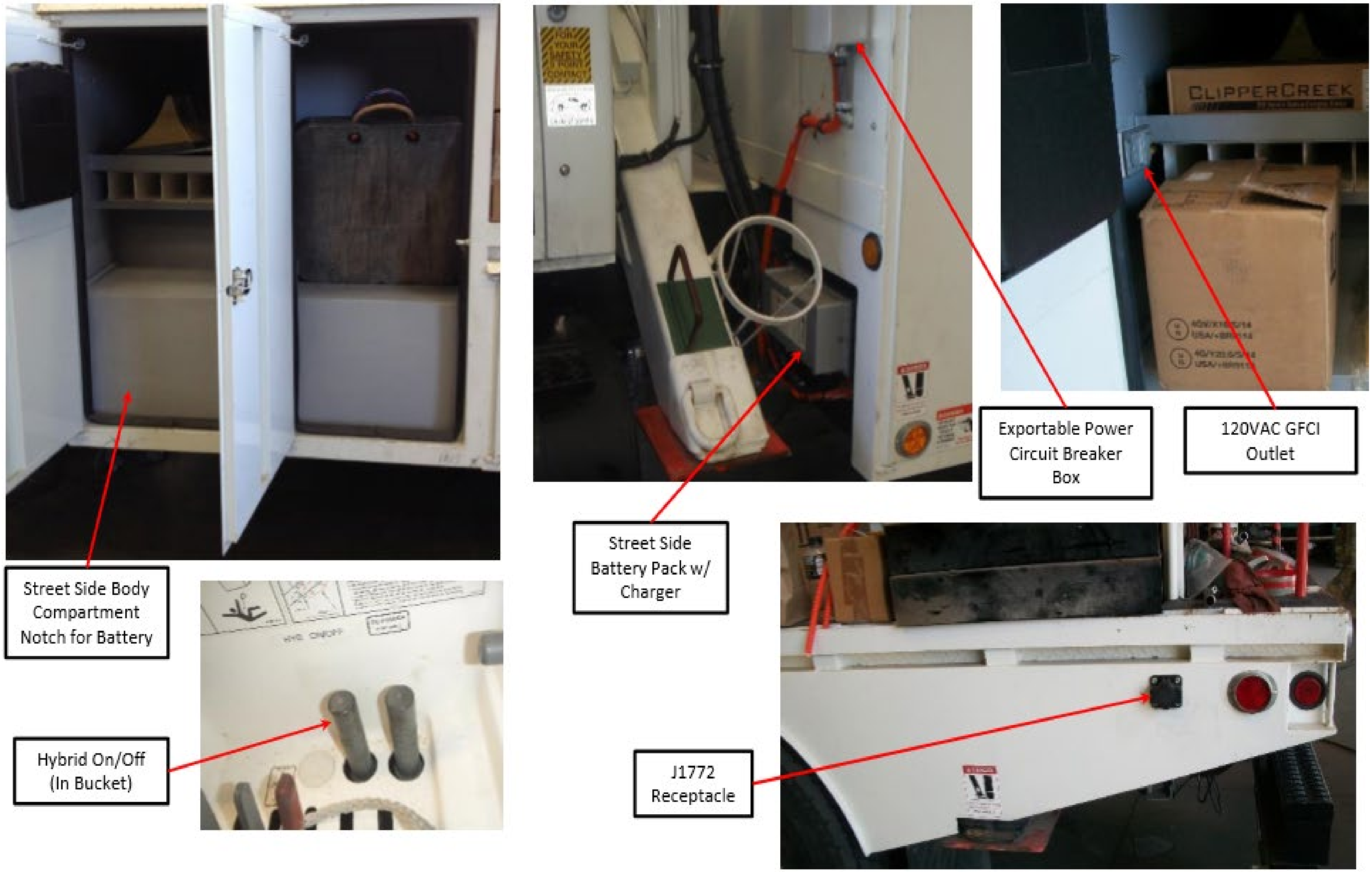
Source: Electric Power Research Institute

Figure 9: SDG&E Aerial Truck



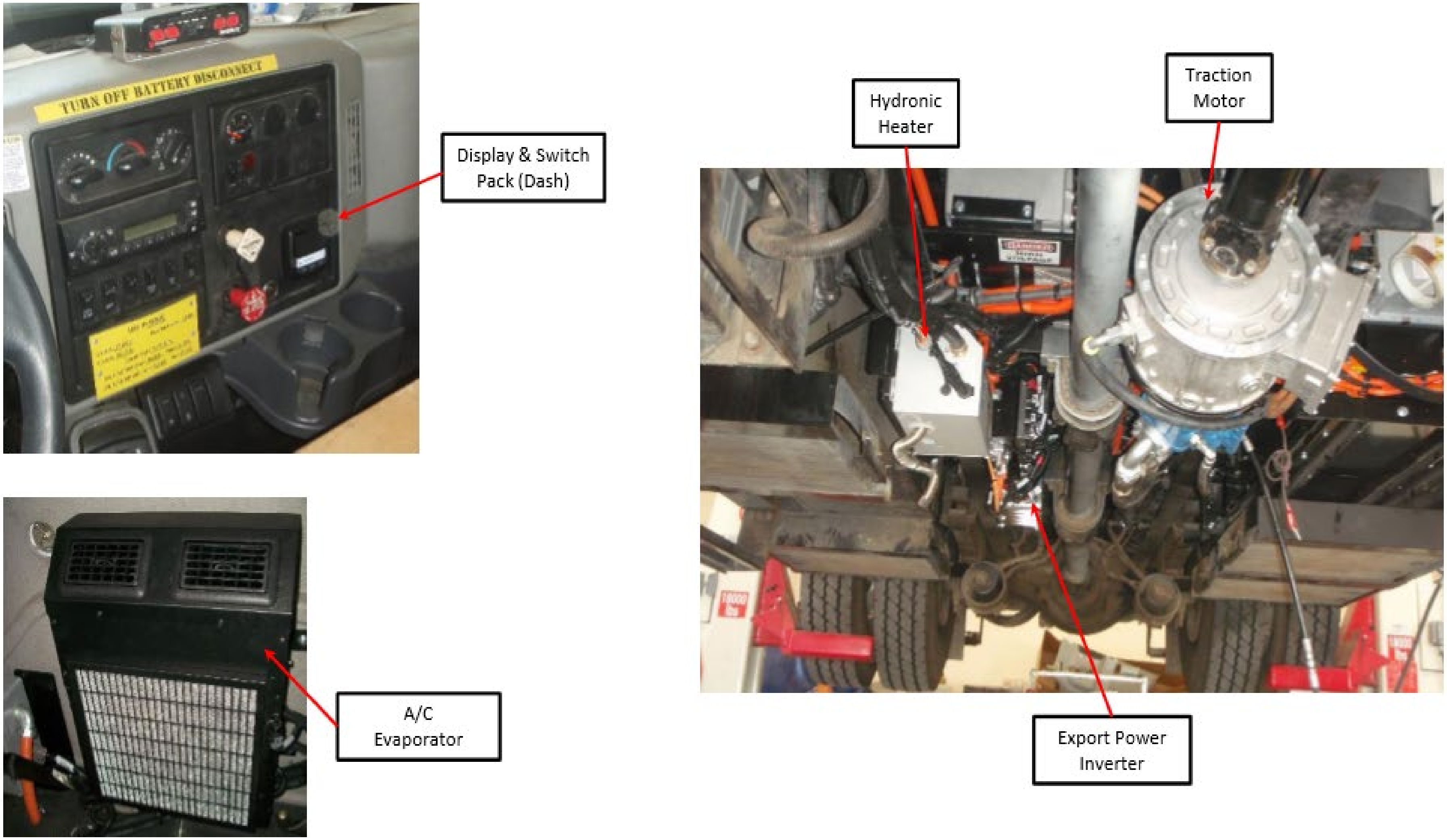
Source: Electric Power Research Institute

Figure 10: SDG&E Aerial Truck



Source: Electric Power Research Institute

Figure 11: SDG&E Aerial Truck



Source: Electric Power Research Institute

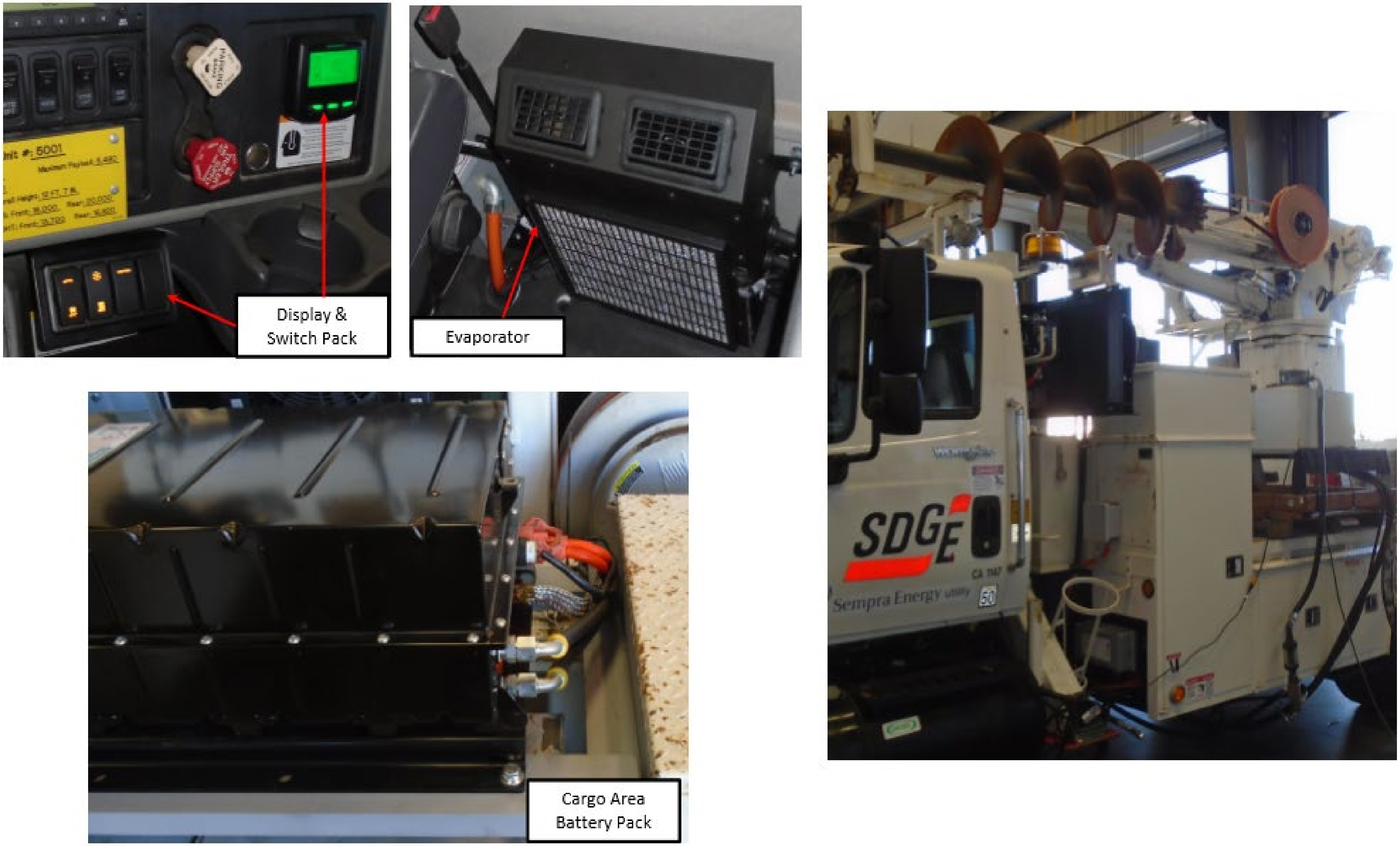
San Diego Gas & Electric Digger Derrick

The pictures below show the hardware that was added to the digger derrick. The hardware added was the same as the on the SDG&E aerial truck. See Figures 12 to 14 below.

Figure 12: SDG&E Digger Derrick

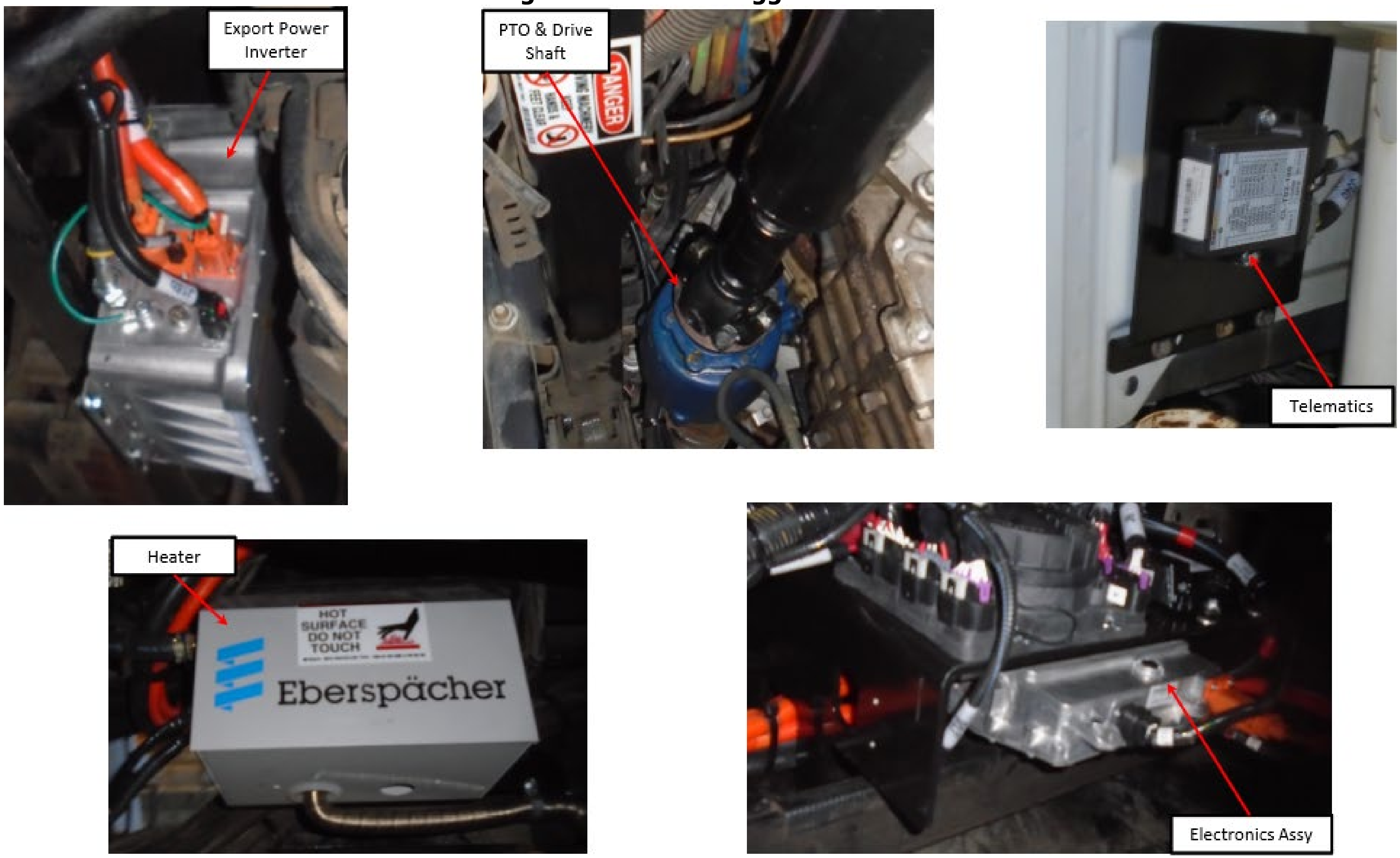
Source: Electric Power Research Institute

Figure 13: SDG&E Digger Derrick



Source: Electric Power Research Institute

Figure 14: SDG&E Digger Derrick

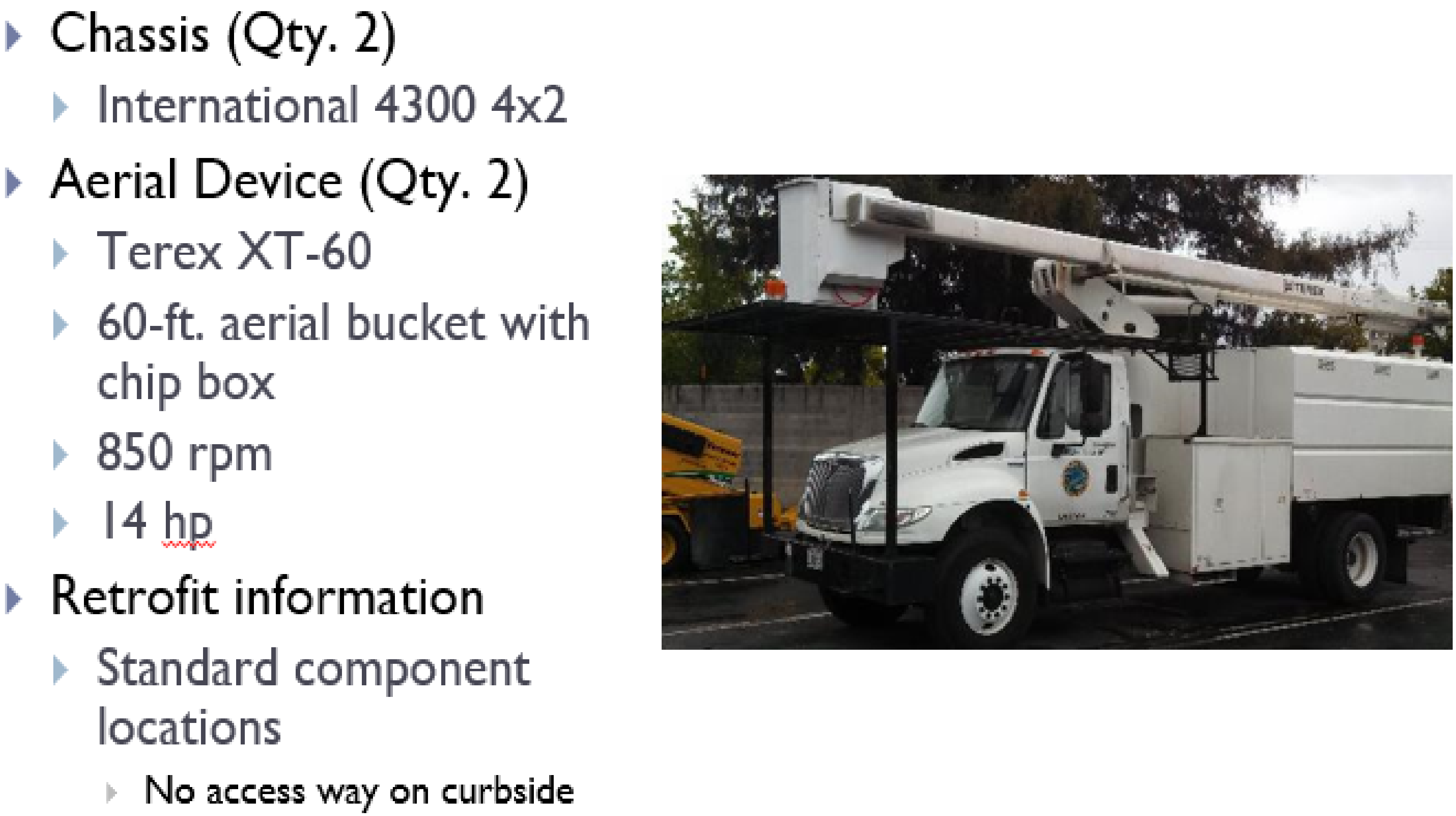


Source: Electric Power Research Institute

City of Sacramento #1 and #2 Aerial Trucks

The pictures below show the hardware that was added to the City of Sacramento's truck. The hardware added was the same as the on the SDG&E aerial truck. See figures 15 to 18 below:

Figure 15: City of Sacramento Truck

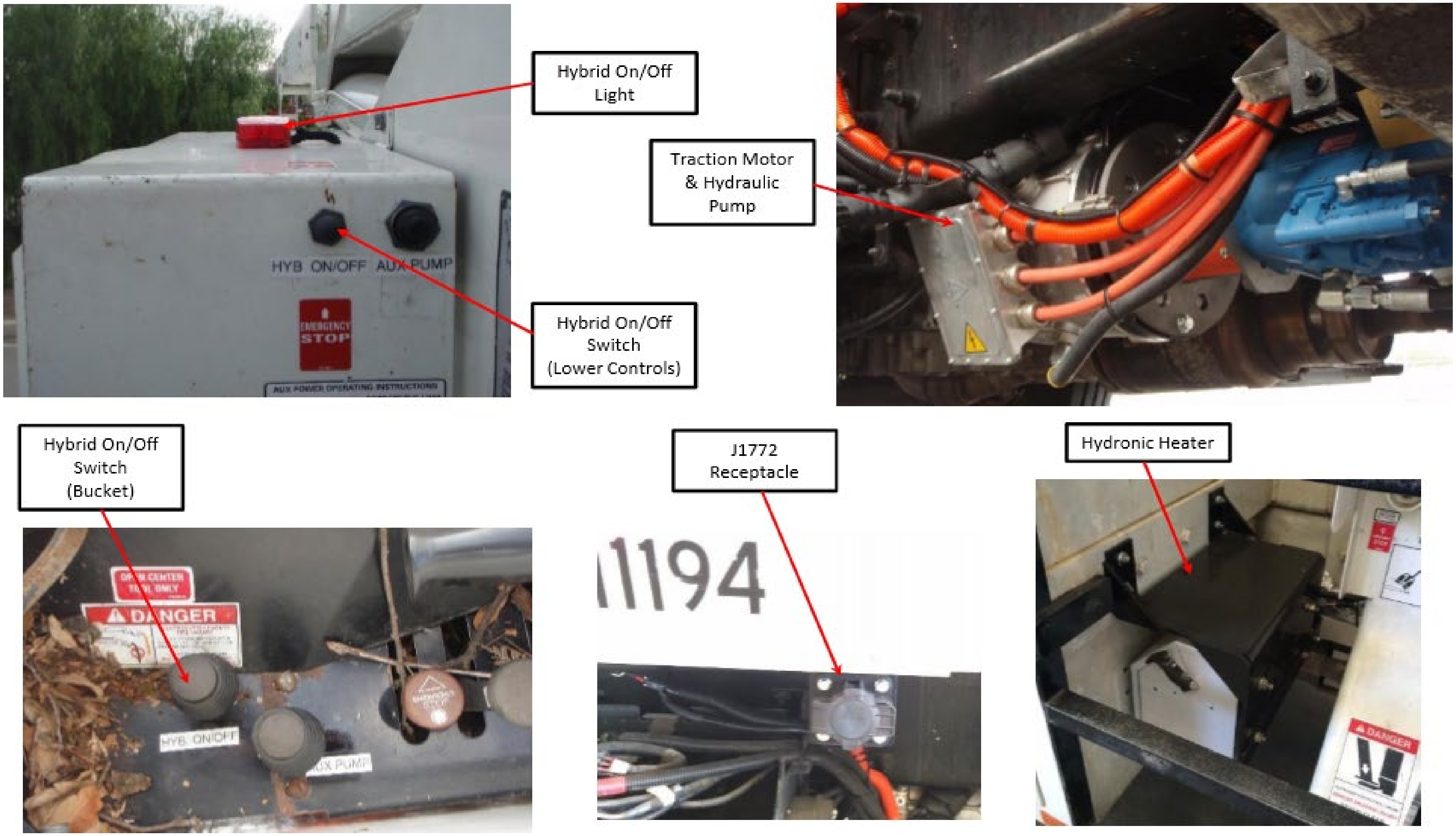


Source: Electric Power Research Institute

Figure 16: City of Sacramento Truck

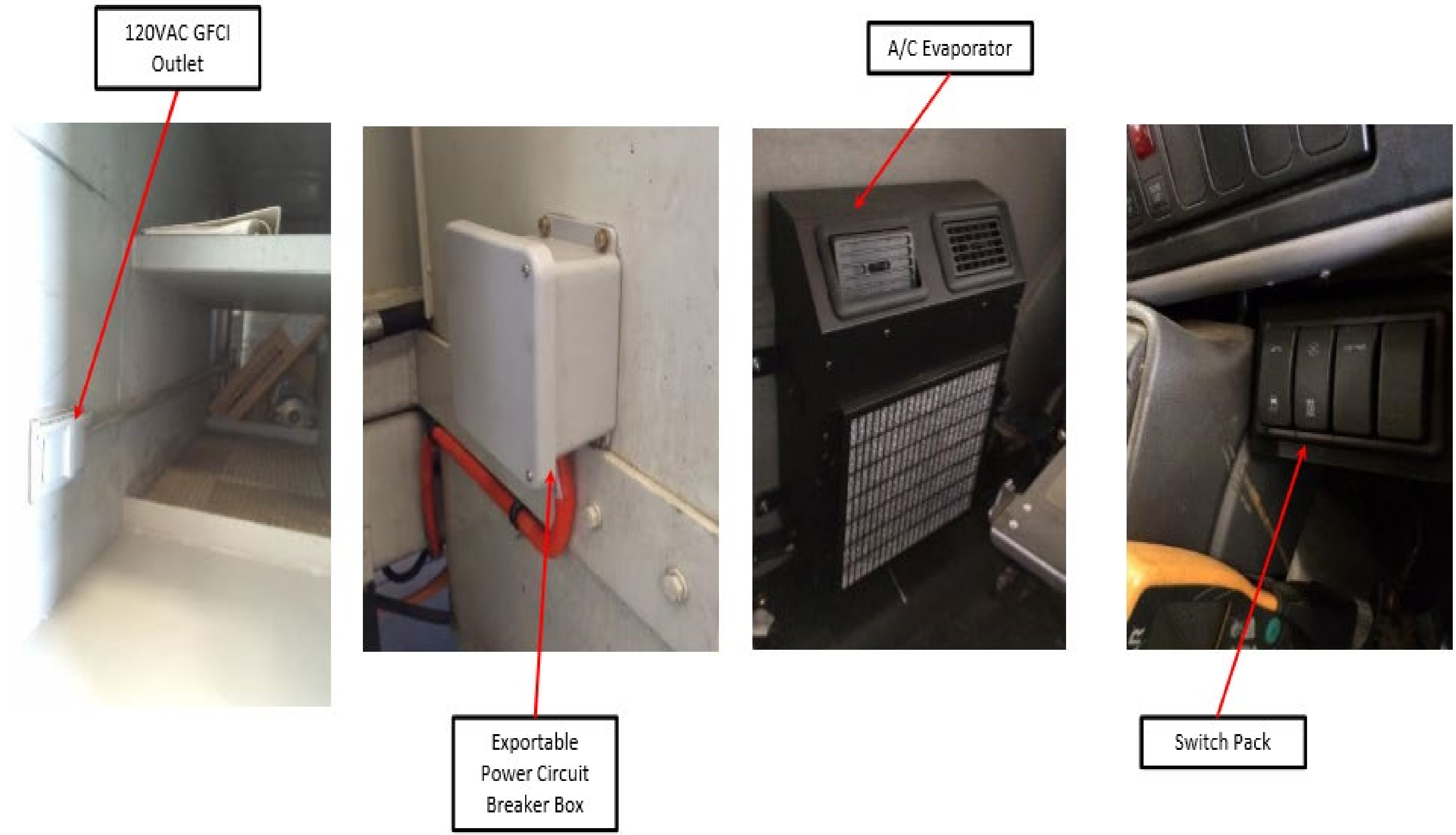
Source: Electric Power Research Institute

Figure 17: City of Sacramento Truck



Source: Electric Power Research Institute

Figure 18: City of Sacramento Truck

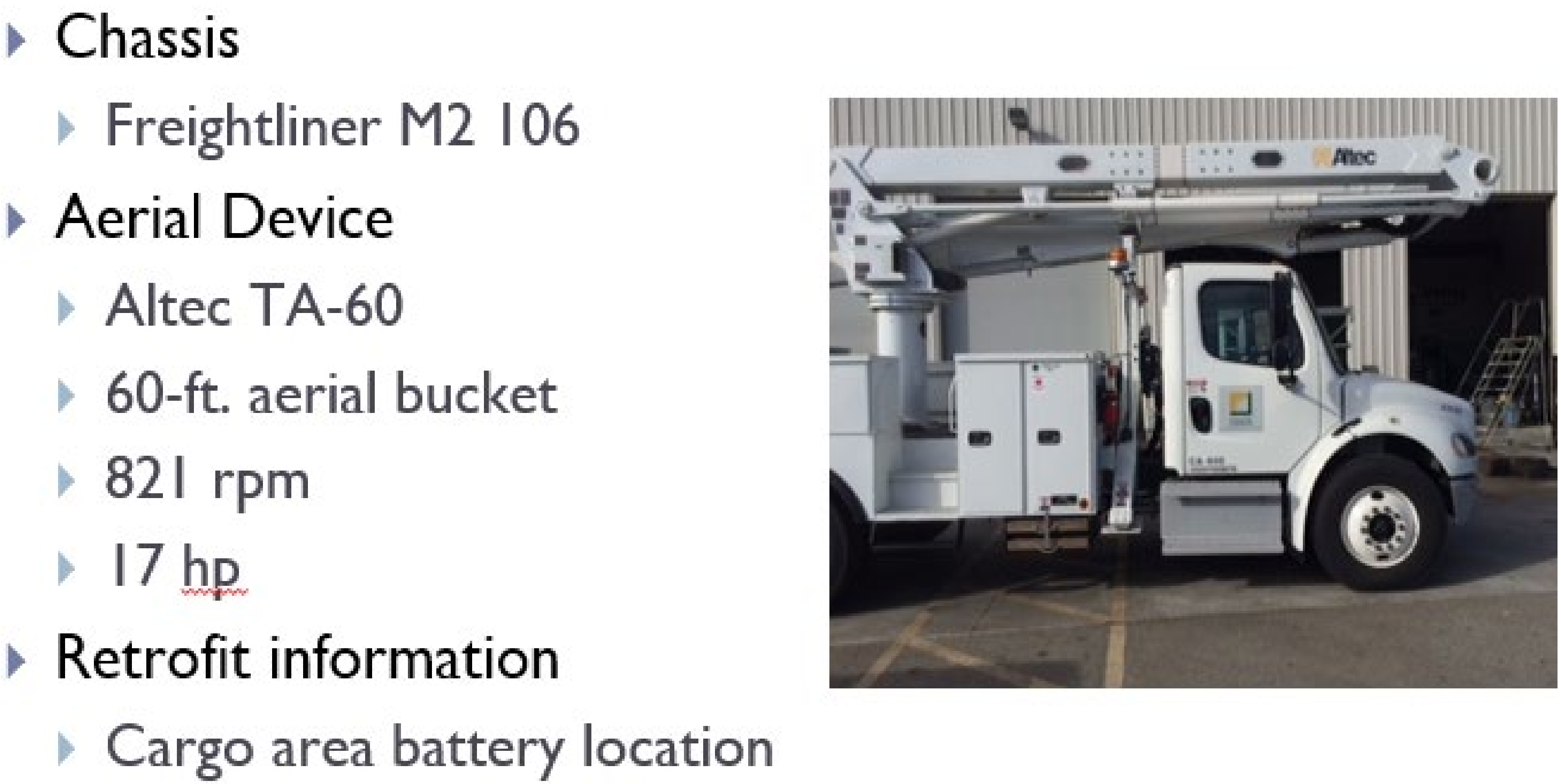


Source: Electric Power Research Institute

Southern California Edison

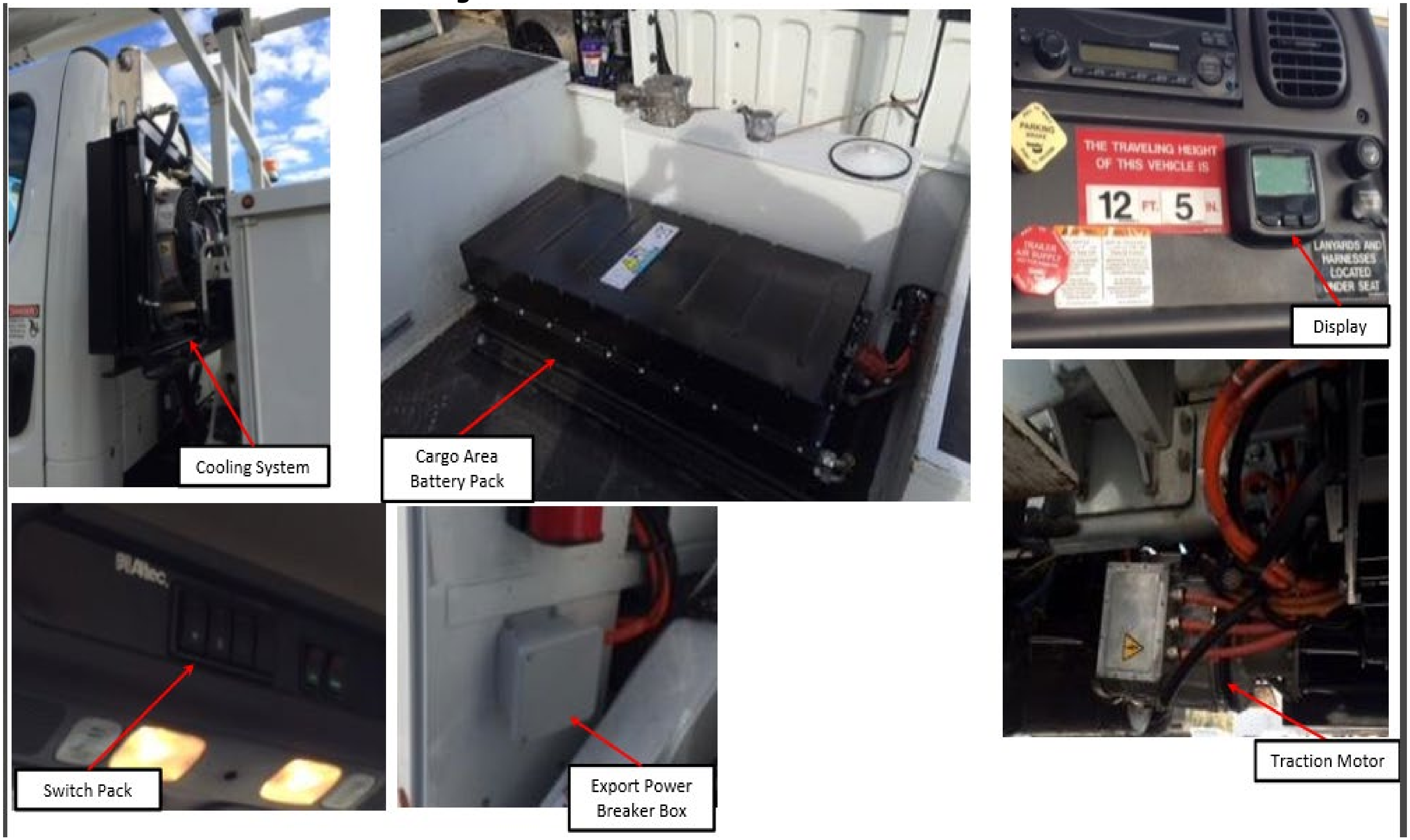
The pictures below show the hardware that was added to the Southern California Edison's truck. This is the same as that on the SDG&E aerial truck. See Figures 19 to 21 below.

Figure 19: Southern California Edison Truck



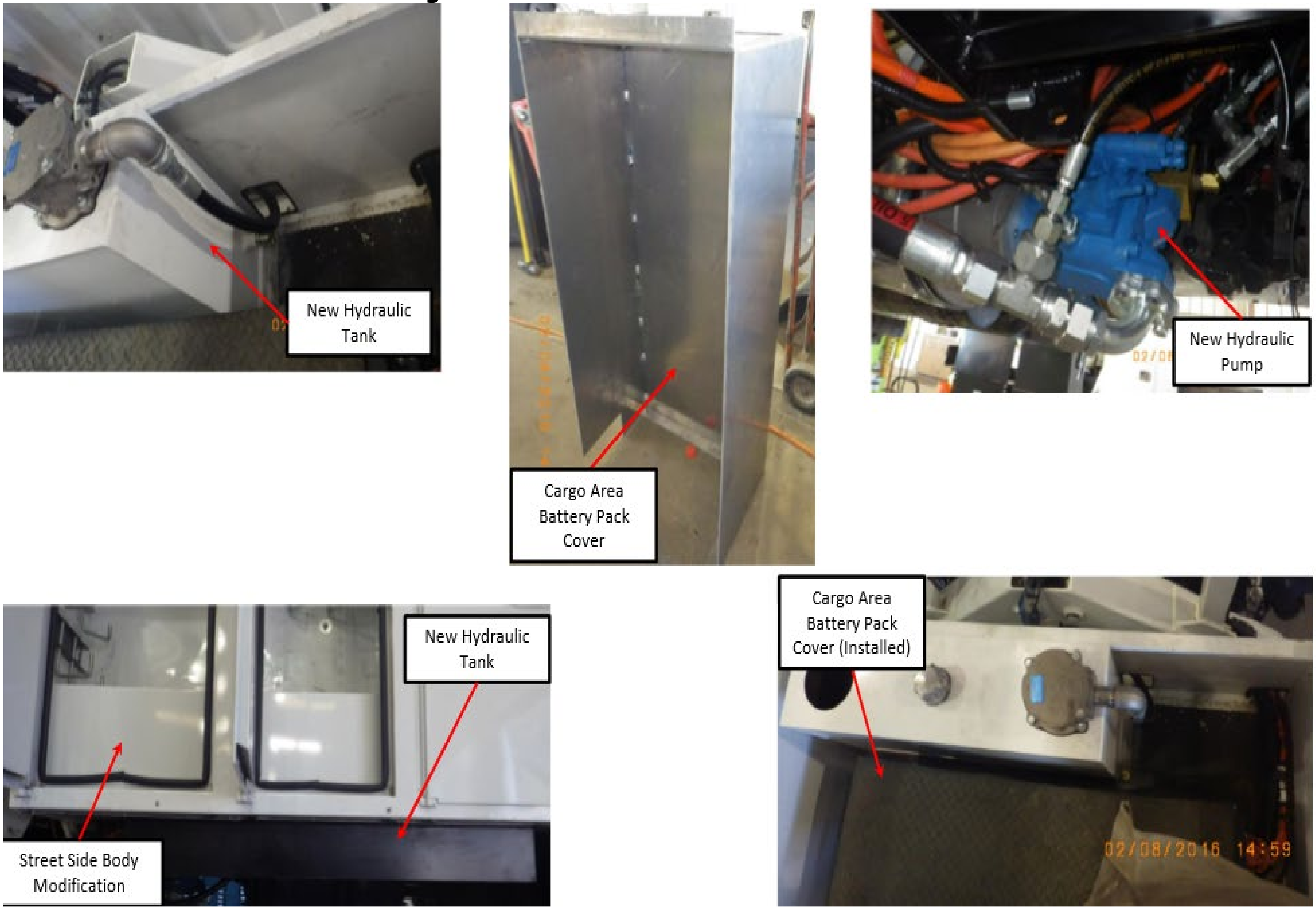
Source: Electric Power Research Institute

Figure 20: Southern California Edison Truck



Source: Electric Power Research Institute

Figure 21: Southern California Edison Truck



Source: Electric Power Research Institute

CHAPTER 6: Emissions and Fuel Consumption Results

Using the fuel and emissions test results from the dynamometer testing and the average use case, Odyne system benefits can be calculated as shown in Table 1 and Figures 22 to 24 for a full-day work cycle. Odyne commissioned the University of California, Riverside to do a report on the effects of the aftermarket exemptions of the project[1]. Some of the results are listed below:

- Reduces full-day fuel use by 50 percent or more
- Reduces greenhouse gas emissions by 50 percent or more
- Reduces NOx emissions by 80 percent or more

Two calibrations were completed for the trucks. One calibration was considered aggressive (strong), and the other was considered mild. The aggressive calibration caused the battery energy to be depleted more quickly during the drive phase to the job site compared to the mild calibration. The mild calibration would allow more battery energy to be used at the job site vis-a-vis the aggressive calibration. The objective was to determine which one would be used more.

The mild calibration applies less motor torque and limits the amount of launch assist to save more energy for the job site later. The aggressive calibration has a higher torque limit and increases the amount of launch assist to increase fuel economy benefits while driving. Table 1 and Figures 22 and 23 show the comparison of fuel consumption for a full-day work cycle across the different calibrations for the trucks.

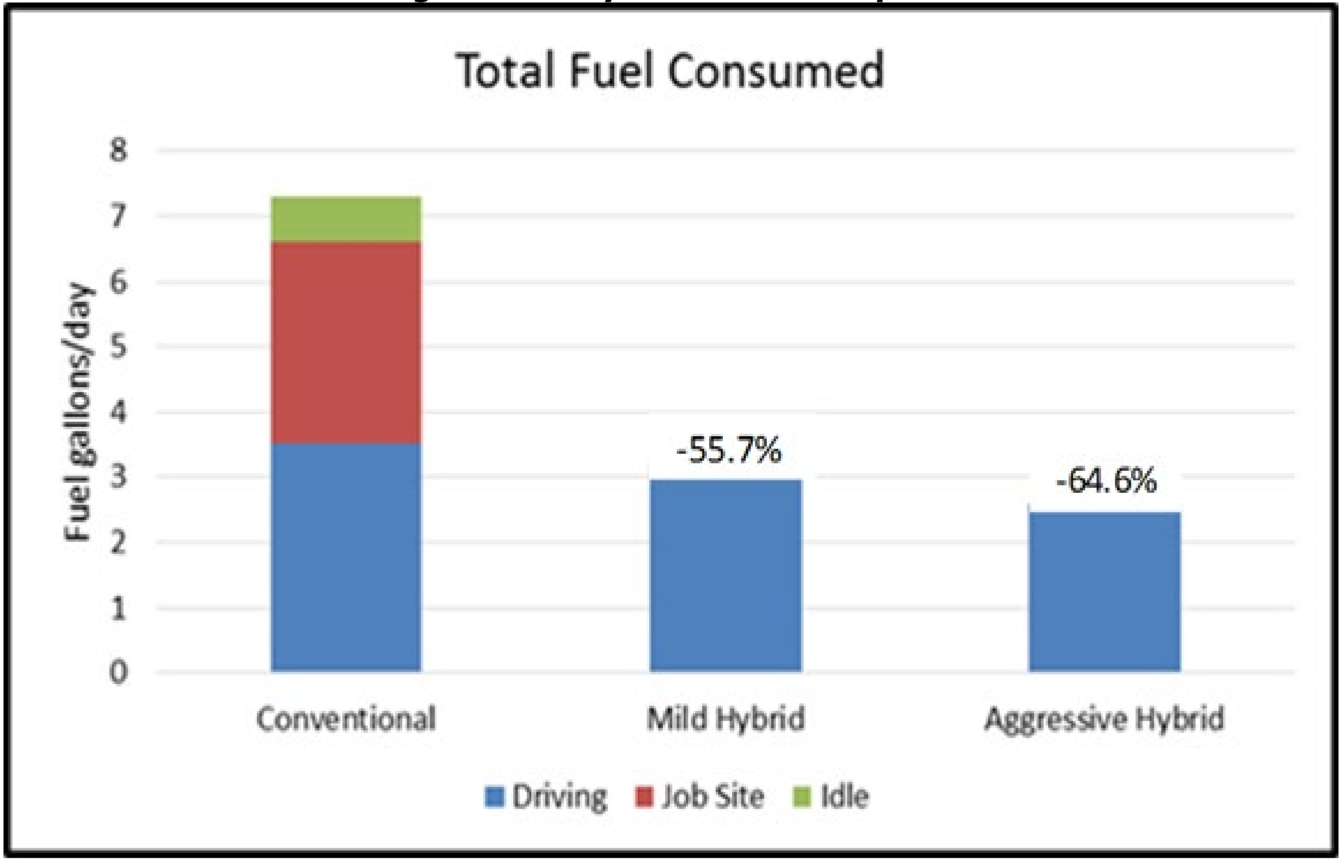
Table 1: Odyne Fuel Consumption (Gallons)

Mode	Baseline Truck	Odyne Mild Calibration	Odyne Aggressive Calibration
Driving (26 miles/day)	3.52	3.23	2.58
electric power takeoff operation at job site (2.8 hours/day)	3.07	0	0
Idle at job site (1.7 hours/day	0.70	0	0
Engine charge (if needed)	N/A	0	0
Workday total	7.29	3.23	2.58
Total savings (gal)		4.06	4.71
Total savings (%)		55.7%	64.6%

Source: Electric Power Research Institute

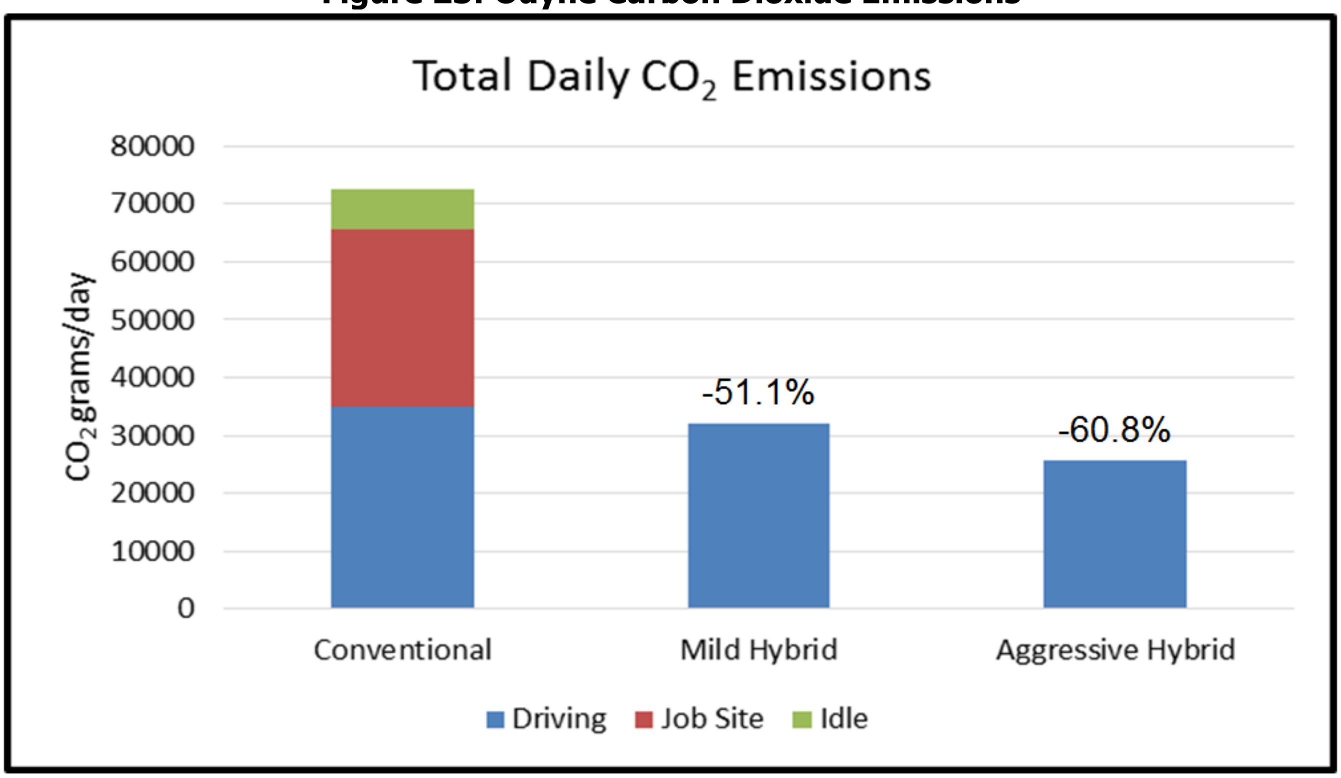
[1] Odyne Heavy-Duty Aftermarket Exemption Study. Johnson, K., Durbin, T., Jiang, Y., Yang, J. *University of California, Riverside.* May 2015.

Figure 22: Odyne Fuel Consumption



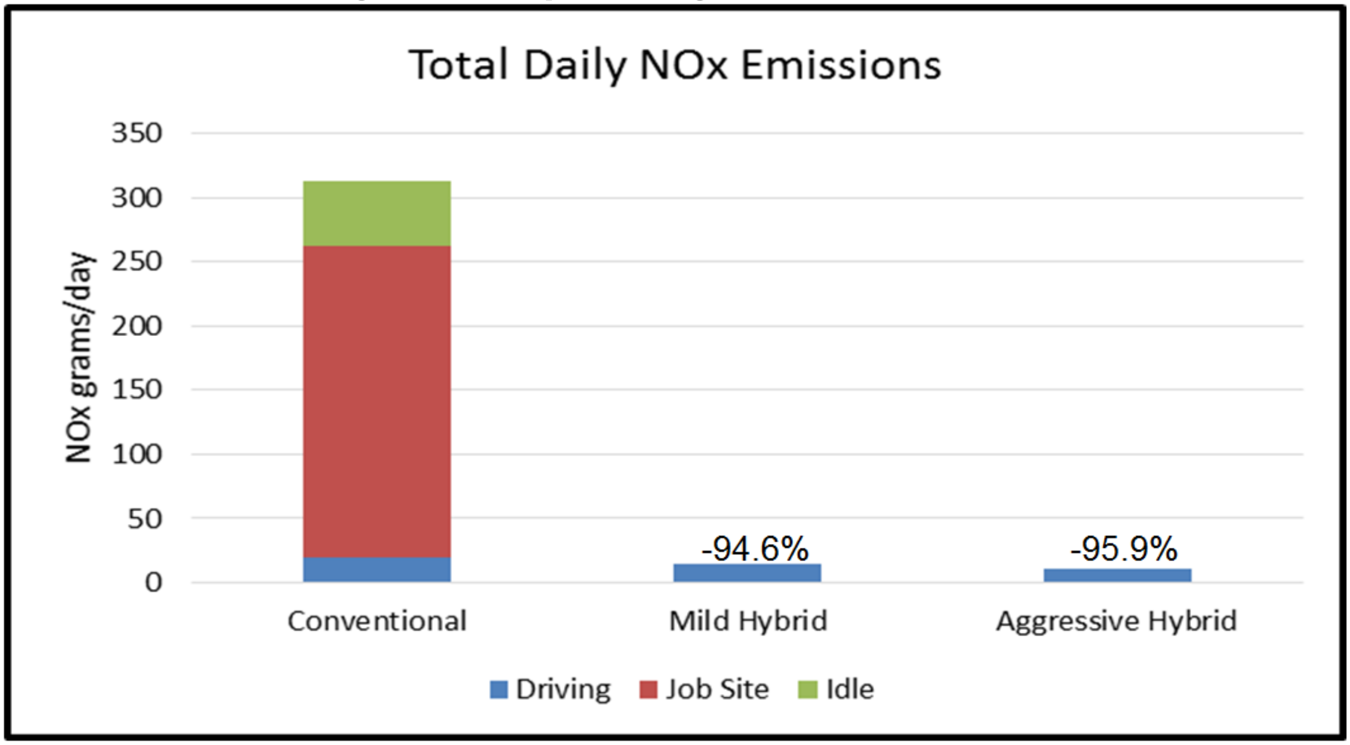
Source: Electric Power Research Institute

Figure 23: Odyne Carbon Dioxide Emissions



Source: Electric Power Research Institute

Figure 24: Odyne Nitrogen Oxide Emissions



Source: Electric Power Research Institute

Testing for California Air Resource Board (CARB) certification submission was performed at the University of California–Riverside's Center for Environmental Research and Technology test facility. The results are a workday summary consisting of weighted Urban Dynamometer Driving Schedule, consisting of cold and hot start cycles, and stationary cycle (two-hour idle plus 30-minute engine charge). Two project trucks were used for testing. Only mild calibration was tested and submitted. Using CARB-recommended procedures, the Odyne system delivered a full-day fuel and carbon dioxide reduction of 40 percent to 50 percent and a NOx reduction of 70 percent to 80 percent. (see Table 2).

Table 2: Air Resources Board test results

	CO_2 (grams per test)	NO*x* (grams per test)	Fuel Usage (gallons per test)
Truck 1			
Conventional	49,415	64.882	4.976
Hybrid	23,823	18.440	2.399
Difference	-51.8%	-71.6%	-51.8%
Truck 2			
Conventional	40,792	198.404	4.108
Hybrid	24,148	39.409	2.430
Difference	-40.8%	-80.1%	-40.8%

Source: Electric Power Research Institute

The Odyne system was reviewed with the United States Environmental Protection Agency (U.S. EPA) in January 2014. It was agreed that no further review or information was needed for Odyne to proceed with production. Odyne is now beginning development of system enhancements to meet the 2017 U.S. EPA heavy-duty truck onboard diagnostics requirements.

CHAPTER 7: Customer Feedback

All three fleet customers gave positive feedback:

Southern California Edison (Shawn Barge and Jordan Smith, Fleet Managers)

"Through a CEC funded program, Odyne installed their G2V2 hybrid system on a SCE TA-60 bucket truck; this is a relatively compact utility line truck with an Altec 60-foot aerial device.

System Build Input

The Odyne G2V2 hybrid system appears to be effectively packaged into the TA-60. The electric motor is closely integrated into the power take off and is not obvious unless one looks under the vehicle specifically for it. One of the two Johnson Controls battery packs is packaged on the driver's side of the vehicle up into the bottom section of the bins. The loss of space is always negative to the user, but it seems mitigated by being on the less used street side.

The second battery pack is located in the bed just behind the hydraulic reservoir under a metal cover. This area is sometimes used for material transport, so the user will not like the loss of space, but the position is much better than if it had been placed up into the curb side bins. There is a sticker that reads "Not a Step," but it is likely it will be walked on and tools and equipment set on it due to its location, so it should be protected by a shield.

The cooling system is installed behind the cabin on the driver's side, and does not seem in the way except it does hang out a little and may in the way for taller users. Moving it inward a couple inches would help to avoid this.

The controls for the electric air conditioning and electric power takeoff operation inside the cabin are simple and easy to use. The electric air conditioning is located deep under the center seat and has proven to not have powerful drawdown cooling power. There are no adjustments for the air conditioning so it will only run full load.

Initial Test Results

The system has been undergoing testing since April 2016. The testing has included freeway and urban drives along with the Southern California Edison Troubleman Loop. The Troubleman Loop simulates a workday in which the vehicle does a combination of urban and freeway driving for 76 miles and makes four 75 minutes work stops. At each work stop, the electric power takeoff operation is engaged, the boom is cycled, the cabin cooling system is activated, and vehicle lights and strobes are activated. A flowmeter was installed in the fuel system to accurately measure fuel consumption.

Though the system is designed mainly for work site electrification, the G2V2 system does provide some drive torque assist through the PTO. However, in pure drive testing on the Pomona Loop and Freeway Loop, the 94 mile freeway drives and 62 mile urban drives showed no difference in fuel consumption with the hybrid drive assist on or off. The vehicle averaged 8.6 mpg on the freeway and 6.7 mpg in the city.

Although the state of charge of the battery system did drop 5-9 percent according to the Odyne system, this was not enough to impact the fuel mileage beyond the 5 percent uncertainty limit. Odyne explained that in mild drive assist mode, the system does not have much effect above 20 mph, so these results are not unexpected considering the driving conditions. Stop and go traffic may result in more significant differences.

In Troubleman Loop tests, the vehicle consumed 15.7 gallons for a day of simulated work with the hybrid system disabled. The fuel consumption dropped to 10.9 gallons with the hybrid system engaged. The results show 31-35 percent fuel savings per workday. When starting fully charged, the system was able to provide engine-off jobsite operation for all four 75 minute work stops.

The converted TA-60 has been tested 1116 miles since the conversion and has experienced no failures. The Odyne G2V2 system has worked without issue and is able to effectively actuate the boom in line with crew expectations. During one test, the boom was cycled in electric power takeoff operation mode until the batteries were depleted, and the system seamlessly transitioned to mechanical PTO without issue. The plug-in charging system has never failed to charge, and the power quality of the charger meets or exceeds all SAE J2894™ requirements. The SAE J1772™ EV supply equipment worked effectively and safely and mated with SCE's existing charging infrastructure."

San Diego Gas and Electric (Tim Devlin, Fleet Supervisor)

"The things we like about the new battery system are:

- It will reduce the run hours on the engine.
- It allows us to run the boom etc. near residential property without the noise of the engine.
- It allows to cool/heat the cab of the truck without the noise of the engine.
- It will reduce our fuel consumption while using electricity instead (a product we produce).
- The engine starts automatically when the batteries are depleted, eliminating the need for the employee to remember.

Some things we don't like about the new system are;

- Long duration to fully charge the batteries
- The small air pump set-up at the Capstan in the front bumper
- Single hydraulic speed of the boom operation

We would recommend other utilities to purchase the Electric Hybrid system.

We like the fact that Odyne can monitor the system/unit remotely via the remote telematics, and notify us if something is out of compliance or specification."

City of Sacramento (Ron Kammerer, Operations General Supervisor, Fleet Management and John Tampas, Fleet Manager)

"All the feedback from my staff has been positive. Easy to enter the bucket, articulates quickly, quiet and easy to operate. "

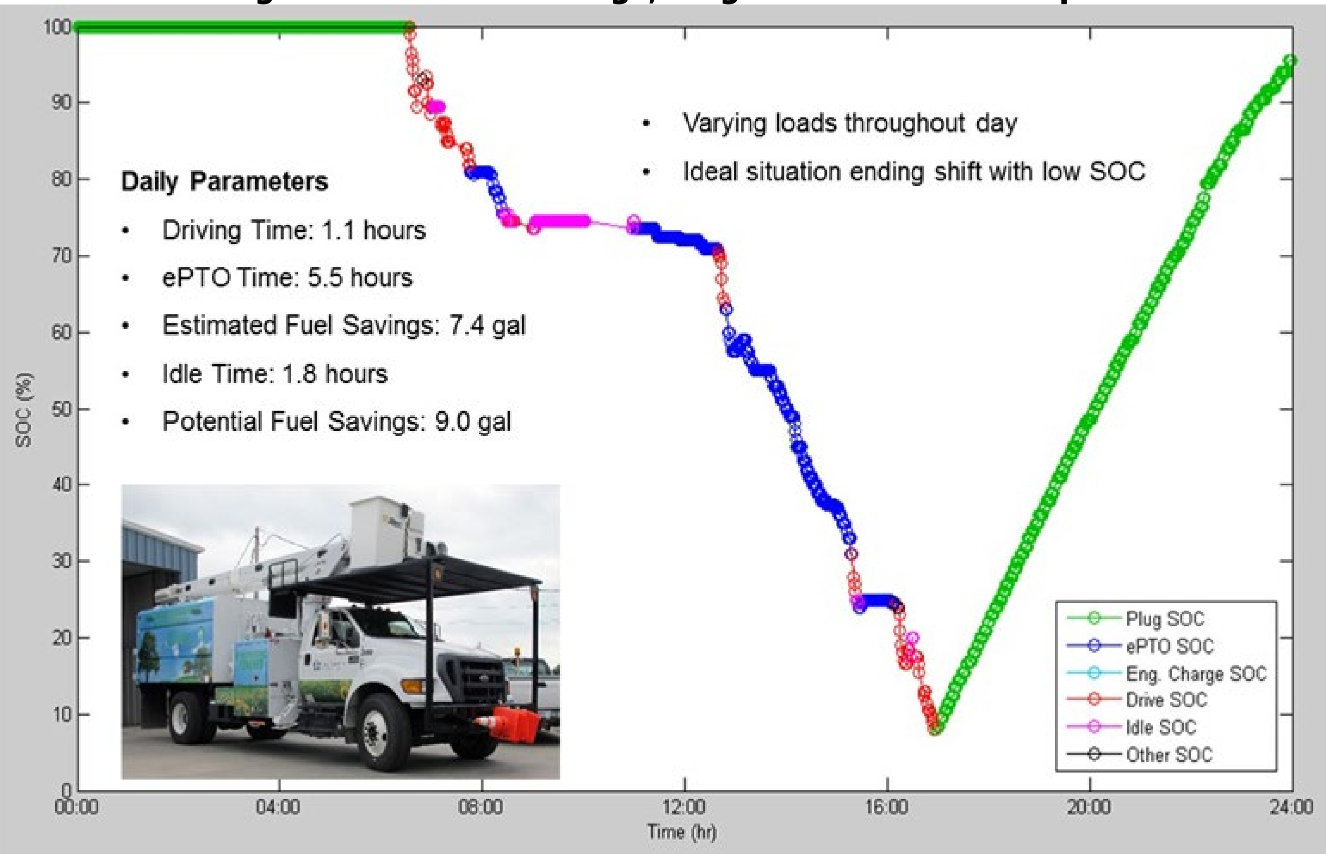
CHAPTER 8: Data Analysis

Data was collected using the data acquisition system. All five trucks were equipped with a data acquisition system that collects data at a rate of up to 1 Hertz. Data collection is done during the day and sent to the server daily. Data included the following:

- Motor current and voltage
- Battery current and voltage
- Charger current and voltage
- Motor and engine torque and speed
- Export power current and voltage
- Odometer
- Truck speed
- Accelerator and brake pedal position
- Fuel used
- Charge time
- Software and calibration level

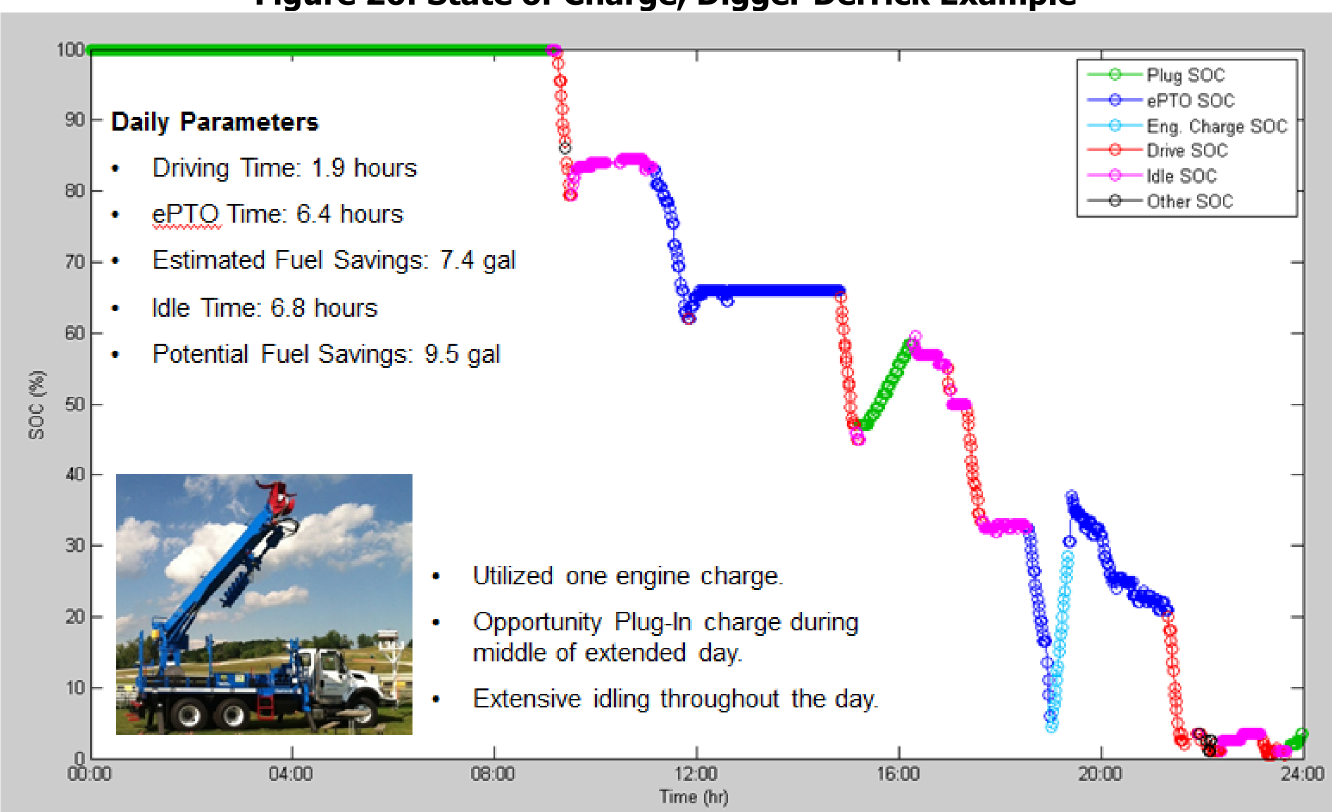
Figures 25 to 27 show examples of typical days for the trucks. The charts plot the state of charge (SOC) of the battery against the time of day on the horizontal axis. Several modes are illustrated, including SOC while plugged in, SOC change due to the PTO, engine charge SOC, drive SOC, and idle SOC. These charts have become known as SOC V charts because, under optimum conditions, the plot looks like a V. Ideally, the V would start at or near the 100 percent SOC point, go to 0 percent, and then return to 100 percent. The left side of the V uses the energy from the battery to drive or move the hydraulics, and the right side is the battery charge.

Figure 25: State of Charge, Large Aerial Truck Example



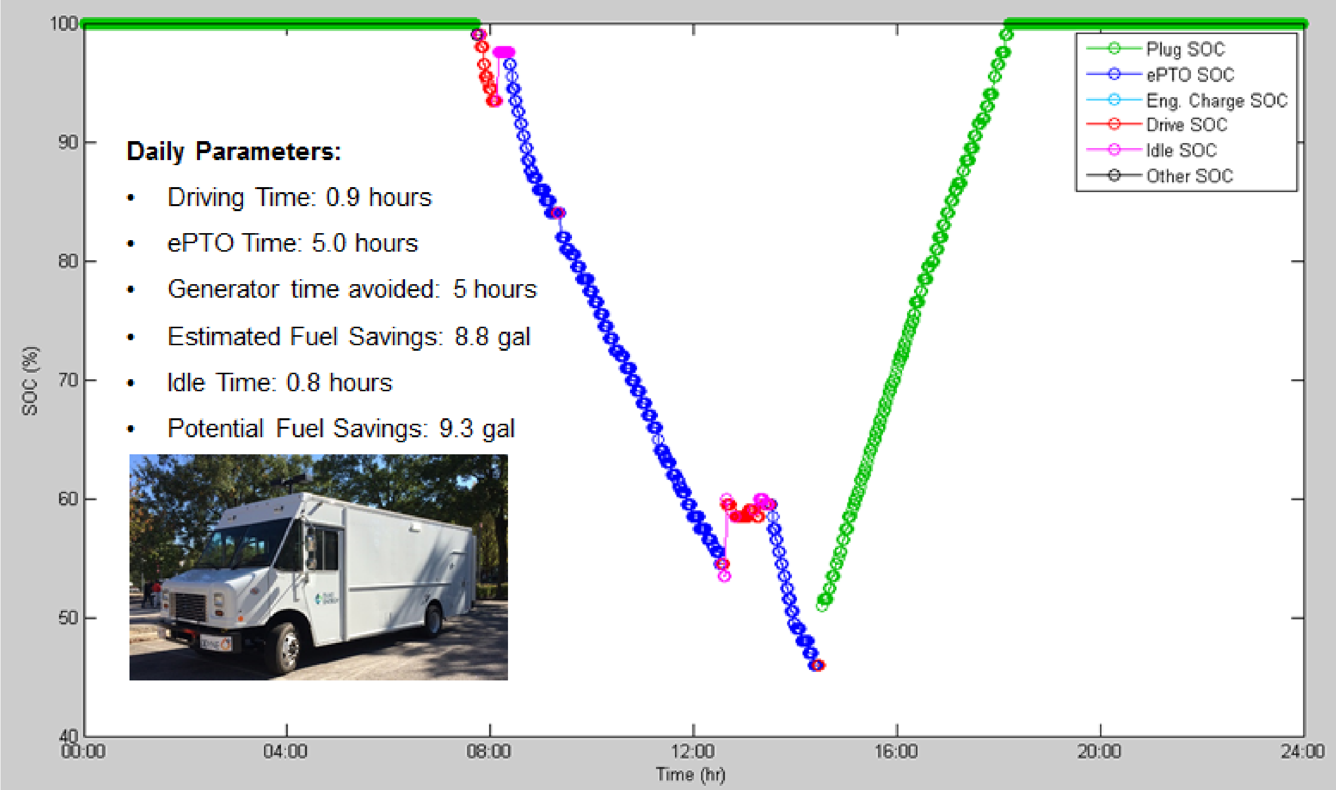
Source: Electric Power Research Institute

Figure 26: State of Charge, Digger Derrick Example



Source: Electric Power Research Institute

Figure 27: State of Charge, Walk-in Van Example

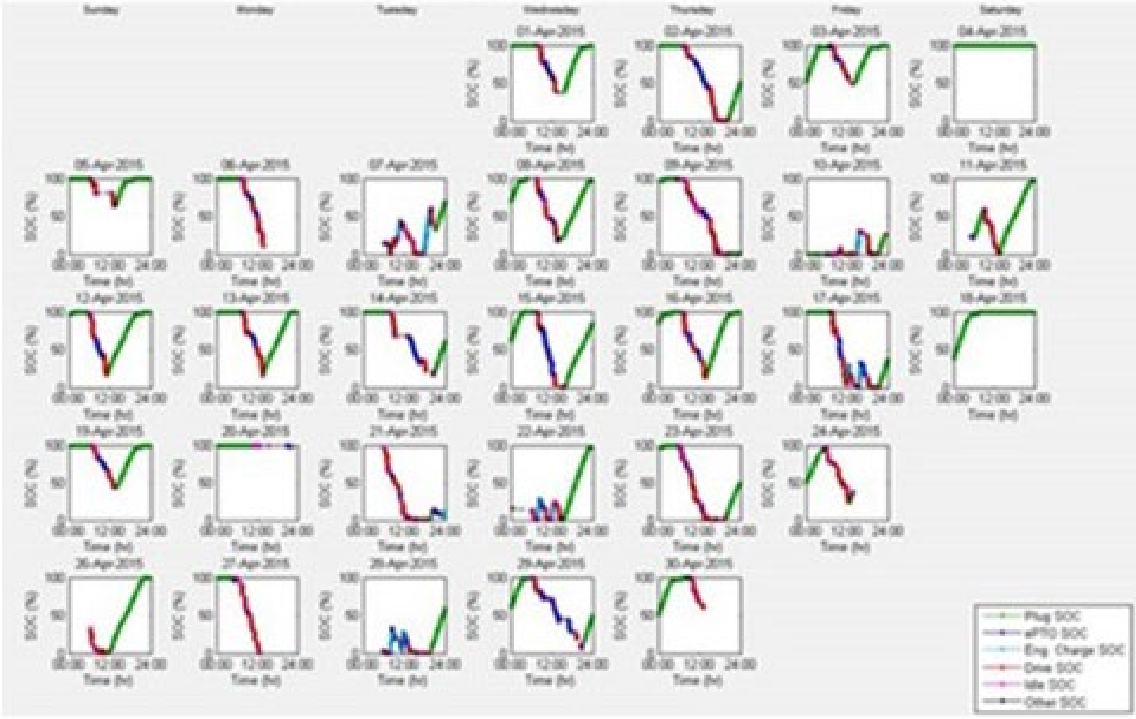


Source: Electric Power Research Institute

As can be seen from Figures 25 to 27, there was some idle time that was not necessary because this is a hybrid and does not require idle time. If the idle time can be eliminated, there is a potential to achieve more fuel savings, as shown in the figures. In Figure 23, it is estimated that 7.4 gallons of fuel were saved over a conventional truck. If the idle time could be eliminated, a total of 9.0 gallons of diesel fuel could be saved. Figures 24 and 25 show other examples of this. Figure 24 has an example of an engine charge. The truck was run until the battery energy was depleted, and then the engine came on near the 19:00 hours mark to charge the battery.

Figure 28 shows how the vehicles are being used. The layout of the data is by day of the month, like a calendar. The data shown are SOC versus time of day, or an SOC V chart, as defined earlier. Figure 28 shows the SOC of a project truck for one month. The vehicle shows significant activity, including many full charges. To provide optimum payback, hybrid systems should be targeted toward more high-usage applications.

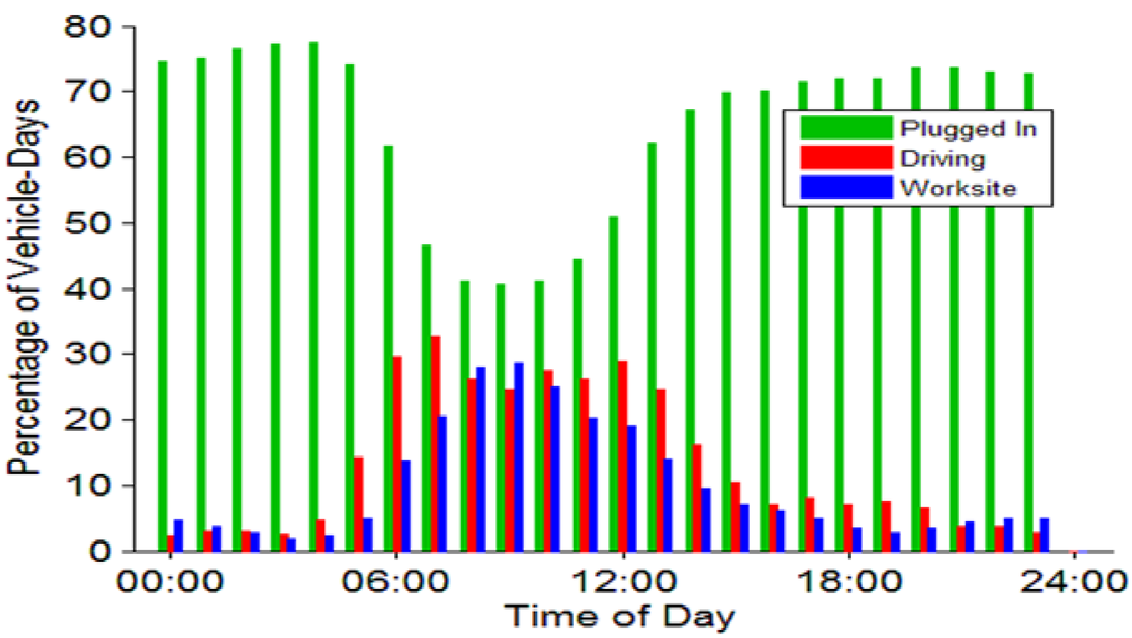
Figure 28: State of Charge for a High-Usage Truck



Source: Electric Power Research Institute

Typically, the vehicles were operated during the early daytime hours and plugged in during the afternoon and night (see Figure 29). Most utilities appear to start their shifts around 5 a.m. to 6 a.m. and finish using the vehicles by 1 p.m. to 3 p.m. Most of the work outside that timeframe is due to emergencies or local restrictions.

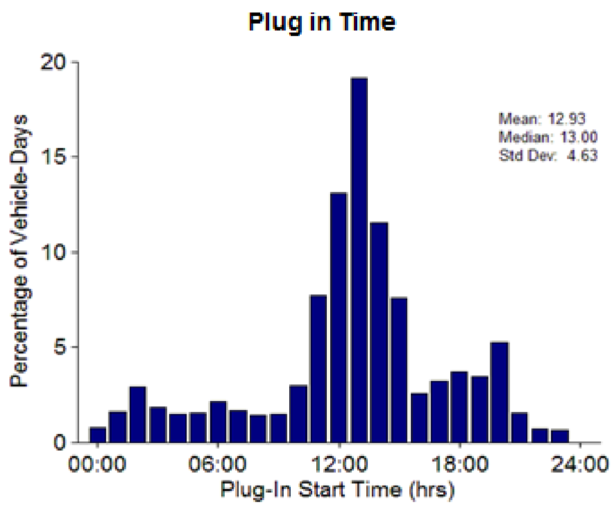
Figure 29: Modal Time of Day

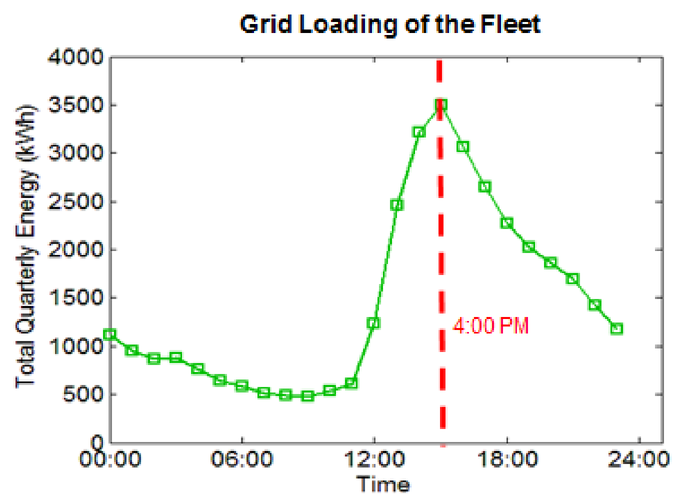


Source: Electric Power Research Institute

As Figure 30 shows, more than 60 percent of plug-ins occurred between noon and 4 p.m., and the peak load on the grid occurs around 4 p.m. Much of the charging is completed by midnight. This shows the opportunity for smart charging—to delay charging until non-peak hours.

Figure 30: Plug-In Charging

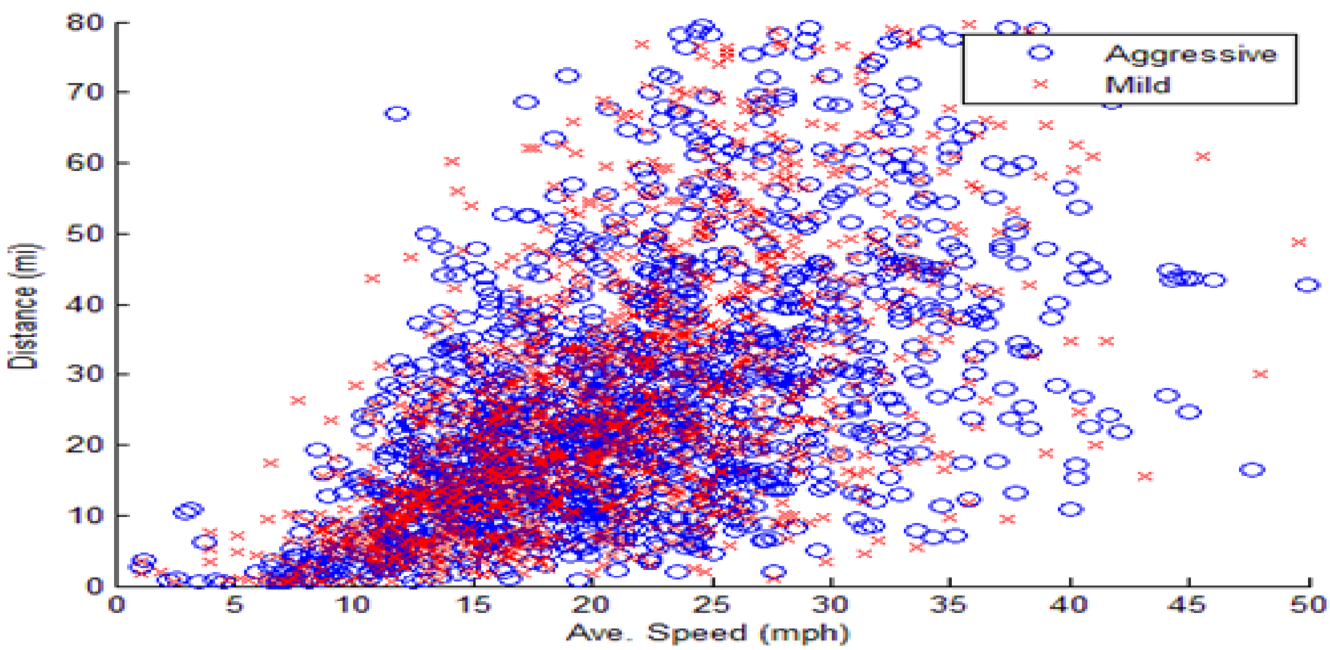




Source: Electric Power Research Institute

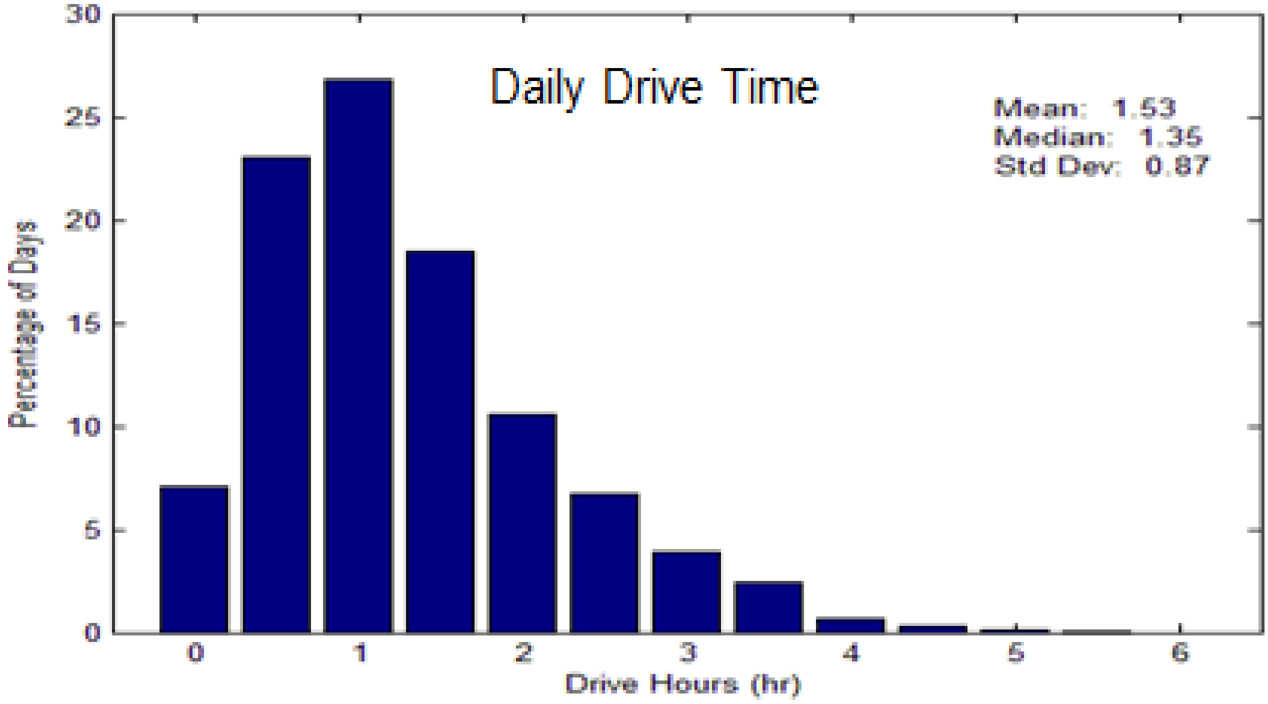
Most utility trucks are driven only for a few hours a day—the fleet average was about 1.5 hours and 26 miles per day (see Figures 31 to 34). These trucks generally operate within the city or locale and drive short distances. Two different truck calibrations were tested on the trucks. One calibration was a mild calibration and the other was a more aggressive calibration with respect to the amount of electric torque added. The calibration differences are shown in Figure 31, 33, 35-37.

Figure 31: Driving—Distance Versus Speed



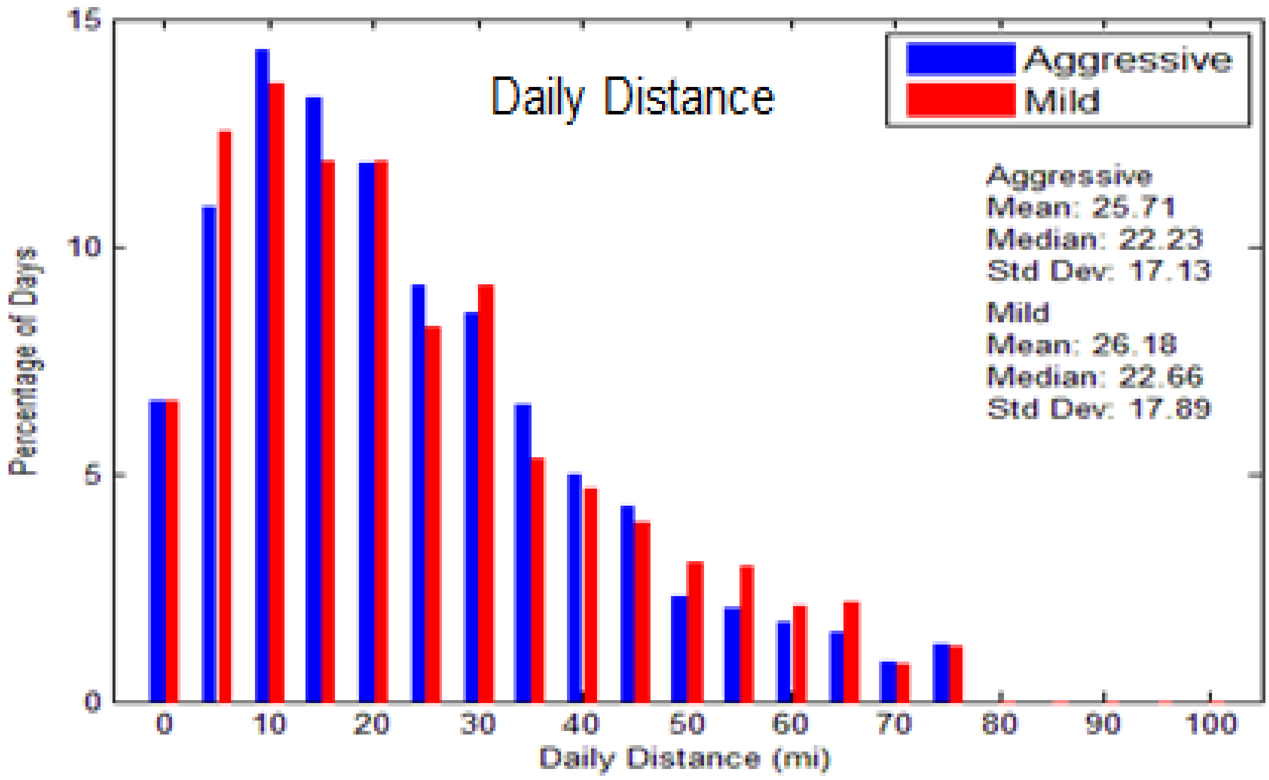
Source: Electric Power Research Institute

Figure 32: Driving—Daily Drive Time



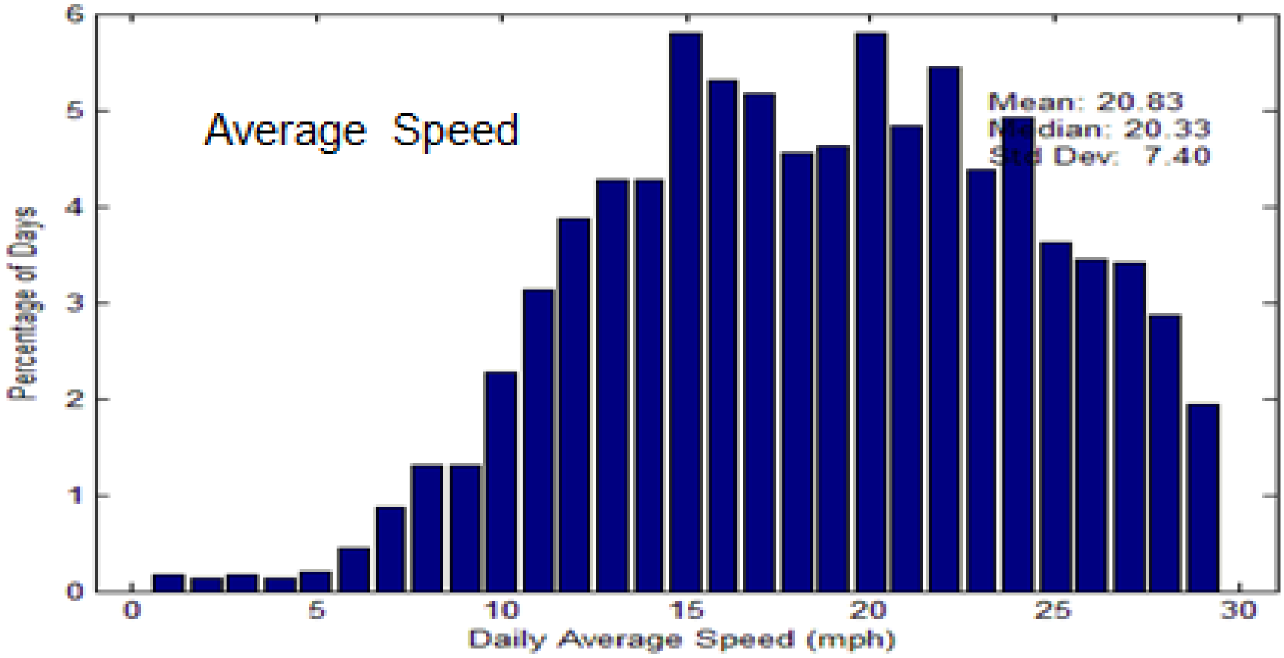
Source: Electric Power Research Institute

Figure 33: Driving—Daily Distance



Source: Electric Power Research Institute

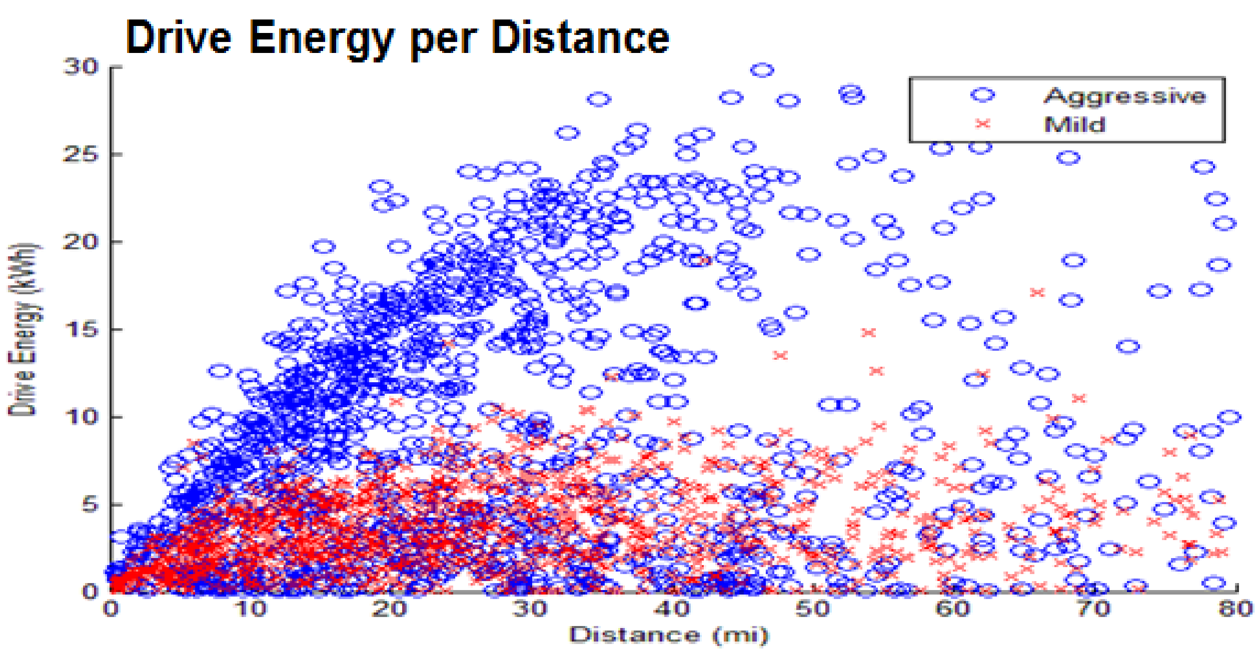
Figure 34: Driving—Average Speed



Source: Electric Power Research Institute

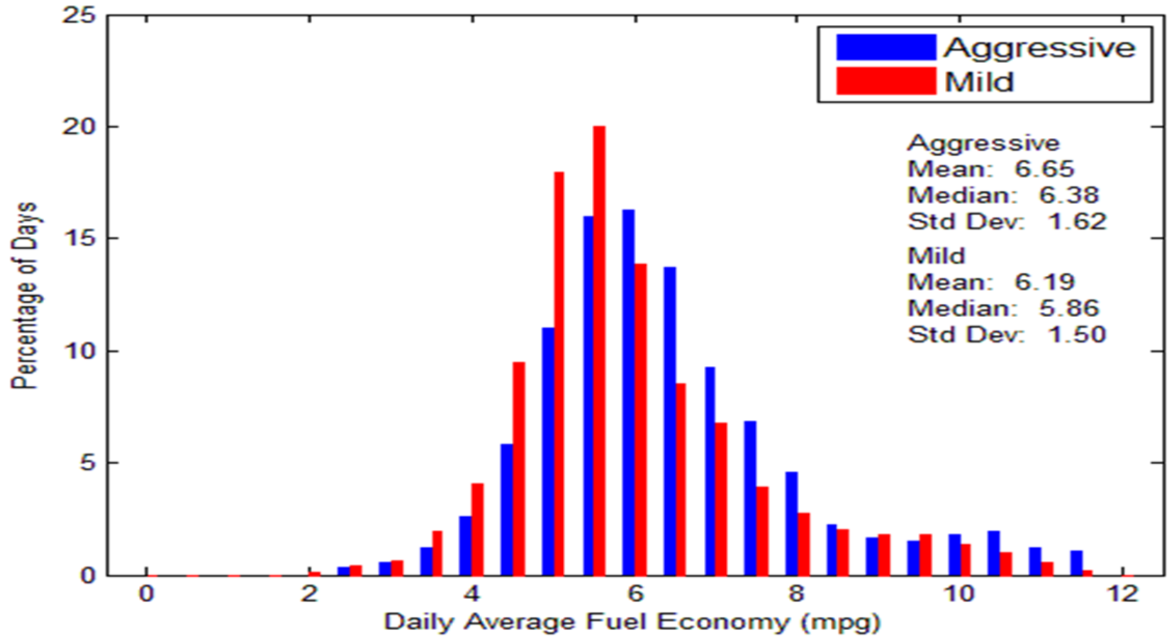
Across the fleet, mild versus aggressive calibration did not affect the basic usage metrics. Measurements such as speed, distance, and hours were quite similar regardless of calibration. Aggressive calibration improved the average fleet fuel economy by 8 percent compared to vehicles with mild calibration but used more than twice the battery power to achieve it. On average, aggressive calibration saved an additional 0.3 gallons of diesel fuel and used 4.8 kilowatt hours more electricity than mild calibration. Figures 35 through 37 illustrate the results.

Figure 35: Torque Calibration—Energy Versus Distance



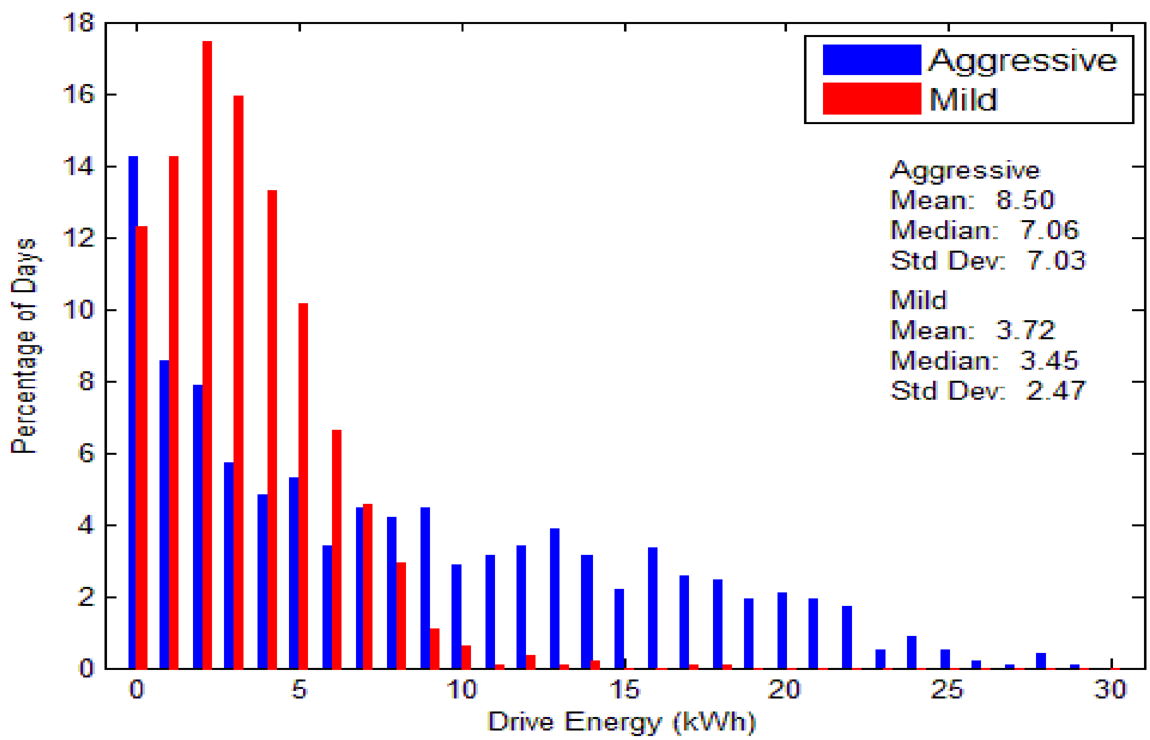
Source: Electric Power Research Institute

Figure 36: Torque Calibration—Daily Fuel Economy



Source: Electric Power Research Institute

Figure 37: Torque Calibration—Drive Energy



Source: Electric Power Research Institute

CHAPTER 9: Recommendations

Odyne Systems develops and manufactures turnkey hybrid solutions for fleet vehicles which continuously start and stop and have long job site idle time. Its parallel plug-in hybrid system can be installed in new and in-use vehicles, lowering fuel consumption by up to 50 percent, depending on application, reducing emissions, and providing quiet work site operation. The system can be applied to a wide range of vehicle configurations without changing the original equipment manufacturer engine. Because of this, the original U.S. EPA certification of the engine still holds.

Retrofitting trucks is a good way to get the older trucks better fuel consumption and emissions. However, the retrofit is more than just adding the hybrid hardware to a new chassis and then adding the body equipment. In-use trucks had to be de-contented and then reassembled. In this project, since the trucks were already being used and the retrofit will not be on bare chassis, the final stage manufacturers needed to remove their equipment from the build. Terex or Altec, the final stage manufacturers, had to remove the aerial device or digger derrick which have already been installed. This meant an additional step and additional cost. After equipment removal, the trucks were moved to Valley Power for retrofitting. Odyne then tested the system. The trucks were moved back to the final stage manufacturers for the equipment to be put back. This is another additional step and cost. Only then, can the trucks be returned to the customers.

Aerial device service facilities should specialize in integrating new hydraulic components and systems. They should be encouraged to work directly with the Odyne assembly facility (Valley Power) to coordinate vehicle hand-offs. It would also be very helpful if the assembly facility is able to work on multiple vehicles at the same time.

It was a good development that later in the project, Valley Power technicians were able to complete testing using phone support from Odyne. It is recommended that training specifically in hydraulic circuit design, be given to more Odyne and Valley Power technicians.

Having customers who can promptly make their vehicles available for retrofitting would also be advantageous. The schedules had to be adjusted a number of times to accommodate the customers' requests to have only one truck out of service at a time.

Other areas that could be improved would be in the planning process, specifically determining what customizations the customer wants. One customer requested fiber optics after the retrofit process has already started. The feasibility study cost estimate and purchase of parts for this add-on delayed the process.

Despite the above-mentioned areas for improvement, the retrofit process was a success. All three customers have given positive feedback and would recommend adoption of the plug- in hybrid electric retrofit technology. Fuel and emissions tests conducted by UC Riverside show that the system reduces full-day fuel use by 50 percent or more, reduces GHG emissions by 50 percent or more, and reduces NOx emissions by 80 percent or more.

GLOSSARY

CONTROLLER AREA NETWORK (CAN)—A serial network technology that was originally designed for the automotive industry, especially for European cars, but has also become a popular bus in industrial automation as well as other applications. The CAN bus is primarily used in embedded systems, and as its name implies, is a network technology that provides fast communication among microcontrollers up to real-time requirements.

CALIFORNIA AIR RESOURCES BOARD (CARB)—The "clean air agency" in the government of California whose main goals include attaining and maintaining healthy air quality, protecting the public from exposure to toxic air contaminants, and providing innovative approaches for complying with air pollution rules and regulations.

ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE)—Infrastructure designed to supply power to EVs. EVSE can charge a wide variety of EVs, including BEVs and PHEVs.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA)—A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting, and enforcement activities.

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (NOx), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

KILOWATT (kW)—One thousand watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon, a typical home—with central air conditioning and other equipment in use—might have a demand of 4 kW each hour.

KILOWATT-HOUR (kWh)—The most commonly used unit of measure telling the amount of electricity consumed over time, means one kilowatt of electricity supplied for one hour. In 1989, a typical California household consumed 534 kWh in an average month.

NITROGEN OXIDES (OXIDES OF NITROGEN, NOx)—A general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide (NO2), and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition. NO2 is a criteria air pollutant and may result in numerous adverse health effects.

POWER TAKEOFF (PTO) - Secondary engine shaft (or equivalent) that provides substantial auxiliary power for purposes unrelated to vehicle propulsion or normal vehicle accessories such as air conditioning, power steering, and basic electrical accessories. A typical PTO uses a secondary shaft on the engine to transmit power... to a hydraulic pump that powers auxiliary equipment, such as a boom on a bucket truck. You may ask us to consider other equivalent auxiliary power configurations (such as those with hybrid vehicles) as power take-off systems.

SAN DIEGO GAS AND ELECTRIC (SDG&E)– An electric and natural gas utility serving the San Diego region.[2]

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)—A global association of more than 128,000 engineers and related technical experts in the aerospace, automotive, and commercial-vehicle industries. The leader in connecting and educating mobility professionals to enable safe, clean, and accessible mobility solutions.

[2] San Diego Gas and Electric Homepage (https://www.sdge.com/)

APPENDIX A: ODYNE SYSTEM SPECIFICATIONS

The figure below lists the technical specifications for the Odyne system retrofit project.

Figure 38: Odyne Systems Technical Specifications

	Odyne Systems
Hybrid Configuration	Parallel through the PTO
AER (up to miles)	0
EAER (up to miles)	7.2
Chassis Manufacturer	Ford, International, Freightlines,Kenworth
Chassis Size	Class 6, 7, or 8
Chassis Configuration	RWD
Battery Energy	28.4
Battery Manufacturer	Johnson Controls
Battery Thermal	Liquid-Cooled
Motor Power (kW) Peak	71 @ 2200 rpm
Motor Power (kW) Cont	42 @ 3000 rpm
Motor Torque (Nm)	315 @ 200 rpm
Motor Manufacturer	Remy
Engine Displacement (l)	6.7, 8.9, 9.0, 93, 12.8
Engine Type	Diesel
Engnie Manuacturer	Cummins, Navistar, Detroit Diesel
Transmission Manufacturer	Allison
Export Power (kW)	6 60 hz 120/240 Vac
Charger Power (kW)	3.00
Power Steering	Standard
HVAC	Electric A/C
Heating	Hydronic
Brakes	Standard
Manufacturing Location	Ontario, CA

Source: Odyne Systems