Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck

Final Report
Prepared for:
Dr. James Burns, VP and Chief Scientist, TransPower

April 2015

Prepared by:

Dr. Kent Johnson
Dr. J. Wayne Miller
Mrs. Jiang (Jade) Yu Xiao (PhD. Candidate)

University of California, Riverside
College of Engineering-Center for Environmental Research and Technology
Riverside, CA 92521
(951) 781-5579

Disclaimer

This report was prepared as the result of work sponsored by the TransPower as part of a larger project funded by the California Energy Commission, U.S. Department of Energy, U.S. Environmental Protection Agency (EPA), Port of Los Angeles, Port of Long Beach, and the South Coast Air Quality Management District. The work was performed at UC Riverside on an all-electric on-road truck designed and manufactured by TransPower. As such the report does not necessarily represent the views of any of the participants, the Energy Commission, Department of Energy, EPA, Port of Los Angeles, Port of Long Beach, the South Coast Air Quality Management District or TransPower or their employees. Further the collective participants, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has neither been approved nor disapproved by the collective group of participants nor have they passed upon the accuracy or adequacy of the information in this report.

Acknowledgements

The author expresses appreciation to the following associates who contributed much to the success of the project and the furtherance of knowledge of the performance of an All-electric yard tractor. We very much appreciated the financial support of the California Energy Commission, U.S. Department of Energy, U.S. Environmental Protection Agency, Port of Los Angeles, Port of Long Beach, and the South Coast Air Quality Management District. We appreciate the technical assistance of the following TransPower personnel, Joshua Goldman, and Ameya Jathar in configuring the vehicle for testing and downloading and supplying the information from the vehicle's Electronic Control Module; Frank Falcone for providing project and engineering support for the electric vehicle systems; and Mike Simon for assistance in editing this report. The authors also thank the following UCR personnel Mr. Don Pacocha, Mr. Edward O'Neil, and Mr. Joe Valdez who setup the vehicle, operated the chassis dyno, and drove the vehicle on the dyno. We also would like to recognize Kurt Bumiller for supervising the setup of the power meter on the all-electric vehicle.

Table of Contents

List of Tables

List of Figures

Executive Summary

Heavy duty vehicles (HDVs) are the primary contributor to NOx emissions in the South Coast air basin and represent a large producer of greenhouse gases (GHG). Reductions in both NOx and GHG are of interest to many stakeholders and various programs are funded to reduce these emissions. This study represents a demonstration and evaluation of a Class 8 all-electric HDV designed for drayage operation, with initial demonstrations taking place at the Ports of Long Beach and Los Angeles, California. The evaluation of the vehicle was performed during laboratory testing of cycles designed around drayage operation and during real world drayage operation with commercial fleet operators such as Total Transportation Services, Inc. (TTSI). This report summarizes the laboratory work, and the results of on-road demonstrations will be presented elsewhere.

Performance measurements were made while running the vehicle on the University of California, Riverside (UCR) heavy-duty chassis dynamometer over port related drive cycles, certification-like drive cycles, cycles to simulate sustained during 7% grade operation, and steady state cruise modes. All cycles were performed with the vehicle loaded to an equivalent gross vehicle weight of 72,000 lb. For the lighter duty cycles (near dock port cycle) the vehicle used 2.06 ± 0.04 kWh/mile of energy and for the heavy use cycles (regional port cycle) 2.10 ± 0.01 kWh/mile of energy, where the ± values represent single standard deviations. The vehicle's reported battery energy storage capacity of 215 kilowatt-hours (kWh) was confirmed during the chassis testing and found to be representative. The vehicle batteries are designed to be safely discharged to a 20% state of charge, providing 172 kWh of usable energy. As such, the HDV range was found to be 84 miles for the Near Dock cycle and 82 miles for the Regional cycle, assuming the vehicle was fully charged and fully drained to 20% SOC.

The all-electric HDV produced zero tailpipe hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide, and particulate matter emissions. This is a 100% reduction in all the emissions in addition to NO_x emissions compared to several conventional vehicles tested previously. Additionally, the all-electric HDV showed no performance difference between short and long drayage driving behavior. This suggests that electric HDVs of this design would be great replacements for diesel trucks where significantly higher emissions are being reported due to low exhaust temperature NO_x reduction performance in port applications.

In general the all-electric HDV performed well on all the cycles and showed a very reliable operation from full to 20% SOC load. Steady state tests were also performed that demonstrated the ability of the all-electric HDV to maintain sustained peaks loads without loss of performance, system deratings, or safety concerns in the range of 80 miles at 72,000 lb GVW. The TransPower electric HDV was almost two times more energy efficient than an all-electric HDVs tested at UCR in 2011 over the same cycles. This suggests the current all-electric HDV is a significant improvement in the state of the art HDVs. Additionally the on-road all-electric HDV performance statistics agreed well with the laboratory results, suggesting the laboratory testing was representative and that the overall on-road and laboratory results can be used to draw comparisons to conventional vehicles and other advanced technologies. In general this demonstration suggests that the TransPower electric HDV is a great success for reducing emissions and GHG for the communities in the South Coast air basin.

1 Introduction

1.1 Motivation

The South Coast and San Joaquin Valley are the only two extreme ozone nonattainment areas in the nation for federal ozone standards. Additionally the national ozone standards are being reduced to even lower levels by 2032. Oxides of nitrogen (NO_x) and volatile organic compounds (VOC) emissions are the primary contribution to ozone formation through secondary atmospheric reactions. Reductions in both NO_x and VOCs are of the highest importance to both air basins to meet current and future federal ozone standards. Additionally, reducing carbon dioxide (CO_2) emissions, a greenhouse gas (GHG), has become a National and California interest where goals of 80% reductions are targeted. The primary pathway to achieve this goal, as identified by the California Air Resources Board (ARB) and others, is to accelerate and expand the deployment of electric vehicles of all weight classes.

As such, regulations focused on reductions of NOx and NMHC from combustion sources have been continually reduced. Emissions from heavy-duty on-road vehicles accounted for about one-third of NO_x emissions and one-quarter of PM emissions from mobile sources when stringent emission standards were introduced by the EPA on December 21, 2000 and by the ARB in October 2001. The new standards, shown below, further reduced PM by 90% and NOx by 95% from existing standards.

- PM—0.01 g/bhp-hr
- NOx—0.20 g/bhp-hr
- NMHC—0.14 g/bhp-hr

The PM emission standard took effect in the 2007. However, the NO_x and NMHC standards were phased in for diesel engines between 2007 and 2010 based on the percent-of-sales basis: 50% from 2007 to 2009 and 100% in 2010. The regulation contained other provisions for meeting the NOx requirement, so very few engines actually met the stringent standard of 0.20 g/bhp-hr before 2010. In addition to transient Federal Test Procedure (FTP) testing, the emission certification requirements included: 1) the 13-mode steady-state engine dynamometer test Supplemental Emissions Test (SET) test, with limits equal to the FTP standards, and 2) the not-to-exceed (NTE) emission testing with limits of 1.5 × FTP standards for engines meeting a NOx FEL of 1.5 g/bhp-hr or less and 1.25 × FTP standards for engines with a NOx FEL higher than 1.5 g/bhp-hr.

The implementation of the more stringent standards for heavy-duty highway engines was a key strategic element of the plan for improving air quality in the South Coast Air Quality Management District (SCAQMD). This project focuses on heavy-duty vehicles (HDVs) because HDVs are anticipated to generate about 80% of NO_x emissions in 2014 and about 70% in 2023, as illustrated in Table 1. Focusing on the HDV category with the greatest emissions contribution to the inventory provides the SCAQMD with the most likely path to achieving its goal of 90% reduction in NO_x by 2023.

To the meet the 2023 targets for NOx, it is expected near-zero emissions may be needed for HDVs, requiring electrification of HDVs to play a significant role. Until recently, though, very few all-electric HDVs have been available.

Table 1 Data from the SCAQMD's 2012 AQMP (tons/day)[1]

Code	Source Category	2014	2023
736	Heavy Heavy Duty Gas Trucks ((HHD)	1.02	0.96
746	Heavy Heavy Duty Diesel Trucks (HHD)	76.43	32.63
760	Diesel Urban Bus (UB)	13.4	11.03
762	Gas Urban Bus (UB)	0.76	0.70
772	Diesel School Buses (SB)	2.15	1.81
777	Gas Other Buses (OB)	0.86	0.53
	Total	94.62	47.66

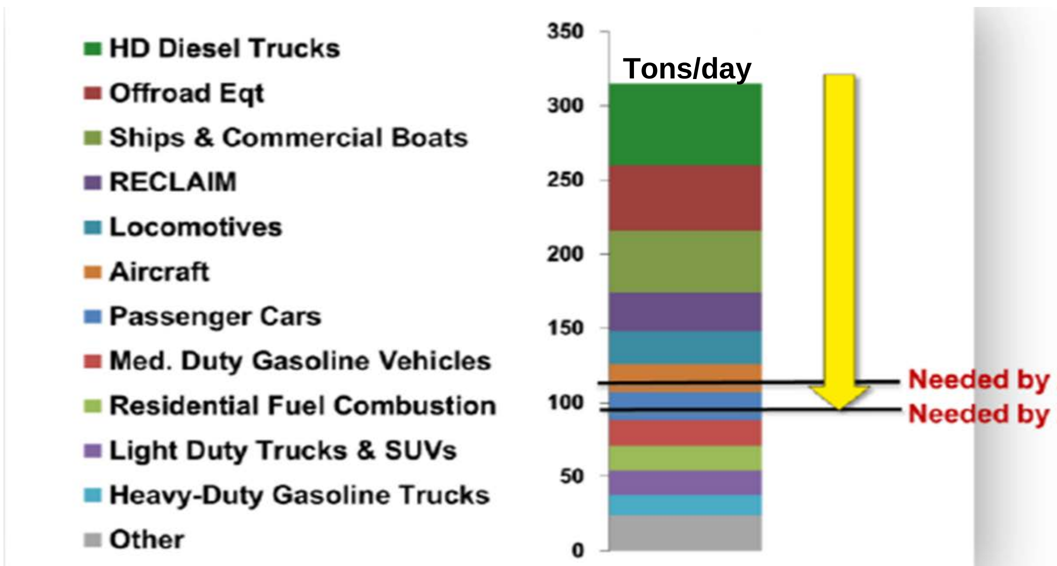


Figure 1: South Coast Air Basin heavy duty NOx inventory and projections [1]

1.2 Low NO_x HDV solutions

There are several HDV solutions to help reduce NO_x pollutants which include advanced after treatment on diesel engines, alternative fueled vehicles, and advanced vehicles. There is currently research funded by the ARB to further reduce NOx emissions by another 90% with diesel SCR technology, to an emission level of 0.02 g/bhp-hr. The SCAQMD, ARB, and California Energy Commission (CEC) are funding several natural gas low NO_x solutions designed to reach 0.02 g/bhp-hr NOx emissions. Some recent presentations at SCAQMD have shown that early versions of the advanced natural gas three way catalytic (TWC) controlled HDV solutions can already achieve the 0.02 g/bhp-hr NO_x emission level. Additionally there are some hybrid diesel configurations that are designed to achieve lower NOx emissions, but these have shown slightly higher NOx emissions in many cases.

[1] *South Coast Air Quality Management District 2012 Air Quality Management Plan AQMP, February 2013*

One solution that promises zero NO_x emissions is an all-electric HDV. Several all-electric vehicles have been demonstrated, but few in the Class 8 category, which encompasses vehicles with gross vehicle weights from 33,000 to 80,000 lb. Class 8 all-electric HDVs produce no local NO_x emissions, and with renewable power sources, these all-electric HDVs produce zero emissions and greenhouse gases (GHG) over the full cycle of the fuel supply (zero "well-to-wheel" emissions).

1.3 Project objective

The project was viewed as an advanced technology demonstration and evaluation program aimed at reducing emissions and GHGs for drayage port-related HDVs. As part of the project, vehicle performance of the all-electric HDV was evaluated and compared with previously tested conventional HDVs operated on port drayage cycles. This report summarizes the approach, results, and conclusions from this all-electric HDV demonstration and evaluation project.

2 Experimental Approach

This section describes the experimental approach for the project. The approach is organized into six sections 1) vehicles specifications, 2) demonstration facility, 3) testing approach, and 4) data analysis.

2.1 Vehicle specifications

The TransPower specifications for their all-electric port drayage HDV are presented in Table 2. The table shows that the all-electric version of the HDV has a total peak power rating of 300 kW, which is within the specifications of conventional diesel and natural gas engines, which have ranged from 260 to 335 kW for the units tested previously at UCR. Conventional drayage HDVs using natural gas are typically are rated at the lower end of the power specification (260 kW) and diesel HDVs are typically rated at the higher end (335 kW). The curb weight of the TransPower electric HDV is presently about 5,500 lb heavier than a conventional diesel HDV, so the comparable operational load will be slightly higher for the all-electric in comparison to the conventional HDV. Additionally the all-electric HDV will have a slightly lower averaging towing capacity compared to the conventional HDV, due to this added weight.

Table 2 Specifications of TransPower All-electric On-Road Class 8 Truck

Description	Specification
Vehicle Curb Weight (lb)	22,000 (~5,500 lb > conventional)
Towing Capacity (lb)	58,000
Motor Power Rating (kW)	300 (260 – 335 kW conventional)
Automated Manual Transmission	10-speed transmission, of which 5 speeds are used for most duty cycles
Energy Stored (kWh)	215 maximum, 172 usable (20% reserve)
Drive Motor	200 kW continuous, 300 kW peak
Inverter/Charger	Two units, each supply 150 kW continuous to drive motors. One is used for conductive battery charging at up to 70 kW using 208 VAC, 200A 3-phase grid power
Batteries	358 VDC, 600 Ah cells. 215 kWh total, 172 kWh usable
Recharge Time using onboard charger (hrs)	<3 hours from 20% to 95%
Loaded Range (Miles)	80 based on 2.0 kWh/mi (400 mi conventional at 4 MPG and 100 gal tank)
Exhaust Emissions	Zero at point of use (not zero conventional)

2.2 Demonstration

The all-electric HDV was designed for operation by commercial drayage operators located near the Ports of Long Beach and Los Angeles in the SCAQMD air basin. The drayage company selected for this demonstration was Total Transportation Services, Inc. (TTSI), a company engaged with sustainable freight solutions that include 57 liquid natural gas HDVs and the world's first hydrogen/electric powered HDV. TTSI operates a fleet of Class 8 drayage trucks with round-trip operating distances ranging from less than 20 miles to as much as about 200 miles. A key issue facing drayage trucks entering the ports is the long wait times often required to access terminals where HDVs spend large percentages of their time idling or operating at very low speeds. TTSI has proposed building a hub at the Ports that would use a large number of trucks to ferry containers from various port terminals to a central location within 1-2 miles of every terminal. Electric HDVs are viewed as providing an effective alternative to conventional diesel and natural gas trucks due to their anticipated performance and emissions reductions benefits. These short routes are within the limitations of current battery technology where validation of this hypothesis was considered as an additional goal of the testing performed under this project.

2.3 Laboratory testing

This section discusses the tools used to load the HDV and the types of duty cycles simulated for the overall vehicle performance evaluation.

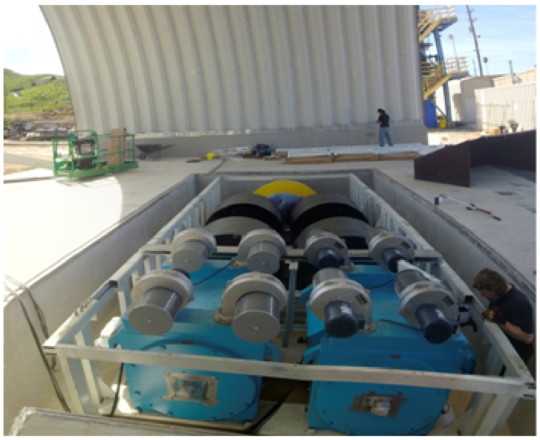
2.3.1 Chassis dynamometer

Dynamometers ("dynos") are essential equipment for the accurate measurement of emission factors. These very useful tools are designed to measure torque and rotational speed (rpm) from which the power produced by an engine can be calculated from the product of torque (τ) and angular velocity (ω) values or force (F) and linear velocity (v). Dynamometers come in various configurations. A dyno directly coupled to an engine is known as an engine dyno. An engine dynamometer measures power and torque directly from the engine's crankshaft (or flywheel) and does not need to account for power losses in the drive train, such as the gearbox, transmission or differential as the engine values are directly measured. An engine dyno can either be a power absorbing or motoring type. The power absorbing-type is limited to steady-state cycles while a dyno with a motoring design can test either steady-state or transient cycles.

A dyno that measures torque and power delivered by the power train at the wheels of a vehicle without removing the engine from the vehicle is a chassis dyno. With a chassis dyno, the vehicle operates with its wheels on rollers, where the output power from the engine is measured. While engine dynamometers provide the most accurate results of an engine operation, a chassis dynamometer is often the most practical approach as it measures the power and torque of an engine without removing the engine, thus saving time and money. The main issue with the chassis dynamometer is that the measured power and torque at the wheels is less than the values at the engine flywheel (e.g. brake horsepower), due to the frictional and mechanical losses in the various components. For example, drive train transmission, gearbox, and tire friction are all factors that need to be considered. The rear wheel brake horsepower is generally estimated to be 15-25 percent less than the brake horsepower due to frictional losses. Fortunately, many current engines have an Electronic Control Module that is calibrated by the engine manufacturer to report brake power, enabling measurement of power both at the wheels and at the fly wheel.

HDVs are generally certified by having their engines tested on an engine dynamometer prior to being installed on a vehicle chassis. More recently, regulatory agencies have moved from this type of engine dyno testing to measurements based on emissions during actual work cycles. Although these new in-use regulations require vehicle compliance on-road, performing on-road tests is difficult and not reproducible. Chassis dynamometers are used for certification of light duty vehicles and are a common tool for research on in-use HDVs.

Testing of the TransPower electric HDV was carried out on UCR's Heavy Duty transient dynamometer (see Appendix B for additional details). The dynamometer is designed to handle a range of vehicles and vehicle loads at on-road driving conditions. It includes a 48" Electric AC Chassis Dynamometer with dual, direct connected, 300 horsepower motors attached to each roll set with a base inertia of 45,000 lb with the addition of a large flywheel. The dynamometer applies appropriate loads to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving. A driver accelerates and decelerates following a driving trace while the vehicle is chained to the dynamometer. Figure 2 provides a photo of this dyno facility, along with summary data.



- Performance
  - 5,000 lb 0-15 mph
  - 600 hp 45-80 mph
  - 200 hp 15 mph
- Acceleration 6 mph/sec
- Inertia Simulation
  - 10 lb increments
  - 10,000 lb – 80,000 lb range
  - 45,000 lb base inertia
- Speed accuracy +/- 0.01 mph
- Acceleration accuracy +/- 0.02 mph/sec
- Response time 44 to 100 ms

Figure 2 Selected Data for UCR HDD Chassis Dyno

2.3.2 Test cycles

Four main cycles are considered as part of this testing, 1) the sustained grade cycle, 2) the simulated drayage truck port cycle, 3) the urban dynamometer driving cycle (UDDS), and 4) a charge depleting cycle. Each of these cycles provides an important metric for the safety, performance, and modeling characteristics for on-road operation of all-electric HDVs. The sustained grade test is to ensure that electric HDVs can operate over steep bridges safely, while maintaining observed speed limits. The port cycles were designed to accurately simulate the duty cycles of typical port drayage trucks, based on a 1,000 HDV drayage truck data logging study at Ports of Los Angeles and Long Beach during a four-week time period in 2010. In essence, the port cycles are designed to mimic operation near congested port centers like the Ports of Long Beach and Los Angeles (see Appendix C for more details). The UDDS cycle is designed to relate to the engine certification test and to draw comparisons to the large data base of heavy duty diesel vehicles, and the charge depletion testing is to understand range and other vehicle specific capabilities that can be cross compared between other all-electric HDV tests.

Table 3 provides summary information on the test setups for each of these driving cycles. The chassis dynamometer simulated load was estimated at 128.6 hp at 50 mph with a test weight of approximately 72,000 lb, which is representative of the average fully loaded weight of a drayage truck supporting the Ports of Long Beach and Los Angeles. Testing at these repeatable cycles provide comparability between different electric vehicle systems to evaluate benefits and dis-benefits for different approaches. Ultimately, the data from such testing can be used to provide a basis for all-electric HDVs performance and to document lessons learned to improve all-electric HDV systems. The test cycles are provided in detail in Appendix A and the calculation methods for the dyno calculation coefficients are provided in Appendix C.

Table 3 Chassis dyno setup, cycles, and test weights utilized

Test Cycle Full Name	Short Name	HP @ 50	Test Weight [2]	A	B	C
Grade test	Grade	128.6	71960	511.09	2.83E-15	0.1814
Urban Dynamometer Driving Schedule	UDDS	128.6	71960	511.09	2.83E-15	0.1814
Regional Port Cycle - complete	DPT3	128.6	71960	511.09	2.83E-15	0.1814
Phase 4 Drayage Port Cycle	DPT_4	128.6	71960	511.09	2.83E-15	0.1814
Phase 3 Drayage Port Cycle	DPT_3	128.6	71960	511.09	2.83E-15	0.1814
Phase 1&2 Combined Drayage Port Cycle	DPT_1&2	128.6	71960	511.09	2.83E-15	0.1814
Steady state 55 MPH cruise	Cruise	128.6	71960	511.09	2.83E-15	0.1814

[1] Test cycles represent full or partial cycles to reduce test time. Full cycle comparison is completed by combining phases of the individual cycles. See Appendix D for combined results.
[2] Test weight of 721960 lb are the baseline loads for the port cycles tested. The electric vehicle was ~5,500 lb heavier than the conventional so the utilized test weight was 66,460+5,500 or 71,960 lb.

2.4 Analysis

The analysis included data collection, time synchronization, and calculations for power and energy from various systems. This section summarizes some of the details of the data collection and calculations used in this report. For a more detailed discussion, please see Appendix C.

Data collection: Four data files were utilized for the processing of the data provided in this report. These include:1) chassis dyno load and speed information, 2) electric power meter systems, 3) vehicle CAN network system, and 4) hand logs on test observations. The chassis data includes dyno roll speed and absorbed, acceleration, and frictional torque/force/hp measurements. The electric power measurements include current, voltage, and integrated power with a Hioki 3390 precision power meter. The vehicle CAN network was sampled using TransPower-provided data logging systems that included vehicle performance and battery performance CAN channels. The engine control unit (ECU) data downloaded by TransPower was provided to UCR in Excel spreadsheets and analyzed as part of this report. The hand logs included information available to the driver which included the odometer, state of charge (SOC), and any warning indicator lights available to the driver.

Time synchronization: The dyno file reports the distance in miles, speed in mph, and other dyno information relative to time in one second intervals from the beginning of the test run. The data from the ECM is recorded approximately every 1014 ms based on CAN signal rates from ECM systems. As such, the chassis and vehicle CAN files are not aligned by row, but can be aligned by time. Therefore, to ensure that the data is analyzed relative to what the dyno is commanding, the vehicle CAN signals require additional analysis. Thus, the figures presented in the results section are plotted on a time basis to prevent issues in data comparison. The accumulated energy results were calculated on a second-by-second basis, where the difference in time for each segment was utilized. For details on the equation, please see Appendix C.

Vehicle CAN power: The vehicle CAN power calculations were performed based on the product of measured DC current and DC voltage. The vehicle CAN current measurement included direction where drive current is energy from the battery and regen current is energy to the batteries (regeneration). The column of data that provided the CAN current was labeled "ESSCurrent". The voltage was available from several difference sources. There were three voltage terms available from the vehicle CAN system. These were the "StackVoltage", "ICUDCVoltage", and "act_DCBusVoltage_14". The "StackVoltage" agreed best with UCR's measurement during transient tests and was used as voltage measurement for the power and energy calculations performed on this HDV vehicle. The calculation of vehicle CAN power was performed on a second-by-second basis using the following formula:

$$\textit{Vehicle CAN Power}_{\,i} = \sum ESSCurrent_i * StackVoltage_i$$

Where:

Vehicle CAN Power	is the instantaneous vehicle CAN power consumption at time *i*, where drive power is the current consumed by the vehicle and regen power is current recovered (regenerated) by the vehicle.
$ESSCurrrent_i$	is the instantaneous vehicle CAN current usage at time *i*
$StackVoltage_i$	is the instantaneous vehicle CAN voltage at time *i*

Vehicle CAN State of Charge: The vehicle SOC represents the vehicle status and is a relative parameter and is dependent on each manufacturer's claims for range and usage and thus may vary by manufacturer due to their utility of the battery systems. Thus, SOC is a generally calculated value, but is still a reasonable metric for the status of the vehicle and when re-charging is needed. The SOC was provided by the vehicle using two methods. One method was the measurement of SOC from the vehicle CAN reporting system and the other was utilizing the display of SOC to the driver. In general, both the ECM-reported value and the visual display were in agreement, suggesting that the SOC-reported data represents the overall status of the vehicle.

Hioki power and energy: The Hioki power system is a very accurate power meter, as described in more detail in Appendix E. The Hioki system measured voltage and current in real-time and utilized internal power calculations at high sample rates and provided power and energy output. The results presented in this report utilize the results provided by the Hioki system.

Chassis absorbed and regenerative measurements: The chassis dynamometer measures torque absorbed by the AC motors, friction torque, and acceleration energy torque from the inertial loads. If we consider an energy balance around the vehicle and the chassis dynamometer, the energy and power absorbed by the chassis dynamometer can be used as a metric for evaluating vehicle supply efficiency and vehicle regeneration (recovery) efficiency. A detailed explanation of the chassis power calculations are provided in Appendix C.

Vehicle efficiency: The vehicle regeneration efficiency and the drive efficiency are considered in this report. The regeneration efficiency is a percentage of total recovered energy of the chassis dyno divided by energy delivered to the batteries as measured by the Hioki system (chassis_regen/Hioki_regen). The drive efficiency is the total energy absorbed by the chassis dyno (accumulation of positive power and no breaking power) divided by the vehicles supplied battery power (Chassis_drive/Hioki_drive).

3 Laboratory Results

This section discusses the results of the heavy duty all-electric HDV during transient and steady state chassis dynamometer testing. The results are organized into three main subsections: 1) real-time transient, 2) real-time steady state, and 3) integrated. The real-time results are presented on a second-by-second basis to consider peak performance and other real-time observations. The integrated results are presented to consider the overall HDV's performance and comparison to previous UCR studies which include several conventional HDVs which include 2007-2009 and 2010 certified engines. The comparison results include a discussion of the energy usage, costs, and fuel economy while operating on cycles designed at mimicking operation near congested port centers like the Ports of Los Angeles and Long Beach.

3.1 Real-time transient

The real-time power, energy, SOC, and accessory loads are presented in this section. These results are presented to show typical loads and energy usage over time for the all-electric HDV.

3.1.1 Power

The power measured by the chassis dynamometer, vehicle CAN, and Hioki measurement systems are shown in Figure 3 and Figure 4 for a portion of the Near Dock and Regional cycles, respectively. The peak power during the phase 1 and 2 of the Near Dock cycle peaked at around 150 kW and averaged very low during driving conditions at 25 kW. During the Regional cycle the peak power and drive power were much higher at 300 and 100 kW respectively. The power during the Near Dock and Regional cycles were about 25% and 50% of the vehicle's rating and 50% and 100% of the maximum rating, see Table 2. The power consumed during zero vehicle speed was low and is representative of accessory loads. The accessory loads were approximately 1.13 kW.

The vehicle power showed a larger drive value than the chassis wheel power during loaded/acceleration conditions and a smaller regen value during deceleration (braking) conditions. During drive power (acceleration) conditions, energy is supplied from the vehicle batteries to an inverter, two permanent magnet AC motors in tandem with a common shaft, automated manual transmission, drive shaft, rear differential, and then finally to the vehicle wheels. During regen power (braking conditions) the kinetic energy stored in the chassis dynamometry is supplied to the vehicle batteries for energy recovery (regeneration). Thus, the chassis dynamometer measures the drive power supplied from the vehicle wheels during acceleration and a maximum potential regenerative capacity during braking. Differences between the vehicle and chassis drive power can be viewed as overall vehicle efficiency and regen power differences represent the regeneration efficiency. A more detailed analysis of the drive power losses from the electric vehicle is presented in the next section during steady-state mode tests. An analysis of the transient efficiencies is presented on a cycle average bases in Section 3.3.

The regen chassis power peaked at -100 kW for the Local cycle and approximately -300kW for the Regional cycle. In general, the regen power was less than the drive power, suggesting the energy to move the vehicle is less than regenerative as would be expected due to losses in the vehicle drive system.

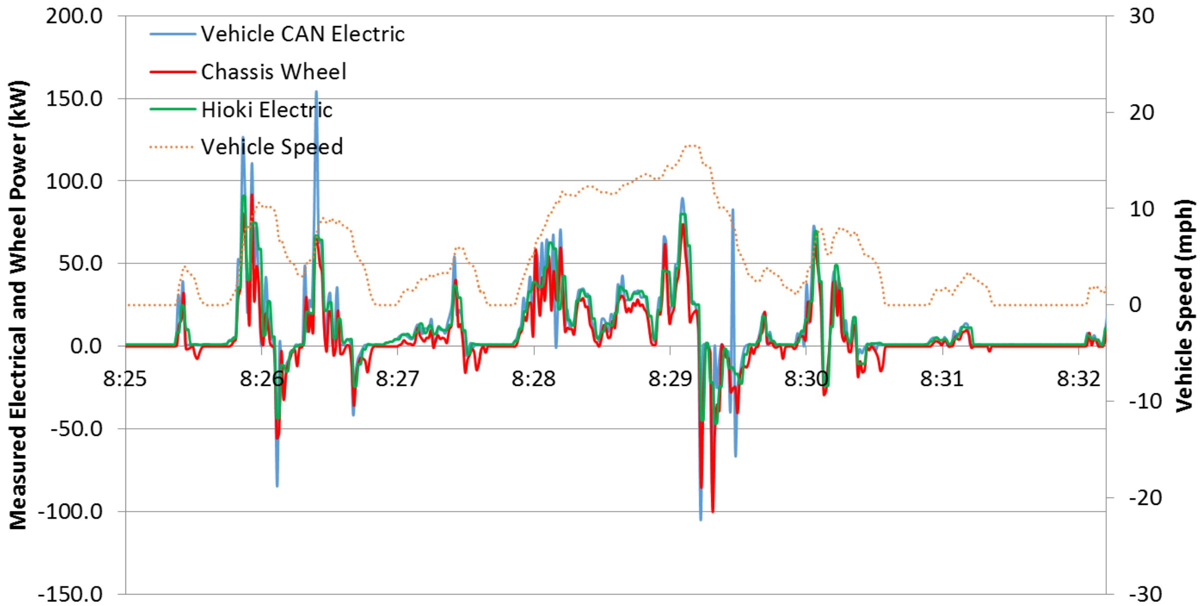


Figure 3 Real-time power measurements for a portion of the near dock port cycle

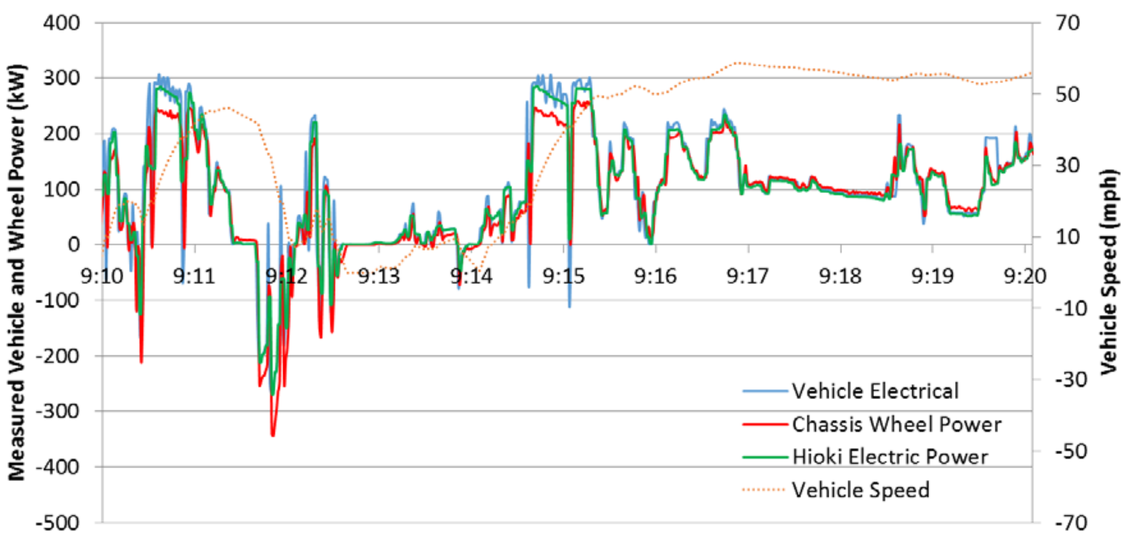


Figure 4 Real-time power measurements for the regional port cycle

3.1.2 Energy

The real-time energy accumulation is shown in Figure 5 for phases 1 and 2 of the Near Dock cycle (ie not phase 3, see Appendix D for details) and Figure 6 for the Regional cycle. The figures show the drive and net chassis dynamometer energy and the net electric energy measured during testing. The chassis net energy is the sum of the absorbed and motored energy measured/calculated by the chassis dynamometer and the vehicle net energy is measured by the Hioki and Vehicle CAN system as described in Section 2.4 and Appendix C.

The Hioki net energy for the NearDock cycle was 1.7 kWhr and for the Regional cycle it was 57 kWhr. The vehicle CAN net energy for phase 1 and 2 of the Near Dock cycle was slightly lower than the Hioki net energy but was higher for the Regional cycle. Although there are differences in the accumulated energy the average percent difference was small and within 1.5% for the lightly loaded Near Dock cycle and 2% for the heavy loaded Regional cycle. The largest bias was found for the grade test where differences of 3.4% were reported. These differences are small, suggesting the energy measurement system from the HDV is accurate and reasonable for in-use characterization at the 5% level.

The chassis drive energy (energy absorbed during accelerations and cruise only) was lower than the Hioki net energy for phase 1 and 2 of the Near Dock cycle but higher than the Hioki net energy for the Regional cycle at 1.14 kWhr and 62.5 kWhr, respectively. The higher chassis drive energy for the Regional cycle compared to the Near Dock may be a result of the higher sustained loads and large energy recovery during the 60 to 0 mph braking event. Additional investigation of the chassis power measurements and frictional loads are being considered to help explain this difference.

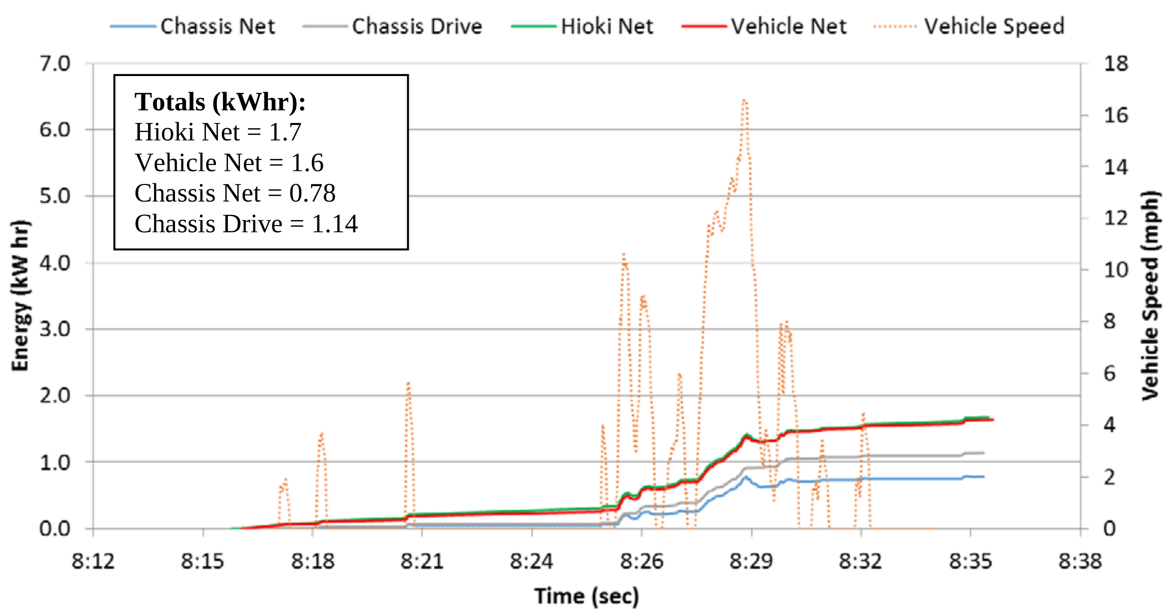


Figure 5 Real-time energy accumulation results for Ph1&2 of the NearDock port cycle

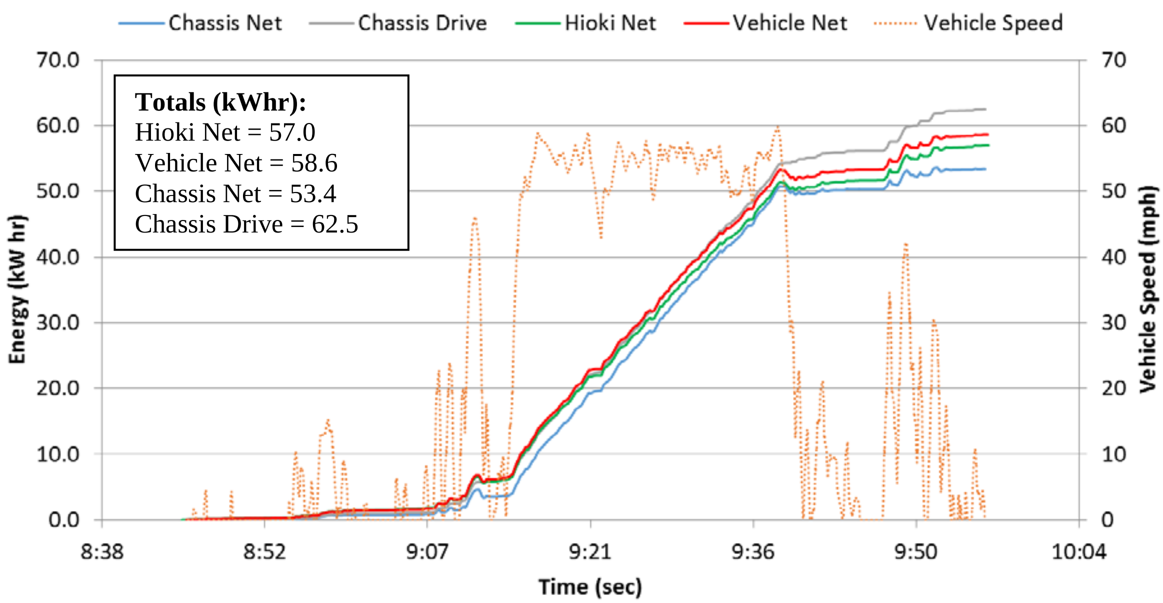


Figure 6 Real-time energy accumulation results for the regional port cycle

3.1.3 SOC

The vehicle CAN real-time SOC was evaluated on the medium transient cycle to quantify the amount of charge used during a transient cycle. Figure 7 shows the real-time SOC plotted on the primary y-axis and the net difference of the accumulated energy (Hioki measurement) on the secondary y-axis. The SOC started at 70% and ended at 43% for a total difference of 27% for the Regional port cycle. The SOC and Hioki net energy real-time measurements showed very similar trends, as illustrated in Figure 7. The close agreement between SOC and Hioki energy usage suggests the vehicle SOC is accurately accounting for the vehicles energy usage.

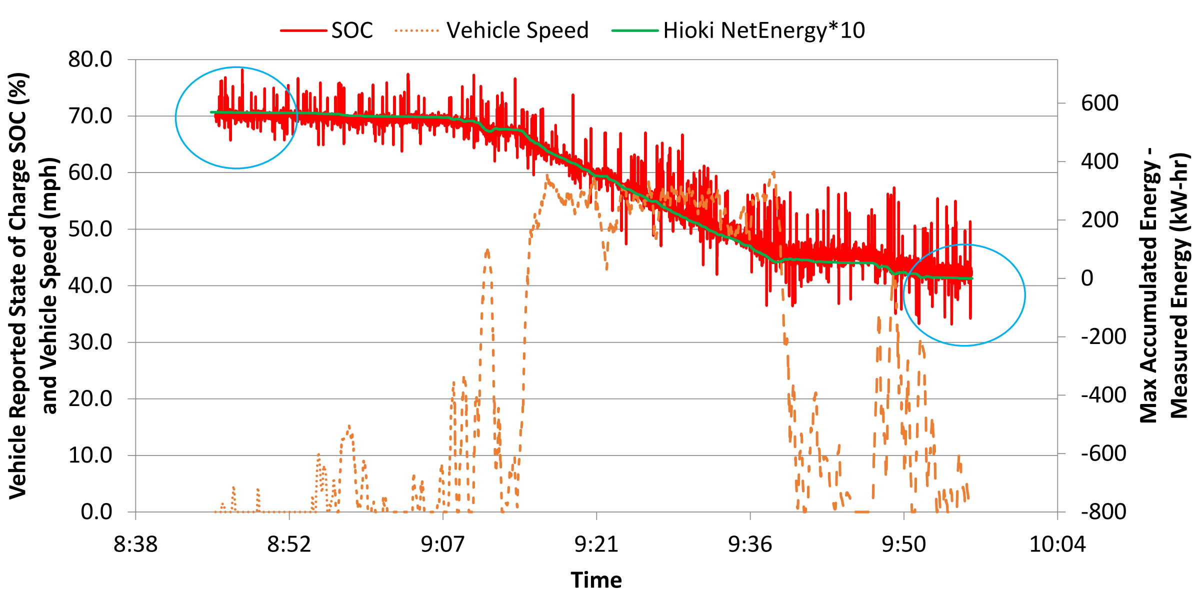


Figure 7 SOC and energy consumption measurements the regional port cycle

[1]This figure shows the energy consumption of the Hioki power measurement system and the vehicle can system by the formula of max accumulated energy – measured value. This approach allows a comparison between the SOC calculation and the measured energy.

3.1.4 Accessory loads

The accessory loads were estimated from the slope of various transient cycles during periods of zero vehicle speed. Figure 8 show a segment of Regional port cycle trace where the vehicle speed was zero and a best fit regression line is plotted. The slope in Figure 8 is 27.1 with an R^2 of 0.9992 where the units of the slope are kWhr/day. Analysis of other cycles showed similar slopes, thus, 27 kWhr/day (1.13 kW) represents the estimated nominal accessory load measured during testing. It is excepted accessory loads will be larger during in-use testing where the vehicle's air conditioner (AC) may be operated. Table 4 shows the AC estimated load during zero vehicle speed operation. The AC appears to utilize 1.09 kW at approximately 68% duty cycle. Thus if he AC was operated for 1 hr this would equate to 1.09 kWhr of total energy where the AC was toggling on and off at a duty cycle of 68%. This is expected to increase the overall zero speed power usage to 2.22 kW where the true energy impact would depend driver demand.

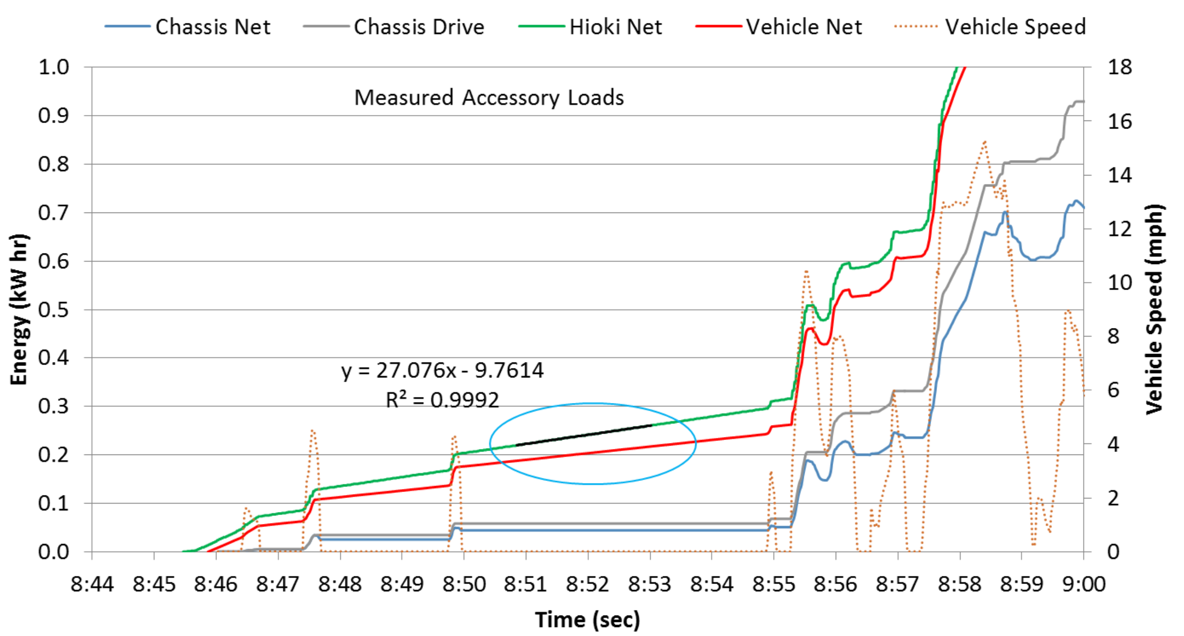


Figure 8 Real-time energy accumulation measurements the Regional port cycle: detail

Table 4 Air conditioning load estimation

Total Seconds	842.639	s
AC On Seconds	576	s
% On	68%	
Average Power when Off	-0.52	kW
Average Power when On	-2.12	kW
Net Power when On	-1.60	kW
Duty cycle adjusted power	**-1.09**	**kW**

3.2 Steady state power

General loaded performance and vehicle efficiency (i.e. the percent power that is delivered to the vehicle wheels) are important for understanding overall improvements and comparisons between different vehicle designs. Drive power efficiency of the electric vehicle propulsion system is difficult to evaluate with transient tests due to the energy recovery design of electric vehicles. In this section we evaluate steady state tests to consider only the drive energy absorbed by the chassis dynamometer during steady state mode testing. Steady-state tests were performed during the sustained grade tests and the charge depletion 55 mph cruise tests.

3.2.1 Performance and grade

One of the recommended tests performed for this project was a simulated grade test. The purpose of the simulated grade test was to evaluate the all-electric HDVs capability to maintain a loaded condition while operating over a cycle designed at simulating crossing the Vincent Thomas Bridge. The bridge is unique to operation in the port of Los Angeles/Long Beach and is part of normal port activity. This bridge has a steep approach grade of 7% and a total span of 6,060 feet. It is important to learn that the new vehicle technologies can cross the bridge with a full load (GVW = 80,000 lb). The bridge is the 4th longest suspension bridge in the world and is relatively high mid span (365 ft) to clear vessels in the navigation channel. Figure 9 shows the real-time speed and power loads for the chassis and Hioki and Vehicle CAN electrical measurement systems while performing the simulated grade cycle. The vehicle approached the bridge at 55 mph then was lugged down to near maximum power of 300 kW where a sustained load of 232 kW was achieved. Loads averaging more than 77% were sustained for approximately 9 minutes for approximately 6 miles which was well beyond the demands of the Vincent Thomas Bridge.

In general the all-electric HDV sustained near full load (77%) for approximately 9 minutes (6 miles) without any deratings, overheating, or other vehicle performance degradation. This suggests the all-electric vehicle is capable of safely operating over the Vincent Thomas Bridge.

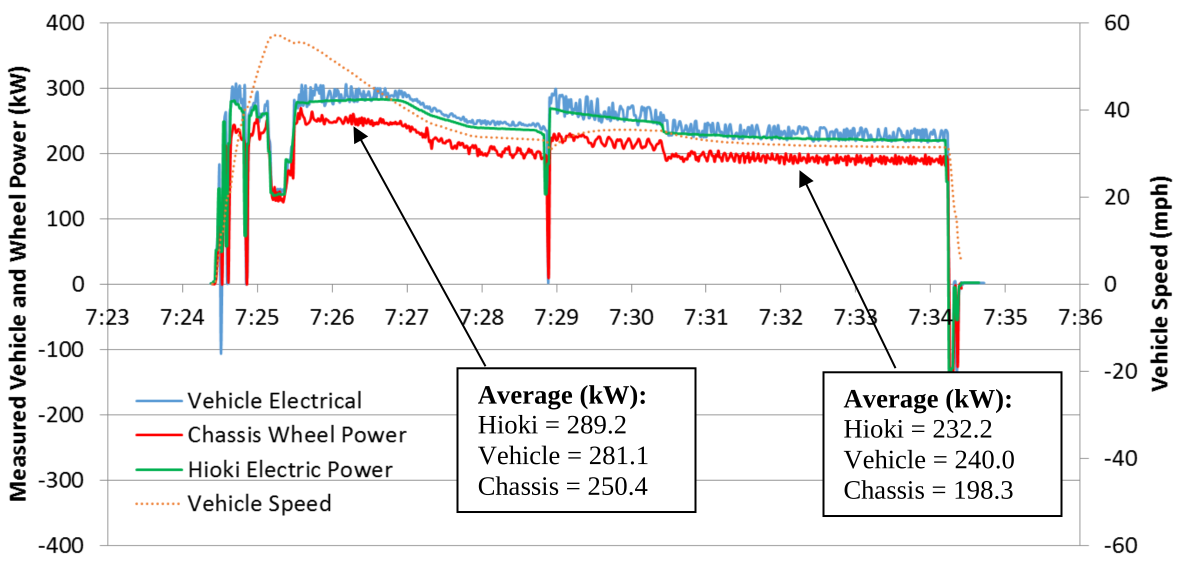


Figure 9 Steady state grade test real time power measurements

3.2.2 Efficiency

The initial power for the vehicle (Hioki and CAN systems) were 289 and 281 kW, respectively, where the chassis absorbed power was 250 kW. For the lower power points the loads were 232, 240 and 198 kW, respectively. The chassis absorbed power was 13% and 17% lower respectively. These differences may represent possible losses in the drive system from the batteries to the wheels. Unlike conventional vehicles it is expected all-electrics may show variations in energy efficiency with vehicle speed (ie motor speed) and not load. As such, it is recommended for future testing of electric vehicles to be operated at constant load while varying motor speed (which will depend on transmission selection). This future investigation will allow a more complete evaluation of all-electric vehicles to further advance the state-of-art all-electric HDVs.

3.2.3 Cruise loads

The steady state 55 mph cruise test was performed at a GVW of 72,000 lb for approximately 20 minutes which equated to a distance of 20 miles. The average load at cruise speeds were 110 kW where some fluctuation of load was noticed between 90 and 110 kWh, see Figure 10. During this test, approximately 23 % SOC was utilized. In general the all-electric vehicle performed well during the loaded cruise testing without any deratings, overheating, or other vehicle performance degradation.

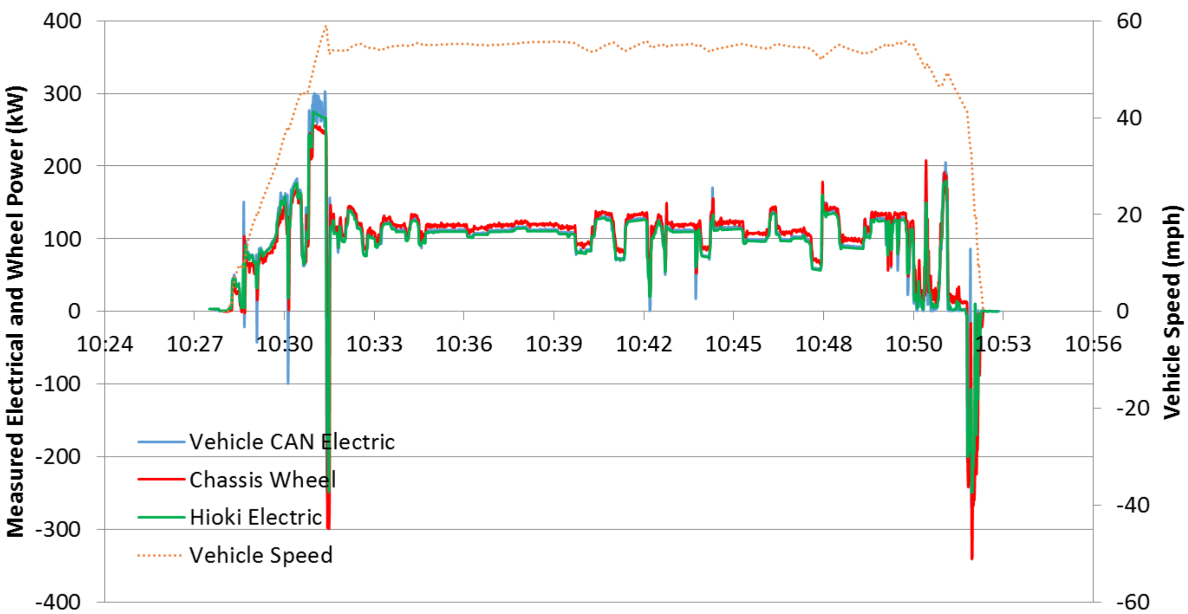


Figure 10 Steady state cruise conditions during charge depletion testing

3.3 Integrated

The overall results for the electric vehicle are presented in this section to provide context for expected average in-use operation and to provide analysis and comparisons to other vehicles to understand the benefit of an all-electric HDV. The analysis includes four main parts 1) energy performance and efficiencies, 2) SOC, 3) vehicle charging, and 4) past comparisons. The first two sections presents the overall drive, regen, and net energy usage on a per mile bases for the steady state and transient tests. The next section considers the energy usage as a function of

SOC with the goal in answering the question "Is the performance of the vehicle different between a full and low battery system?" The next section discusses the vehicle charging results. The final section considers the comparison to past vehicles which includes energy usage, costs, and fuel economy.

3.3.1 Energy usage

As discussed previously, the net energy is the energy used to drive the vehicle plus the energy recovered during braking. This sub-section presents the results for the energy rate on a per mile basis and in the next sub-section the performance of the drive and regen energy is presented.

Table 4 summarizes the results from the various simulated tests cycles. The results include average speed, test duration, distance, average power usage, energy usage, and SOC status. The average speed varied from 6.61 mph to 50.17 mph for the Near Dock and Cruise cycle, respectively. The test duration ranged from 507 seconds at 7% grade to 4,231 seconds for the Regional cycle (just over an hour and ten minutes). The average power was lowest for the Near Dock cycle had highest for the 7% grade test at 12.7kW to 200kW, respectively. The SOC usage increased with increasing distance as would be expected. The SOC usage for the Near Dock operation averaged 5.23 SOC, Local at 9.19 SOC, and 27.52 SOC for the regional cycle. This suggests up to three regional trips or one regional round trip could be performed with-in the capacity of the electric HDV. In total, 88.11% of the battery subsystem's available energy was used to run these tests, covering a simulated total of 73.5 miles.

Table 5 Test result summary of transient and steady state tests

cycle	Ave Speed	Duration	Distance	Ave Power	Net Energy	Total Energy Usage	SOC usage
n/a	mi/hr	sec	mi/cycle	kW	kWhr	kWhr/mi	%
NearDock	6.61	3051	5.6	12.7	13.85	2.06	5.23
Local	9.53	3367	8.9	21.8	23.85	2.09	9.19
Regional	23.39	4231	28.1	45.8	65.00	2.10	27.52
UDDS	19.13	1061	5.6	53.8	17.35	2.42	6.28
7% Grade	34.39	507	4.9	200.5	32.91	7.01	16.55
Cruise	50.17	1461	20.4	102.8	41.00	1.96	23.34

Figure 11 shows a graphical depiction of the energy use of the TransPower electric HDV, expressed in kWh per mile, for each of the six drive cycles tested. Again, these tests were all performed with the truck loaded to an equivalent gross vehicle weight of 72,000 lb, roughly representative of the average fully loaded weight of a drayage truck supporting the Ports of Long Beach and Los Angeles. The total energy usage was similar between the Near Dock cycle and the Regional cycle at 2.06 to 2.10 kWhr/mi (~1% range) suggesting the energy rate per mile is not a function of average power during port driving behavior. This is an interesting statement since for fixed size class 8 conventional HDVs energy usage per mile increases as average vehicle speed (ie average power) is reduced. The all-electric HDV energy usage per mile was higher, though, for the UDDS cycle in comparison to the port cycles. This is also interesting since the UDDS cycle is designed to represent the chassis version of the HDV engine certification cycle. Additional investigation is needed to understudy why the certification like engine cycle would show a higher energy per mile usage rate. It may have to do with the kinetic energy differences between the cycles. The grade test showed the highest overall energy consumption of 7 kWhr/mi.

During previous testing of a 2011 version of electric HDV by a different manufacture, the Near Dock energy consumption was 3.97 kWh per mile and the UDDS energy use was 4.39 kWh/mile. The current electric HDV is showing a reduction in energy usage of 48.1% and 45.9%, respectively for the Near Dock and UDDS transient cycles. TransPower attributes these energy efficiency improvements to several factors, including the mechanical efficiency of its automated manual transmission, the electrical efficiency of its inverter-charger unit and electrically-driven accessories, and the effectiveness of its battery management. These improvements could only be captured during chassis testing where like conditions can be controlled and repeated. The reported improvements show the importance of laboratory testing and suggests future all-electric HDV should be evaluated during similar performance tests.

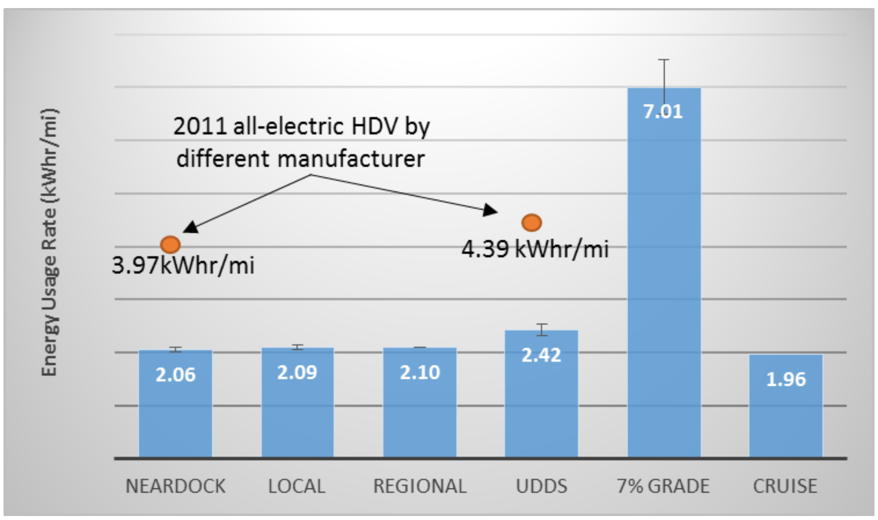


Figure 11 Integrated energy consumption all cycles

[1] Error bars represent standard deviation (1 stdev). Red dot represents the energy usage during testing on the local port cycle during previous testing of a 2011 Class 8 all-electric HDV designed for drayage operation by a different manufacturer.

3.3.2 Energy performance

As presented in the experimental section, the drive energy is energy supplied by the vehicle and regen energy is supplied back to the vehicle from the chassis dynamometer (ie the recovered energy). An analysis of these energies provides the reader a feel for the overall efficiency of the electric vehicle and the ability of the vehicle to do work. This section discusses these different energy sources and presents the overall performance of the HDV.

Regen energy: Table 6 provides detail on the energy measurements summarized for the drive, regen, and net energy for the chassis and vehicle measurement systems. The vehicle recovered 2.46 kWhr and 6.95 kWhr of energy for the full Near Dock and Regional cycles, respectively, as measured from the Hioki power meter. This represents an overall energy recovery efficiency of 22% and 12%, respectively for each cycle as listed in Table 6. The UDDS cycle showed the highest energy recovery efficiency, but also the highest energy usage rate as discussed previously.

Drive energy: The drive energy averaged 13.85 kWhr for the Near Dock cycle and 65.0 kWhr for the Regional cycle as measured by the Hioki system. TransPower's vehicle CAN network system produced measurements that were slightly higher, but often differing by less than 1%. The chassis drive energy was suspicious and thus is not presented here, but is available in Appendix D. The energy recovered for each of the transient cycles varied from 6.95 kWhr to 2.46 kWhr where the Regional cycle showed the highest energy recovery and the Near Dock the lowest as would be expected. The energy recovery efficiency (hioki/chassis) averaged 74% for the four transient drive cycles and varied by only 1-2%.

Table 6 Test results energy analysis for the transient and steady state results

	Chassis			Hioki Measurment			Vehicle Measurment			Overall Efficiency [2]	
cycle	Drive [1,3] Energy	Net [1] Energy	Regen [1] Energy	Drive Energy	Net Energy	Regen Energy	Drive Energy	Net Energy	Regen Energy	Regen	Drive [3]
n/a	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	%	%
NearDock	-	7.77	3.37	13.85	11.39	2.46	14.03	11.56	2.47	73%	-
Local	-	13.57	7.18	23.85	18.54	5.31	24.73	18.71	6.02	74%	-
Regional	-	53.87	9.31	65.00	58.05	6.95	66.37	59.13	7.24	75%	-
UDDS	-	10.17	5.69	17.35	13.20	4.15	18.23	13.67	4.55	73%	-
7% Grade	-	28.02	0.21	32.91	32.70	0.21	34.00	33.79	0.21	-	-
Cruise	-	41.74	1.54	41.00	39.10	1.90	41.37	39.93	1.44	-	-

[1] **Drive**, Net and Regen power as measured by the chassis dynamometer, Hioki power meter, and the Vehicle CAN network system. The Drive power is the power absorbed by the chassis dyno during accelerations or supplied by the battery system to move the vehicle forward. Net power is the sum of the Drive – the Regen power (ie the overall energy usage). Regen power is the power absorbed by the chassis dyno during decelerations or supplied to the battery system (ie enegy recovery). [2] **Drive** efficiency is calculated as Chassis_drive/Hioki_drive and the Regen efficiency is the recovery efficiency is calculated as Hioki_regen/Chassis_regen. [3] **Drive** energy for the chassis appeared to be in error due to some values exceeding Hioki system. As such, the values are removed from the main report, but are provided in the Appendix D to prevent confusion. Additional investigation is needed to understand the Chassis Drive results.

3.3.3 Performance at low SOC

There is concern with battery technology that vehicle performance may be a function of SOC. Unlike conventional fuel where energy density is similar with a full or empty fuel tank, battery systems may exhibit performance differences at low SOC compared to high SOC. At the time of testing it was not known how much energy (or SOC) per cycle the HDV would consume, thus this low SOC test was not performed. During testing of a different all-electric HDV by the same manufacturer it was shown that the energy rate per mile was similar at full SOC and at 20% SOC[2]. Additional tests are recommended to confirm 5% SOC provides similar performance (kWhr/mi) at full SOC. Future tests with drayage type operation it is recommended to perform phase 3 of the drayage port cycle. Approximately 4 SOC is used on this cycle so one can perform it at full SOC and start a test at ~5 SOC.

[2] *Johnson et al, Performance and Evaluation of a Second Generation All-Electric Yard Tractor, final report TransPower, February 2015.*

3.3.4 HDV range

The range of the all-electric HDV is estimated in this sub-section for each of the drive cycles. Figure 12 shows a comparison between the vehicles SOC % and the energy usage (kWhr) for both days of testing. The best fit regression line can be used to estimate total capacity from measured energy usage and reported SOC. The intercept of the regression line (ie zero capacity) occurs at -4.11 % SOC with the manufacturer's claim of 215kWhr of maximum battery capacity as listed in Table 2. At a capacity of 207 kWhr the intercept becomes zero suggesting the real maximum capacity based on 0% SOC is around 207 kWhr.

The range of the vehicle for each cycle is shown in Figure 13 based on a total recommended usable capacity of 172kWhr. The range for the port cycles was very similar and varied from 84 mi to 82 miles for the Near Dock and Regional cycle, respectively. The Cruise cycle represented the longest range of 88 miles and the 7% grade showed the lowest overall range of 25 miles.

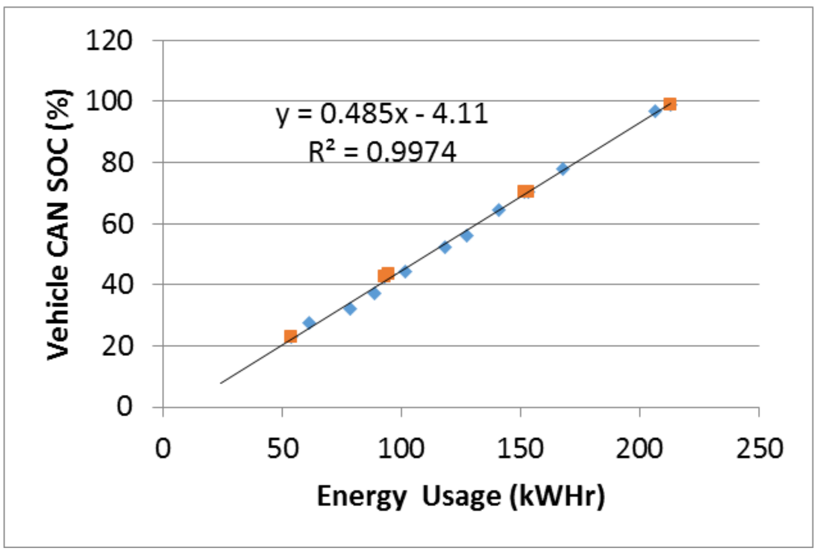


Figure 12 Hioki vehicle energy consumption (kWhr) as a function of SOC

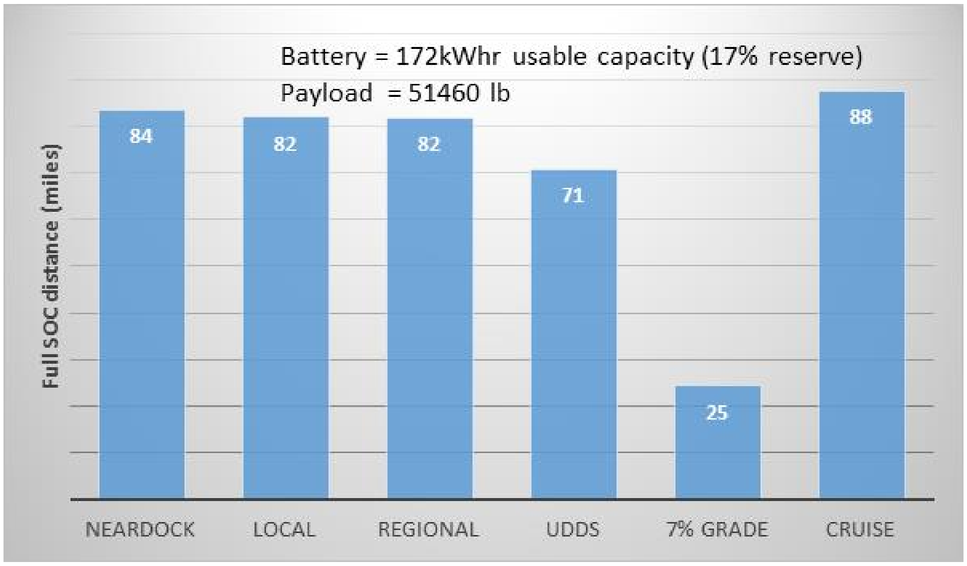


Figure 13 Calculated range for all the drive cycles evaluated

3.3.5 Charging

The vehicle was charged to 100% SOC prior to each day of testing. The vehicle was then operated for a full day of transient and steady-state testing where 47.6 miles were accumulated on day one and 76.6 miles were accumulated on day two. A total of 145 kWhr of energy was consumed from the batteries based on the net energy measured by the Hioki system and a total of 171.5 kWhr was added back to the battery system during a 15 hr charge, see Figure 14 and Table D1 Appendix D. The total energy consumed the second day was 158.7kWhr with a recharge of 173.6 kWhr. The difference between energy usage and charging is unusual and will be investigated at a later time. The charging accumulated energy increased steadily from 0 to 171.5 kWhr in approximately 15 hr for the first day of charging. This suggests the actual charge rate was 11.4 kW/hr for this configuration. The all-electric HDV was equipped with a 72 kW/hr charger, but UCR did not have the facilities to support this high charge rate at the time of testing, so the slower charger rate was used.

UCR did not measure the power from the grid to characterize the charger efficiency. Future research will add this feature to assess the overall impact of charging electric vehicles.

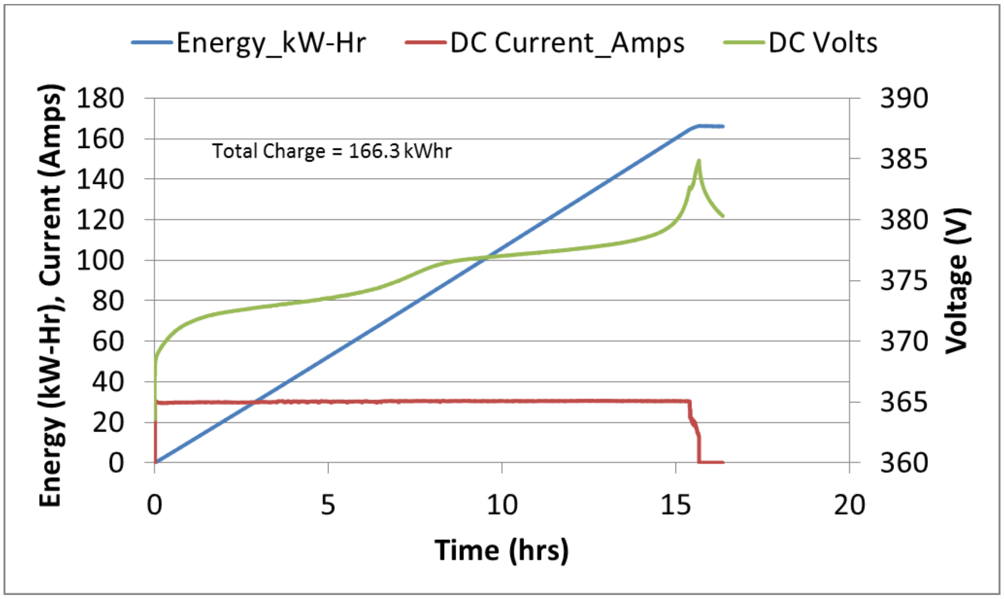


Figure 14 Real-time energy and voltage during charging of an electric HDV

3.3.6 HDV comparisons

The final analysis considers the overall results in comparison to several certification model year (MY) conventional diesel HDVs. Additional HDVs have been evaluated by UCR such as NG and hybrid diesels, but these alternative fueled and advanced vehicles are not considered here, but will be addressed in a future publication. Energy cost per mile can be evaluated between technologies by considering average fuel and utility costs in California and the Nation. Figure 15 shows the California and National average fuel costs for diesel[3]. Since 2011 diesel fuel prices in California have been above \$4.0/gal and Nationally below \$4.0/gal. An average fuel cost of \$4.11 /gal was used for California and the utility cost for California was estimated from EIA 2014 at 0.17 \$/kWhr, for more details see Table 7 footnote.

[3] *Annual Energy Outlook 2014, May 7, 2014, US Energy Information Administration http://www.eia.gov/forecasts/aeo/?src=email*

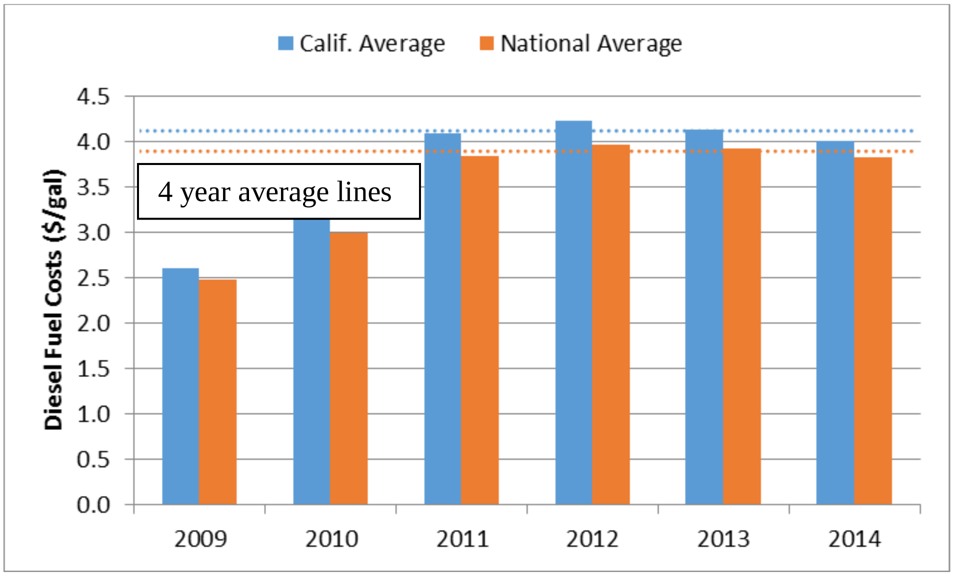


Figure 15 California and national average of diesel fuel costs by year[4]

Table 7, Table 8, and Table 9 lists the energy usage, fuel costs, and fuel economy in miles per gallon diesel equivalent (MPGde) between the conventional diesel HDV and the electric HDV based on the California and National averages. Table 7 lists the results for the conventional, Table 8 lists the results for the all-electric vehicle, and Table 9 lists the percent difference by cost/mi, MPG, and gal/1000ton-mi with the conventional as the basis. Table D3 in Appendix D lists selected specifications for the range of vehicles completed. The CA based cost savings for the all-electric was 78% for the Near Dock cycle and 58% for the Regional cycle.

Table 7 Summary energy usage and FE of results for the conventional HDV

Cycle	Vehicle	Energy Usage		$/100 mi		F.E.	
name	name	value	units	Calif	National	MPG_{de}	Gal_{de}/1kton-mi
NearDock	Conv.	38.2	gal/100 mi	157	148.5	2.62	14.0
Local	Conv.	37.2	gal/100mi	152.8	144.6	2.69	13.6
Regional	Conv.	20.9	gal/100mi	86.0	81.4	4.78	7.7
UDDS	Conv.	30.2	gal/100mi	124.2	117.5	3.31	11.1
7% Grade	Conv.	58.8	gal/100mi	241.8	6.5	1.70	21.6
Cruise	Conv.	18.2	gal/100mi	74.7	70.7	5.50	6.7

[1] Conv. = conventional heavy duty vehicle. California average diesel fuel cost of $4.11/gal (based on 4 year average) and National average diesel fuel cost = $3.89/gal (based on 4 year average) (source EIA 2014). Electrical costs based on California and National average for industry rates of 0.17 $/kWhr and 0.11 $/kWhr (EIA 2014). MPG_{de} is miles per gallon diesel equivalent. The conversion is based on 37.6 kWhr/gal diesel equivalent energy content (source US EPA). NHTSA FE std. is 10.2 gal/1000 ton-mi for Class 7 day cab low roof category. The Gal_{de}/ton-mile results are based on a payload capacity of 51460 lb (5.5 tons) for the elec and 54500 for the conventional.

[4] *Annual Energy Outlook 2014, May 7, 2014, US Energy Information Administration http://www.eia.gov/forecasts/aeo/?src=email*

Table 8 Summary energy usage and FE of results for the all-electric HDV

Cycle	Vehicle	Energy Usage		$/100 mi		F.E.	
name	name	value	units	Calif	National	MPG_{de}	Gal_{de}/1kton-mi
NearDock	Elec.	205.7	kWhr/100 mi	35.0	22.6	18.3	2.1
Local	Elec.	209.5	kWhr/100 mi	35.6	23.0	17.9	2.2
Regional	Elec.	210.1	kWhr/100 mi	35.7	23.1	17.9	2.2
UDDS	Elec.	242.4	kWhr/100 mi	41.2	26.7	15.5	2.5
7% Grade	Elec.	700.9	kWhr/100 mi	119.2	77.1	5.4	7.2
Cruise	Elec.	196.1	kWhr/100 mi	33.3	21.6	19.2	2.0

[1] Conv. = conventional heavy duty vehicle. California average diesel fuel cost of $4.11/gal (based on 4 year average) and National average diesel fuel cost = $3.89/gal (based on 4 year average) (source EIA 2014). Electrical costs based on California and National average for industry rates of 0.17 $/kWhr and 0.11 $/kWhr (EIA 2014). MPG_{de} is miles per gallon diesel equivalent. The conversion is based on 37.6 kWhr/gal diesel equivalent energy content (source US EPA). NHTSA FE std. is 10.2 gal/1000 ton-mi for Class 7 day cab low roof category. The Gal_{de}/ton-mile results are based on a payload capacity of 51460 lb (5.5 tons) for the elec and 54500 for the conventional.

Table 9 Percent difference compared to the conventional HDV

Vehicle	$/100 mi		F.E.	
name	Calif	National	MPG_{de}	Gal_{de}/ton-mi
NearDock	-78%	-85%	598%	-84%
Local	-77%	-84%	567%	-86%
Regional	-58%	-72%	274%	-74%
UDDS	-67%	-77%	369%	-80%
Cruise	-55%	-69%	248%	-73%

Figure 13 shows the energy usage costs on a per mile basis between conventional and electric HDVs operating on the various cycles. As illustrated in Figure 13, usage costs for the TransPower electric HDV are projected to be less than one-quarter of the costs for a comparable conventional truck. For the drive cycles of greatest interest (Near Dock and Local), the TransPower electric HDV saves $117 to $122 per 100 miles. This projects out to estimated cost savings of more than $350,000 over a ten-year operating life (assuming 30,000 miles of operation per year).

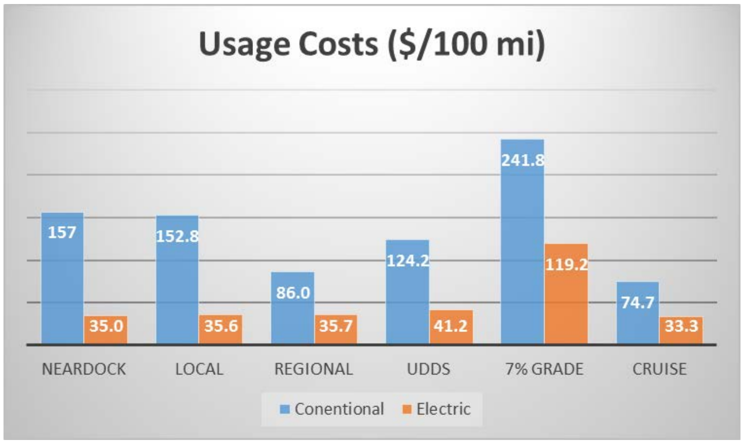


Figure 13 Usage costs for conventional trucks versus TransPower electric HDV.

Fuel Economy (FE): The fuel economy for the all-electric HDV is listed in Table 8 and for the conventional in Table 7. Figure 16 below shows the comparison between the conventional and electric HDV for each of the cycles performed on an equivalent diesel gal equivalent (Gal_{de}). The FE ranged from 18.3 to 17.9 MPG_{de} for the transient port cycles and reached as high as 19.2 MPG_{de} for the cruise 55 mph cycle. The lowest fuel economy was for the simulated grade test and averaged 5.4 MPG_{de}. The all-electric FE was almost twice as high compared to the DOE funded Super Truck MPG_{de}, as shown in the far right corner of Figure 16. Although the FE is twice that of the SuperTruck program the electric HDV represents inter-city short range operation and the SuperTruck HDV represent long haul high VMT operation so their individual success are still both important for each of their designed targets.

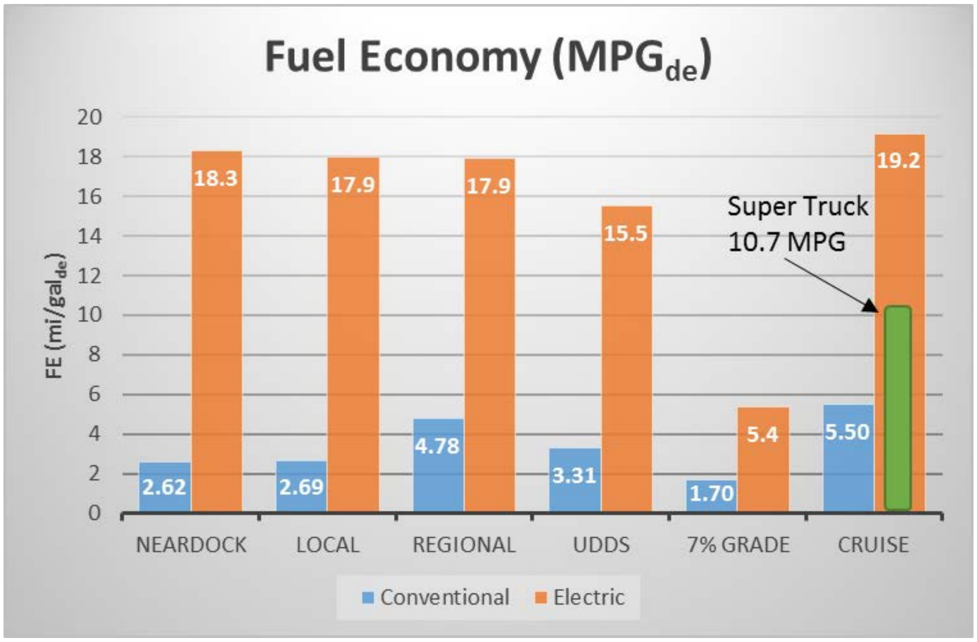


Figure 16 FE for the conventional and the electric HDV: MPG_{de} [5]

[1] MPG_{de} is miles per gallon diesel equivalent. The conversion is based on 37.6 kWhr/gal diesel equivalent energy content (source US EPA). NHTSA FE std. is 10.2, 7.8, 6.5 gal/1000 ton-mi for Class 7, 8 day cab low roof category and Class8 sleeper, respectively[6].

The FE benefit for the electric HDV in comparison to a conventional diesel was highest for the Near Dock cycle (598% higher FE) and least for the steady test cruise cycle (248% higher FE), see Table 9. The National Highway Traffic Safety Administration (NHTSA) recognizes that HDV fuel economy should be presented on a per ton-mile bases to consider the loads HDVs carry. As such, a more reasonable metric for comparing fuel economy is to compare the gallons consumed on a per 1000 ton-miles basis (1kton-mi). Figure 17 shows the fuel economy usage on a per 1kton-mi basis between conventional and electric HDVs operating on the various cycles. The all-electric HDV FE ranged averaged 2.1 Gal_{de}/1kton-mi for the transient port cycles and as low as 2.0 Gal_{de}/1kton-mi for the 55 mph cruise cycle and as high as 7.2 Gal_{de}/1kton-mi for the 7% grade test. In all cases the all-electric FE exceeds the NHTSA FE

[5] Cummins Social Media News Hub, accessed February 24, 2014.
http://social.cummins.com/cummins-peterbilt-supertruck-passes-important-milestone/

[6] *Federal Register/Vol. 76, No. 179/September 15, 2011/Rules and Regulations Table I-3*

standards required for HDVs by more than 70% thus representing a good investment by HDV manufacturers to increase their corporate average fuel economy requirement. The all-electric HDV FE benefit was greatest for the Near Dock and Local port cycles (85% and 84%) and 72% for the Regional cycle. The benefit was least for the 7% grade test at 66%.

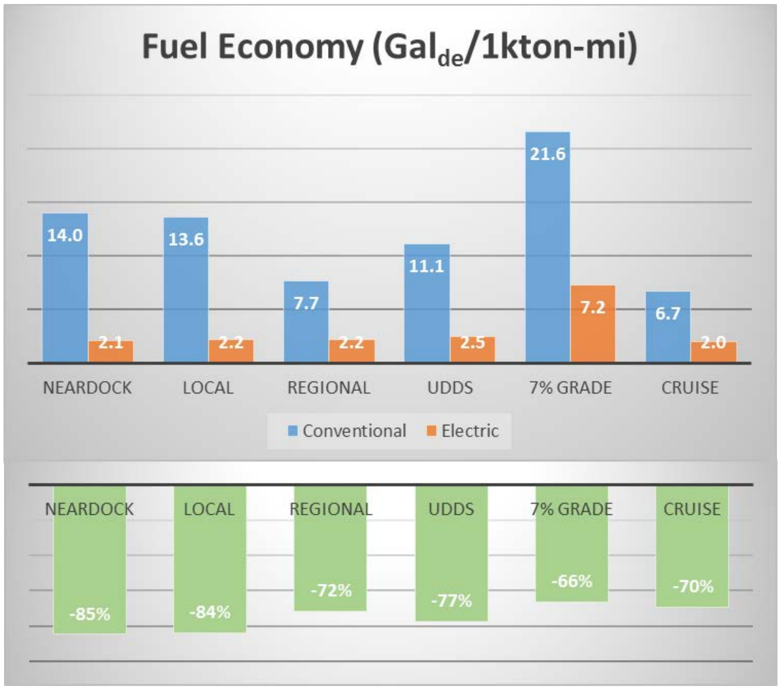


Figure 17 Fuel usage for the conventional and the electric HDVs: Gal$_{de}$/1kton-miles

[1] Gallons of diesel equivalent Gal$_{de}$. The electrical conversion is based on 37.6 kWhr/gal diesel equivalent energy content (source US EPA). NHTSA fuel usage standard is 10.2, 7.8, 6.5 gal/1000 ton-mi for Class 7, 8 day cab low roof category and Class8 sleeper, respectively[7].

[7] *Federal Register/Vol. 76, No. 179/September 15, 2011/Rules and Regulations Table I-3*

4 On-Road Results

The on-road results are presented in this report for context and to represent a comparison to the laboratory results. These on-road results will be only briefly described and presented where a more through reporting will be presented by others. Figure 18 shows a pictorial view of various routes operated by the electric HDV during drayage TTSI operation. Table 10 lists the average, 10th, 50th, and 90th percentile statistical results from the on-road drayage port operations.

The electric HDV appears to be operated down to an average SOC of 62% with a 10th percentile utilization down to 32% SOC. The 90th percentile daily trip usage was almost 81 miles which is very aggressive for the electric vehicle user. The range of energy usage per mile is very reasonable and convers a spread from 1.4 to 2.33 kWhr/mi. This suggests the laboratory testing rate of 2.1 kWh/mi was representative of the on-road conditions. The regeneration energy recovered ranged from 4.6kWhr to 27.1kWhr which agrees well with the chassis testing. The idle (zero velocity) energy ranged from 0.22 kWhr to 3.53 kWhr for the 10th and 90th percentile values.

In general the on-road statistics agree well with the laboratory testing. This suggest the laboratory testing was representative and that the overall on-road and laboratory results can be used to draw comparisons to conventional vehicles and other advanced technologies.

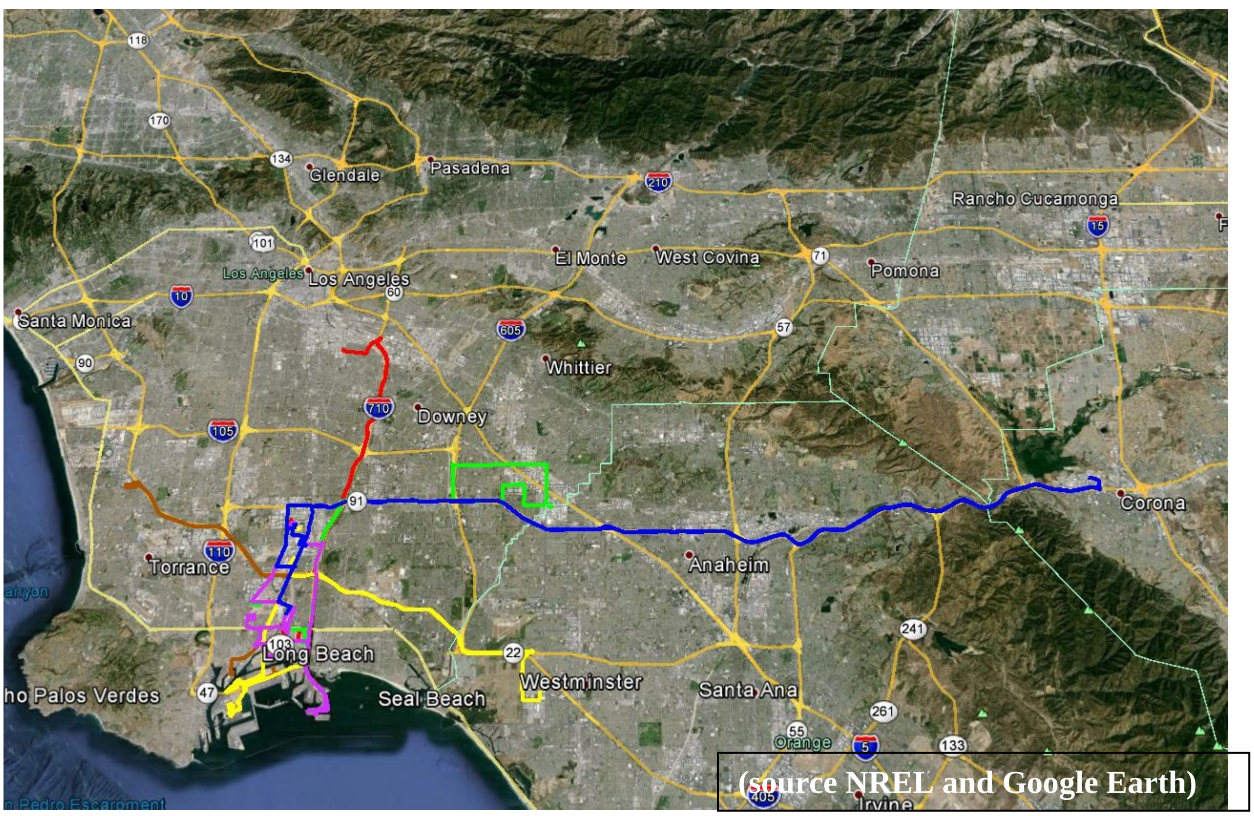


Figure 18 Pictorial view of selected routes for the all-electric HDV

Table 10 On-road statistical performance results for the all-electric HDV

Description	Average	Percentiles		
		10th	50th	90th
SOC % minimum	62.6	87.95	67.33	32.85
Distance (mi)	41.7	6.59	35.92	80.78
Energy rate kWhr/mi	1.9	1.41	1.91	2.33
Drive Energy kWhr	74.1	11.21	70.82	124.6
Regen Energy kWhr	16.3	4.60	15.73	27.14
Idel Energy kWhr	2.0	0.22	2.00	3.53
Average Speed (mph)	19.4	14.81	18.64	25.63

5 Discussions

In this section some discussion is provided to put the benefits of electrifying the heavy-duty fleet and its overall benefit into context. These discussions are not complete and would require additional analysis, such as a full well-to-wheel analysis, which is outside the scope of this project, but they do provide some context for the results.

5.1 Estimated GHG emissions

Potential GHG emissions reductions from use of the TransPower electric HDV were shown to be significant. Table 11 lists the GHG emissions estimated in generating electricity to recharge the electric HDV batteries. As illustrated in the far right two columns of Table 11, the TransPower electric HDV is projected to reduce GHG by 68% and 67% for the Near Dock and Local drayage port operations, which are the two drive cycles of greatest interest. Figure 19 shows the comparison between the conventional and electric HDV on a 100mi basis. The figures shows a benefit in GHG emissions for all the cycles expect the sustained grade test where the all-electric showed slightly higher GHGs compared to the conventional. Reductions of GHG in drive cycles characterized by higher operating speeds and more steady-state operation are less dramatic but remain meaningful. This suggests that as an instrument for reducing GHG emissions for port drayage trucks, electric trucks of the TransPower HDV can be extremely effective, but not for long haul applications.

Table 11 GHG estimated emission comparison between conventional and electric HDV

	Conventional			Electric			(Elec-Conv.)/Conv.	
Cycle	Calififornia		National	California		National	California	National
name	kg/100mi	$kgCO_2$/ton-mi	kg/100mi	kg/100mi	$kgCO_2$/ton-mi	kg/100mi	% chng.	% chng.
NearDock	390	143	390	124	52	171	-68%	-56%
Local	380	139	380	127	53	175	-67%	-54%
Regional	214	78	214	127	53	175	-41%	-18%
UDDS	243	89	243	146	61	202	-40%	-17%
7% Grade	472	173	472	424	177	584	-10%	24%
Cruise	146	54	146	119	49	163	-19%	12%

[1] GHGest is an estimated greenhouse gases which are estimated from CO_2 emissions estimates using EIA's power distribution for California (54% NG, 7.3% coal, 1.4% fuel-oil) and Nationally (49.6% Coal, 18.8 NG, and 3.0% fuel-oil) (source EIA 2014). CA GHG_e is 0.604 GHG-kg/kWhr and Nationally it is 0.833 GHG-kg/kWhr. US EPA CO_2 standard for a day cab class 7 low roof vehicle is 104 g/ton-mi.

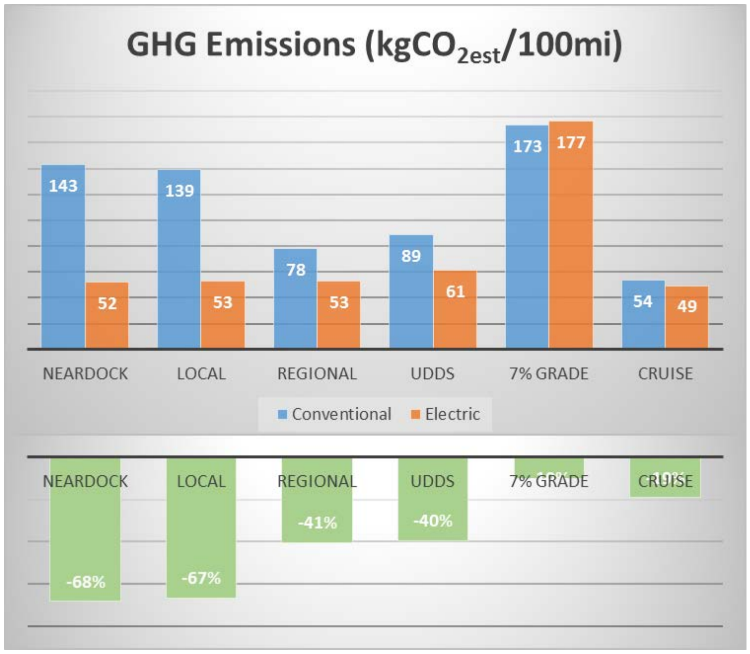


Figure 19 Estimated GHG emissions differences between conventional and electric

5.2 NO_x and PM emissions benefit

A true emissions difference between conventional and electric heavy duty vehicles also requires a well-to-wheel emissions analysis which is beyond the scope of this report. Although an emissions comparison is not presented, it is well known that the tailpipe emissions are zero for the all-electric HDVs and non-zero for the diesel or diesel-hybrid HDVs. Thus, the benefit of an all-electric vehicle is the emissions resulting from the all-electric HDV could be generated in a location other than where the vehicle is performing its work. One major benefit is this could greatly facilitate high impact regions such as South Coast and San Joaquin air basins where NO_x emissions are the highest in the nation.

Recently, UCR evaluated truck emissions in the South Coast communities following the same transient port cycles Near Dock, Local, and Regional in addition to the other cycles. UCR performed this testing on three categories of vehicles which included 2009-2007 certification MY, 2010 certification MY without SCR and 2010 certification MY with SCR. Figure 20 shows the NOx emissions (g/mi) for the average of several HDVs tested in each category. For the higher loaded Regional and UDDS cycles the most recent emissions certification showed NOx emissions approximately 91% lower than the previous certification year. The larger percent reduction was only 65% lower for the Near Dock cycle. Additionally the NOx emissions for the Near Dock cycle were three to four times higher than the certification standard[8]. The reason for the higher emissions is that the duty cycles near the port area of South Coast are so low the NO_x after treatment system is inactive 90-100% of the time[9]. This

[8] *Dixit, P., Miller, W., Durbin, T., Cocker, D., Oshinuga, A., and Johnson, K., 2015 Real World Emissions from Heavy-duty, Diesel Engines with Modern Control Technologies, Env. Sci. and Tech. in preparation.*

suggest new emission regulations may not be effective at controlling emissions near the ports. Interestingly the low load Near Dock and Local port cycles represent ideal operational conditions for the all-electric vehicle. Thus, if the emissions at the tailpipe could be located outside these high-impact regions, these "hot spots" could be managed with electric vehicles. Further analysis of the grid system and regional dispersion modeling is needed to quantify the impact of a large fleet of electric vehicles.

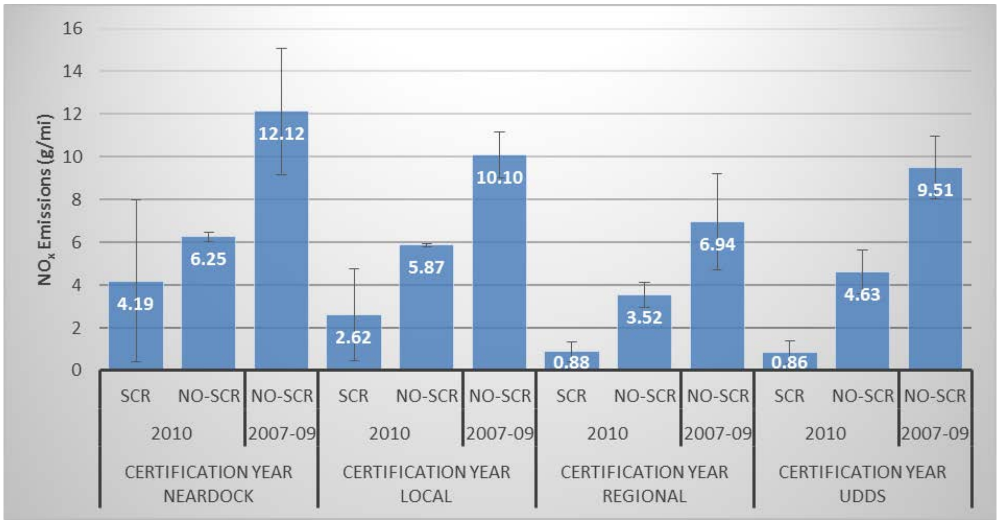


Figure 20 Conventional HDV NOx emissions during port and UDDS testing
[1] The error bars represent single standard deviations between a population of three vehicles per category.

5.3 Battery replacement costs

One cost that is not considered in the cost per miles analysis is the battery replacement cost. Although batteries have been utilized on light duty since the 2000's these designs are significantly different than those of HDVs due to load and charge depletion details. As such drawing comparisons to battery replacements is too speculative at his stage and thus, are not performed.

6 Conclusions

The TransPower all electric heavy duty vehicle (HDV) was evaluated on several transient and steady state cycles. The cycles represented simulated behavior at the ports or in congested areas, certification like cycles, and sustained grade and steady state cycles. All the tests were performed at a test weight of 72,000 representing a typical loaded HDV during drayage port operation. In all cases, the electric HDV had favorable performance, reduced fuel consumption, improved fuel economy, and significant emission reductions compared to current model year conventional-diesels.

The following are the highlighted conclusions that can be made for the all-electric HDV tested at UC Riverside:

- The on-road all-electric HDV performance statistics agree well with the laboratory results. This suggest the laboratory testing was representative and that the overall on-road and laboratory results can be used to draw comparisons to conventional vehicles and other advanced technologies.
- TransPower's electric HDV performed all tests with a high degree of reliability, suggesting that recent advanced in electric vehicle technology make applications to on-road Class 8 trucks practical for drayage and intercity operation with distances averaging less than 80 miles/day operation.
- In general the all-electric HDV sustained near full load (77%) for approximately 9 minutes (6 miles) without any deratings, overheating, or other vehicle performance degradation. This suggests the all-electric vehicle is capable of safely operating over the Vincent Thomas Bridge which is a unique operation in the port of Los Angeles and part of normal port activity. This bridge has a steep approach grade estimated at 7% and a total span of 6,060 feet.
- The SOC usage for the Near Dock operation averaged 5.23%, Local 9.19 %, and 27.52 % SOC for the regional cycle. This suggests up to 3 Regional trips or one Regional round trip could be performed with-in the capacity of the electric HDV.
- 88.11% of the battery subsystem's available energy was used to perform a total of 73.5 simulated transient miles.
- The initial power for the vehicle (Hioki and CAN systems) were 289 and 281 kW, respectively, where the chassis absorbed power was 250 kW. For the lower low point the loads were 232, 240 and 198 kW, respectively. The chassis absorbed power were 13% and 17% lower respectively.
- The vehicle recovered 2.46 kWhr and 6.95 kWhr of energy for the full Near Dock and Regional cycles, respectively, as measured from the Hioki power meter. This represents an overall energy recovery efficiency of 22% and 12%, respectively for each cycle.
- The total energy usage was similar between the Near Dock, Local, and the Regional cycle at 2.06 to 2.10 kWhr/mi (~1% range). This suggests the energy rate per mile is not a function of average power during port driving behavior.
- Energy usage was greatly increased (7 kWhr/mi) during sustained load operation such as with a 7% grade
- The FE ranged from 18.3 to 17.9 MPG_{de} for the transient port cycles and reached as high as 19.2 MPG_{de} for the cruise 55 mph cycle. The lowest fuel economy was for the

simulated grade test and averaged 5.4 MPG_{de}. The all-electric FE was almost twice as high compared to the DOE funded Super Truck 10.7 $MPG_{de.}$

- The FE benefit for the electric HDV in comparison to a conventional diesel was highest for the Near Dock cycle (598% higher FE) and least for the steady test cruise cycle (248% higher FE)
- The all-electric HDV FE ranged averaged 2.1 Gal_{de}/1kton-mi for the transient port cycles and as low as 2.0 Gal_{de}/1kton-mi for the 55 mph cruise cycle and as high as 7.2 Gal_{de}/1kton-mi for the 7% grade test. The all-electric HDV FE benefit on a 1000 ton-mi basis was greatest for the Near Dock and Local port cycles (85% and 84%).
- The range for the port cycles was very similar and varied from 84 mi to 82 miles for the Near Dock and Regional cycle, respectively. The Cruise cycle represented the longest range of 88 miles and the 7% grade showed the lowest overall range of 25 miles.
- For typical drayage drive cycles, usage costs for the TransPower electric HDV are projected to be less than one-quarter of the costs for a comparable conventional truck, resulting in estimated cost savings of more than $350,000 over a ten-year operating life (assuming 30,000 miles of operation per year).
- In general the on-road statistics agree well with the laboratory testing where the truck showed an energy usage rate between from 1.4 to 2.33 kWhr/mi. This suggest the laboratory testing was representative and that the overall results can be used to draw comparisons to conventional vehicles and other advanced technologies
- TransPower's electric HDV consumed only about half as much battery energy per mile as an electric truck tested by UCR in 2011. Significant improvements in energy efficiency were expected during the product development cycle for a zero-emissions, all electric heavy duty truck and the latest results showed significant progress is possible.
- Zero speed accessory loads for the electric HDV were 1.13 kW without the air conditioning and are expected to be 2.2 kW with the air conditioning.
- The TransPower's electric HDV is expected to reduce GHG in typical drayage drive cycles by 67-68% based on an estimated CO_2 analysis from California power plants emissions resulting from electricity generation (ie not a full well-to-wheel analysis).

7 Recomendations

This research was unique and represents first ever in-use evaluation of an all-electric on-road truck. The growing need to reduce GHG emissions has been considered at all levels of government and policy makers where a dependence on electric HDVs is the primary path to achieve proposed reduction targets. Thus, the results presented here are important and need to be further analyzed in order to help meet those targets. The following are recommendations proposed as part of this research:

- Future tests with drayage type operation it is recommended to evaluate battery usage at full and partial SOC with Phase 3 of the drayage port cycle. Approximately 4 SOC is used on DPT_Phase3 cycle so one can perform the final test down to ~5 SOC.
- Perform a well-to-wheel analysis to evaluate the GHG and emissions benefit of the all-electric HDV compared to conventional, alternatively fueled, and hybrid HDVs.
- Analysis of the grid system and regional dispersion modeling is needed to quantify the impact of a large fleet of electric vehicles. The purpose of this added analysis is to consider what type of new power generation facilities should be located by high impact regions.
- Investigate power calculation terms for the chassis dynamometer to understand how drive energy can exceed vehicle net energy for high loaded tests. Look at kinetic energy calculation predictions form simulated cycles and analysis methodologies reported in the literature.
- Future testing of all-electric vehicles should include a modified steady state mode cycle to consider all-electric vehicle efficiencies. It is recommended to evaluate the electric motor efficiency by maintaining a constant load, but evaluate six motor speeds (RPM) such as 100%, 80%, 60%, 40%, 20%, and 10% of the nominal design speed.

Appendix A - Test Cycles

Four main cycles are considered as part of this testing, 1) the sustained grade cycle, 2) the simulated drayage truck port cycle, 3) the urban dynamometer driving cycle, and 4) a charge depleting cycle. Each of these cycles provides an important metric for the safety, performance, and modeling characteristics for all-electric HDVs on-road. The sustained grade test is to ensure that the EDV's can manage to operate over the bridge safely while maintaining observed speed limits. The port cycles are to characterize the all-electric HDVs while performing typical port operations. The UDDS cycle is desired to relate to the large database of heavy duty diesel vehicles, and the charge depletion testing is to understand range and other vehicle specific capabilities that can be cross compared between vehicle tests.

Additionally these repeatable cycles provide comparability between different electric vehicle systems to evaluate benefits and dis-benefits for different approaches. Ultimately the data will be used to provide lessons learned to improve our all-electric HDV systems.

Sustained Grade (SG) cycles

Crossing the Vincent Thomas Bridge is unique to operation in the port of Los Angeles and part of normal port activity. This bridge has a steep approach grade so it is important to learn that the new vehicle technologies can cross the bridge with a full load (GVW = 80,000 lb). The bridge is the 4th longest suspension bridge in the world at 6,060 feet long and is relatively high mid span (365 ft) to clear vessels in the navigation channel. The maximum grade of the bridge is estimated at 7%. Both high speed and low speed approaches are comment when traveling across the bridge due to traffic conditions.

Two sustained grade (SG) test cycles were created to evaluate the performance of the all-electric HDVs while crossing the bridge. SG-1 cycle simulates approaching the bridge at 50 mph and increasing load until the vehicle reduced to 30 mph. SG-2 cycle simulates approaching the bridge at 0 mph (standstill traffic) and accelerating up to 20 mph under full load conditions. Each cycle is 400 seconds (< 10 minutes) long and represents approximately 250 hp of sustained power representing about 3 miles of distance traveled.

Figure B-1 Vincent Thomas Bridge crossed regularly during port activity.

Drayage Truck Port (DTP) cycle

TIAX, the Port of Long Beach and the Port of Los Angeles developed the port cycle. Over 1,000 Class 8 drayage trucks at these ports were data logged for trips over a four-week period in 2010. Five modes were identified based on several driving behaviors: average speed, maximum speed, energy per mile, distance, and number of stops. These behaviors are associated with different driving conditions such as queuing or on-dock movement, near-dock, local or regional movement, and highway movements. The data was compiled and analyzed to generate a best fit trip. The best-fit trip data was then additionally filtered (eliminating accelerations over 6 mph/s) to allow operation on a chassis dynamometer.

The final driving schedule is called the drayage port tuck (DPT) cycle and is represented by 3 modes where each mode has three phases to best represent Near Dock, Local, and Regional driving as shown in Table A-1, A2 and Figure A-1. The near-dock (DTP-1) cycle is composed of phase 1, 2, and 3a from Table A-1. This gives the complete near-dock cycle listed in Table A-2. Similarly, for the Local and Regional cycles (DPT-2 and DPT-3) the main difference is phase 3, which changes to 4 and 5 respectively. Phase 1 and 2 remain the same for all three cycles where creep and low speed transient are considered common for all the port cycles.

Table A-1. Drayage Truck Port cycle by phases

Description	Phase #	Distance mi	Ave Speed mph	Max Speed mph	Cycle length
Creep	1	0.0274	0.295	4.80	335
low speed transient	2	0.592	2.67	16.8	798
short high speed transient	3	4.99	9.39	40.6	1913
Long high speed transient	4	8.09	13.07	46.4	2229
High speed cruise	5	24.6	35.04	59.3	2528

Table A-2. Drayage Truck Port cycle by mode and phases

Description	Distance mi	Ave Speed mph	Max Speed Mph	Mode 1	Mode 2	Mode 3
Near-dock PDT1	5.61	6.6	40.6	Creep	Low Speed Transient	Short High Speed Transient
Local PDT2	8.71	9.3	46.4	Creep	Low Speed Transient	Long High Speed Transient
Regional PDT3	27.3	23.2	59.3	Creep	Low Speed Transient	High Speed Cruise

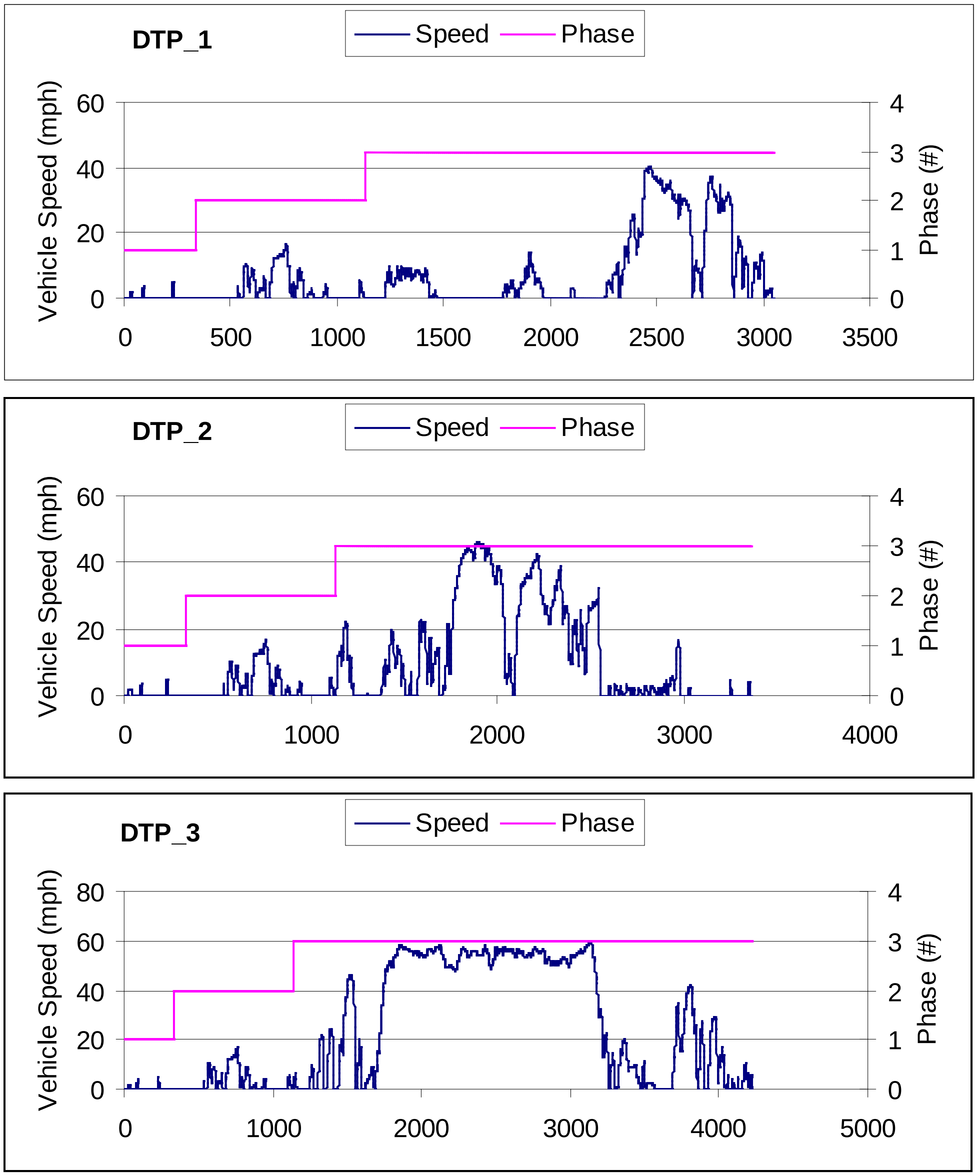


Figure A-1 Drayage truck port cycle Near Dock (DTP_1), local (DTP_2), and Regional (DTP_3)

Urban Dynamometer Driving Schedule (UDDS) description

The Federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel (HHD) trucks. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph, sample time of 1061 seconds, and maximum speed of 58 mph. The speed/time trace for the UDDS is provided below in Figures A-2.

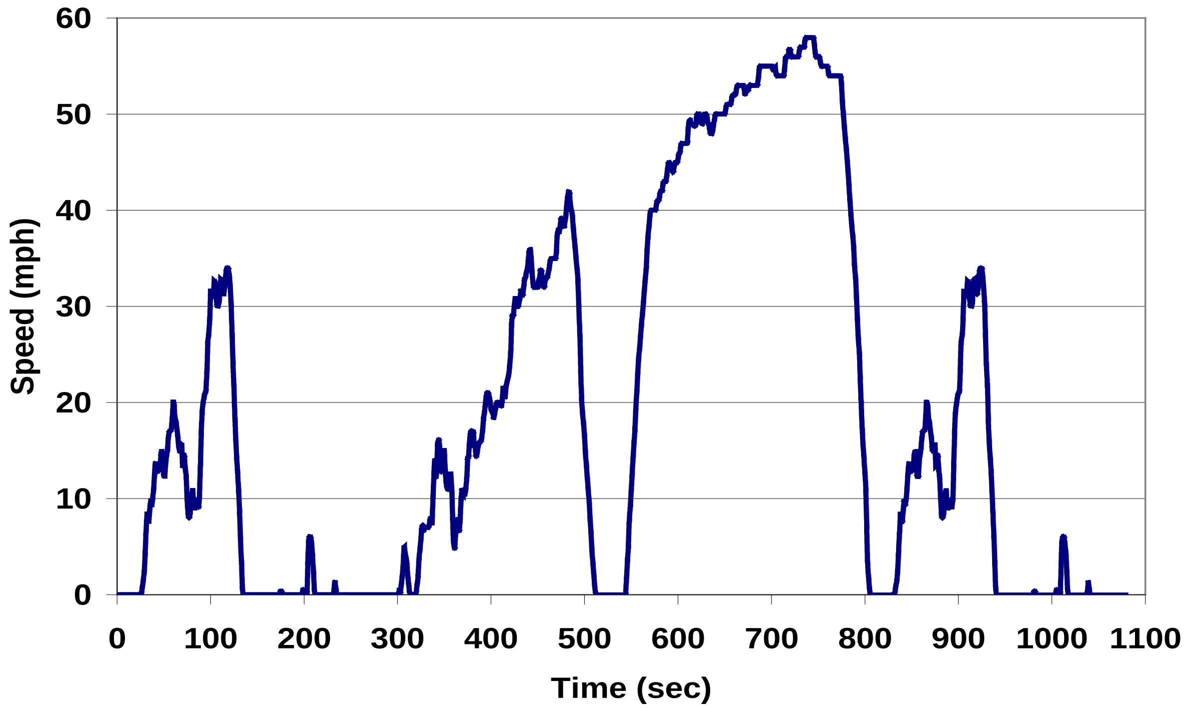


Figure A-2. Speed/Time Trace for a 1xUDDS cycle for the chassis dynamometer.

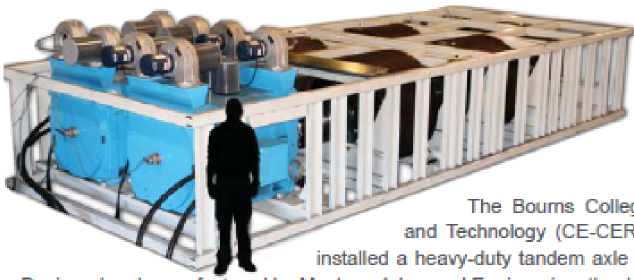
Charge Depletion cycle (CD)

The charge depletion test incorporates a 75,000 load at 55 mph cruise condition until the batteries are fully depleted. This test will be performed at the end of each day to characterize the true range of the system and compare this range between other vehicles tested.

Appendix B – Chassis Dyno Specifications

Specifications for UCR's Motored Chassis Dynamometer
From Mustang Publication "Project Spotlights"   March 2010

Mustang Advanced Engineering delivers a newly designed 48" Electric AC Heavy-Duty Truck Chassis Dynamometer with dual, direct-connected 300-hp AC motors to The University of California - Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT).



The science of measuring emissions from mobile and other sources has evolved significantly over the past several years. The most important changes in the nature of emissions measurement science has been a shift to examining emissions from diesel sources and to understanding emissions under in-use driving conditions.

The Bourns College of Engineering – Center for Environmental Research and Technology (CE-CERT) at The University of California Riverside has recently installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area. Designed and manufactured by Mustang Advanced Engineering, the development of this chassis dynamometer design was based on targeting vehicles in the medium to heavy-duty diesel vehicle range. Heavy-duty applications that can be tested at the facility include on-highway trucks, buses, waste haulers, yard tractors, and more - under test conditions representative of their specific in-use operations. The facility couples the new heavy-duty chassis dynamometer from Mustang Advanced Engineering with CE-CERT's Mobile Emissions Laboratory (MEL), to perform precise vehicle simulation and in-operation emissions measurements.

The first research conducted on the new facility will be a comparison of federally mandated diesel fuel formulas versus the stricter formulation required in California. The program calls for 10 heavy-duty trucks to be tested with several different fuels.

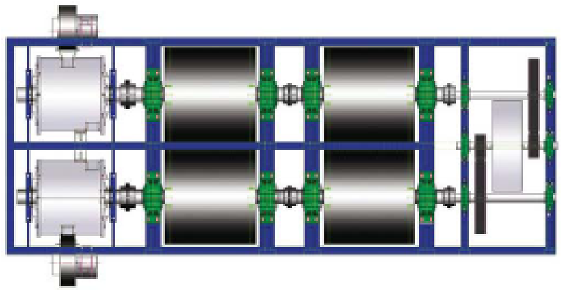
The new dynamometer will simulate on-road driving conditions for any big rig using its 48" precision rollers with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies the appropriate loading to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving conditions. An additional large inertia weight was incorporated into the dynamometer to increase the base mechanical inertia and enable the dynamometer to provide precise on-road simulation for a wide range of vehicle weights. The driver accelerates and decelerates according to a driving trace which specifies the speed and time over a wide range of vehicle simulation cycles. As the on-road driving conditions are being simulated on the dynamometer, emissions measurements will be collected with CE-CERT's Mobile Emissions Laboratory (MEL).

"This adds new capabilities in California that are only available at a limited number of facilities around the country," said Tom Durbin, who with J. Wayne Miller, are the principle investigators for the project. At both the state and federal levels, scientific requirements for emissions testing are trending away from steady state engine testing in favor of transient conditions found in typical driving, Durbin explained. "This addition will significantly expand our laboratory and measurement capabilities and help us continue our role as leading experts in the field of emissions research," said CE-CERT Director Matthew Barth.

CE-CERT's new heavy-duty chassis dynamometer will allow the testing of a variety of heavy vehicles under loaded and transient in-use conditions with corresponding emissions measurements. The dynamometer configuration is capable of meeting the inertia simulation range requirements of 10,000 to 80,000 lb for each of the cycles listed below. This includes acceleration rates up-to 6 mph/sec, as found in the UDDS Section D Drive Schedule and deceleration rates of up to 7 mph/sec as required for the WHM Refuse Drive Schedule. The dynamometer can also provide a load in excess of 600 HP @ 70 mph. The dynamometer also has the ability to continuously handle 200 Hp @ 15 mph for applications such as yard tractors.

The Dynamometer system is designed to meet the Heavy Duty Drive Schedules for diesel trucks in the weight range of 10,000 to 80,000 lb with acceleration rates for the following cycles:

- CARB HHDDT Cruise Mode Drive Schedule
- UDDS (Urban Dynamometer Drive Schedule)
- CARB 50 mph HHDDT Cruise Cycle
- HHDDT Transient Mode Drive Schedule
- WHM Refuse Drive Schedule
- Bus cycles such as, the CBD, OC Bus cycle, NY bus cycle
- In-use cycles for applications such as yard tractors.



"As part of our strategic plan, Mustang has developed a cost effective series of diesel, petroleum and hybrid certification grade dynamometer systems to address the needs of the global emissions and R&D market. There is a clear and present demand for a full performance cost effective dynamometer systems that offer all of the capabilities and confidence of a certification system at a price point that makes it no longer cost-prohibitive for organization to perform critical emissions studies, hybrid system calibration development, performance evaluation and other cutting edge research technologies. Researchers are in need of dynamometer systems to develop the next generation technologies which mimic the capabilities of the certification requirements, but at a fraction of the cost of a true certification system. That is what we are developing with this series of dynamometers and universities are lining up for them", said Executive Vice President, Donald Ganzhorn.

Appendix C – Calculations

The analysis included time synchronization and calculations for power and energy from various systems. This section describes some of the details of the calculations used in this report.

Time synchronization: The dyno file reports the distance in miles, speed in mph, and other dyno information relative to time in even one second intervals from the beginning of the test run. The data from the ECM is recorded approximately every 1014 ms based on CAN signal rates from ECM systems. As such the chassis and vehicle CAN files are not aligned by row, but can be aligned by time. Therefore to ensure that the data is analyzed relative to what the dyno is commanding the vehicle CAN signals requires additional analysis. The figures presented in the results section are, thus, plotted on a time basses to prevent issues in data comparison.

The accumulated energy results were calculated on a second-by-second basis, where the difference in time for each segment was utilized. The general formula for calculating accumulated energy from the vehicle CAN is below:

$$\textit{Vehicle CAN Energy} = \sum Power_i * DeltaT_i$$

Where:

Vehicle CAN Energy	is the accumulated energy consumed by the vehicle. The net energy is accumulation of the dissipated and recovered energy of the vehicle system. The drive energy is the accumulation of only the drive power and the regen energy is the accumulation of the recovered power (regenerated energy).
$Power_i$	is the instantaneous vehicle CAN power at time *i*
$DeltaT_i$	is the time difference between *i* and *i-1*

Vehicle CAN power calculations: The vehicle CAN power calculations were performed based on the product of measured DC current and DC voltage. The vehicle CAN current measurement included direction where drive current is energy from the battery and regen current is energy to the batteries (regeneration). The column of data that provided the CAN current was labeled “ESSCurrent”. The voltage was available from several difference sources. There were three voltage terms available from the vehicle CAN system, see Figure C1. These were the “StackVoltage”, “ICUDCVoltage”, and “act_DCBusVoltage_14”. During previous testing of a different HDV from this manufacturer it was shown the “StackVoltage” agreed best with UCRs measurement. As such “StackVoltage” was used as voltage measurement for the power and energy calculations performed on this vehicle.

The calculation of vehicle CAN power was performed on a second-by-second basis using the following formula:

$$\textit{Vehicle CAN Power}_{\,\mathrm{i}} = \sum TotalICUCurrent_i * StackVoltage_i$$

Where:

Vehicle CAN Power	is the instantaneous vehicle CAN power consumption at time *i*, where drive power is the current consumed by the vehicle and regen power is current recovered (regenerated) by the vehicle.
$ESSCurrent_i$	is the instantaneous vehicle CAN current usage at time *i*
$StackVoltage_i$	is the instantaneous vehicle CAN voltage at time *i*

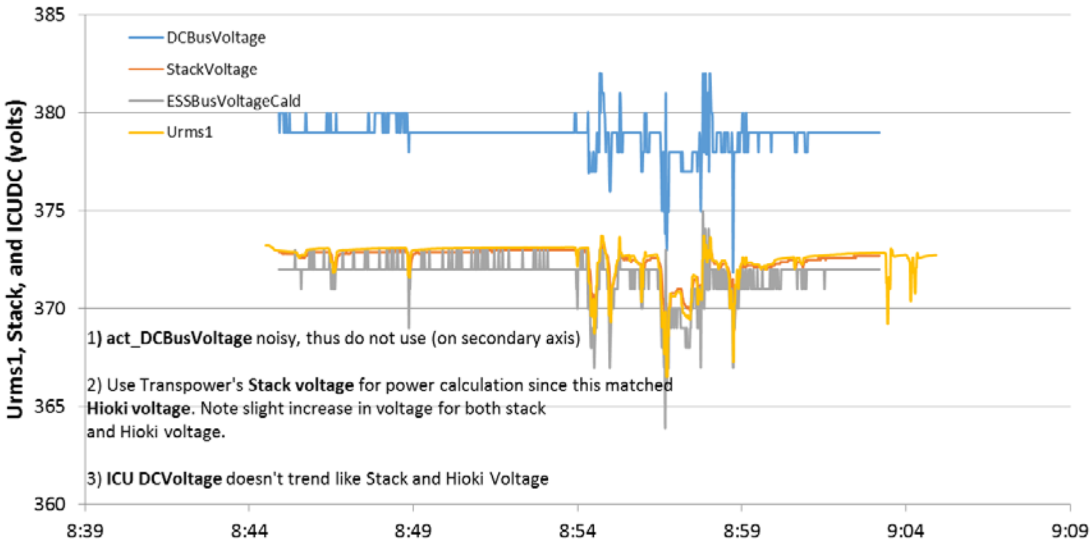


Figure C1 Voltage measurement utilized on the CAN electric vehicle system.

Vehicle CAN State of Charge measurement: The vehicle state of charge (SOC) represents the vehicle status and is a relative parameter and dependent on each manufactures claims for range and usage and thus may vary by manufacturer due to their utility of the battery systems. Thus, SOC is a generally calculated value, but is still a reasonable metric for the status of the vehicle and when re-charging is needed.

The SOC was provided by the vehicle using two methods. One method was the measurement of SOC from the vehicle CAN reporting system and the other was utilizing the display of SOC to the driver. In general both the ECM reported value and the visual display were in agreement suggesting the SOC reported represents the overall status of the vehicle.

Hioki power and energy calculations: The Hioki power system is a very accurate power meter as described in more detail in Appendix E. The Hioki system measured voltage and current in real-time and utilized internal power calculations at high sample rates an provided power and energy output. The results presented in this report utilize the results provided by the Hioki system.

Chassis coast down calculations: The method for determining coast down coefficients at UCR was published and evaluated as part of a previous report to the South Coast Air Quality Management District[9]. Typical coastdown procedures assume that vehicle loading force is a

[9] Draft Test Plan Re: SCAQMD RFP#P2011-6, "In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines", October 2011

function of vehicle speed, drag coefficient, frontal area and tire rolling resistance coefficient and takes the form of equation 1:

$$M\frac{dV}{dt} = \frac{1}{2}\rho A C_D V^2 + \mu M g cos(\theta) + Mgsin(\theta) \qquad \text{(Equation 1)}$$

Where:
M = mass of vehicle in lb
ρ = density of air in kg/m^3.
A = frontal area of vehicle in square feet, see Figure 1
C_D = aerodynamic drag coefficient (unitless).
V = speed vehicle is traveling in mph.
μ = tire rolling resistance coefficient (unitless).
g = acceleration due to gravity = 32.1740 ft/sec^2.
θ = angle of inclination of the road grade in degrees.

Constant parameters for equation 1	
μ	0.007
C_D	0.75 for Truck 0.79 for Bus 0.80 for Refuse Truck
g	32.1740 ft/sec^2

Assuming that the vehicle loading is characteristic of this equation, speed-time data collected during the coastdown test can be used with static measurements (Mass, air density, frontal area, and grade) to solve for drag coefficient (CD) and tire rolling resistance coefficient (μ). The frontal area is measured based on the method described in Figure C2 below.

However, experience performing in-use coast downs is complex and requires grades of less than 0.5% over miles of distance, average wind speeds < 10 mph ± 2.3 mph gusts and < 5 mph cross wind[10]. As such, performing in-use coast downs in CA where grade and wind are unpredictable are unreliable where a calculated approach is more consistent and appropriate. Additionally vehicles equipped with automatic transmissions have shown that on-road loading is also affected by the characteristics of the vehicle transmission, especially when reverse pumping losses at low speed begin to dominate.

UCR's and others recommend a coast down method that uses a characteristic coast down equation, with a measured vehicle frontal area (per SAE J1263 measurement recommendations), a tire rolling resistance of 0.007, and a Cd 0.75 (Truck) 0.79 (Bus) and 0.80 (Refuse Truck) in the above equation to calculate coastdown times to be used for calculating the A, B, C coefficients in equation 2 for the dyno operation parameters. This

[10] EPA Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium and heavy duty engines and vehicles, Office of Transportation and Air Quality, August 2011 (Page 3-7) and J1263 coast down procedure for fuel economy measurements

approach is consistent and has proven very reliable for chassis testing heavy duty vehicle and has been used for years. For evaluation of aerodynamic modifications and body styles, UCR recommends investing the time perform in-use coast downs.

$Y = C(x^2) + B(x) + A$

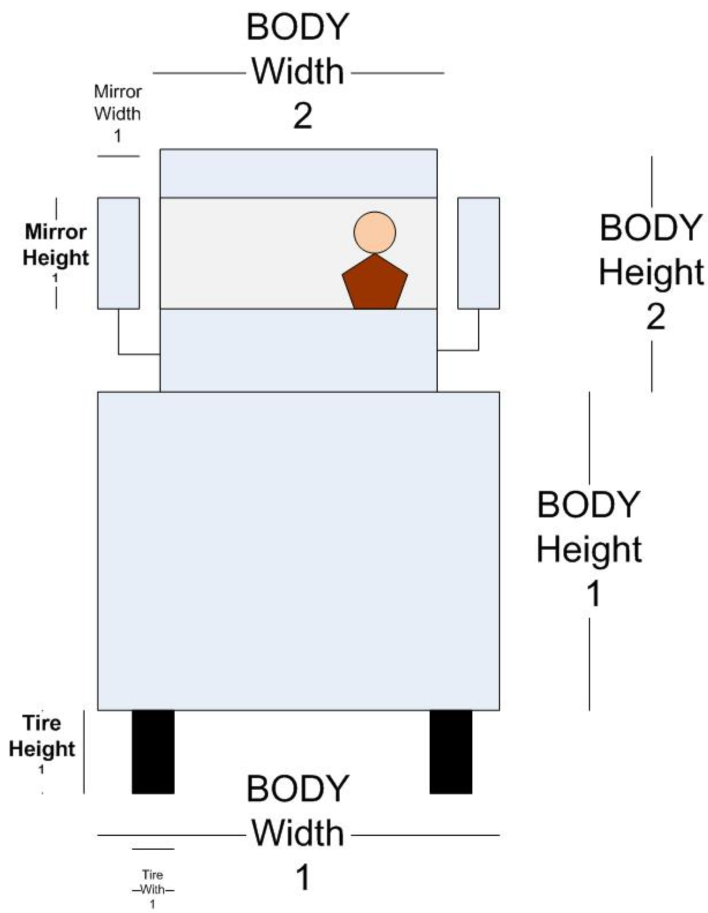


Figure C2 Vehicle frontal area dimensions method

Chassis absorbed and regenerated power/energy: The chassis dynamometer measures torque absorbed by the AC motors, friction torque, and acceleration energy torque from the inertial loads.

If we consider an energy balance around the vehicle and the chassis dynamometer, whatever energy is removed from the batteries is captured by the chassis dynamometer except for losses to the environment in various forms. During positive power (acceleration) conditions energy is supplied from the vehicle batteries to a DC motor controller, DC motor, drive shaft, rear differential, and then finally to the vehicle wheels. During negative power (braking) conditions kinetic energy stored in the chassis dynamometry is supplied by the chassis dynamometer to the vehicle batteries for regeneration. Thus, the chassis dynamometer measures the positive power supplied from the vehicle wheels during acceleration and a maximum potential regenerative capacity during braking. Differences between the vehicle and chassis positive power can be viewed as overall vehicle efficiency and negative power differences represent the regeneration efficiency.

Thus, we can consider a best case scenario where the chassis dynamometer represents a best case metric of available power in the form absorbed energy during accelerations and recovered (regenerative) energy during braking. In summary the chassis dynamometer estimates the total absorbed power and regenerated braking in real time.

The sample rate and control of these systems is 100 Hz and is reduced to 1 Hz with a filter to provided power measurements of the energy absorbed supplied at the roll/wheel interface. The total power absorbed by the chassis is characterized by the following equation.

$$\text{Chassis Energy} = \sum PAU\ power_i + Accel\ power_i + Frict\ power_i$$

Where:

Chassis Energy	is the accumulated energy consumed by the chassis dynamometer. The net energy is accumulation of the absorbed and motored energy from the test vehicle. The positive energy is the accumulation of only the positive power and the negative energy is the accumulation of the negative power (regenerated energy).
$PAU\ power_i$	is the measured power (torque and RPM) of the AC motors attached to the wheels at time *i*,
$Accel\ power_i$	is the calculated power from the rotating inertial loads of the chassis dynamometer at time *i*,
$Frict\ power_i$	Friction power is the calculated frictional power estimated by the chassis dyno. This value is estimated with each vehicle and represents the frictional losses from 0 to 70 mphs. The frictional energy increases with increasing speed. Typically this energy term is small and less than 5% of the total energy. The frictional power is reported at each second at time *i*.

Appendix D – Data and Results

Table D1 lists the individual tests for the all-electric HDV. The results are listed for both days and the accumulated charge between day 1, day 2, and day 3. The results in Table D2 are processed from combining selected tests from D1 to perform a direct comparison to the near dock (PDT1), local (PDT2), and regional (PDT3).

Table D1 Individual measured test results for the electric port HDV

		Chassis Dyno								Hioki System			Electric HD Vehicle					
TEST NAME	Cycle [1]	Ave Speed	Test Duration	Distance		Ave Pos Wheel Power	Drive [1,3] Energy	Net [1] Energy	Regen [1] Energy	Drive Energy	Net Energy	Regen Energy	Drive Energy	Net Energy	Regen Energy	start SOC [4]	delta SOC [4]	Hioki Energy Rate
n/a	n/a	mi/hr	sec	mi/cycle	accum mi	kW	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	%	%	kWhr/mi
201410290725.csv	SG-1	35.9	602	6.009	6.0	201.27	33.66	33.42	0.234	38.9	38.7	0.2	40.2	40.0	0.25	96.8	19.3	6.44
201410290752.csv	SG-2	32.8	411	3.749	9.8	199.78	22.81	22.62	0.192	26.9	26.7	0.2	27.8	27.6	0.17	77.8	13.7	7.12
201410290824.csv	UDDS	19.2	1061	5.665	15.4	54.46	16.05	10.20	5.852	17.6	13.6	4.0	18.7	14.2	4.53	64.5	6.2	2.40
201410290928.csv	DPT_P3	8.9	1916	4.745	20.2	17.47	9.30	6.611	2.686	11.0	9.2	1.8	11.4	9.3	2.16	56.2	4.0	1.94
201410291004.csv	DPT_P4	13.3	2232	8.28	28.4	31.19	19.34	12.73	6.607	21.7	16.6	5.1	22.4	16.8	5.58	52.2	8.3	2.00
201410291054.csv	UDDS	19.0	1061	5.616	34.1	53.15	15.66	10.14	5.527	17.1	12.8	4.3	17.8	13.2	4.57	44.5	6.4	2.28
201410291204.csv	DPT_P3	9.8	1916	5.204	39.3	20.14	10.72	7.37	3.353	12.7	10.3	2.4	13.0	10.7	2.34	37.2	4.8	1.98
201410291258.csv	DPT_P4	13.4	2232	8.301	**47.6**	32.07	19.88	12.840	7.044	22.0	17.2	4.8	23.5	17.5	6.02	32.0	8.4	2.07
																27.4		
						Totals	**147.4**	**115.9**	**31.5**	**167.9**	**145.1**	**22.8**	**174.7**	**149.1**	**25.6**			
										Charge [2]	**171.5**							
TEST NAME	Cycle	Ave Speed	Test Duration	Distance		Ave Wheel Power	Drive [1,3] Energy	Net [1] Energy	Regen [1] Energy	Drive Energy	Net Energy	Regen Energy	Drive Energy	Net Energy	Regen Energy	start SOC [4]	delta SOC [4]	Hioki Energy Rate
n/a	n/a	mi/hr	sec	mi/cycle	accum mi	kW	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	%	%	kWhr/mi
201410300645.csv	DPT3	23.55	4230	27.674	27.7	46.26	63.79	54.35	9.435	66.0	59.3	6.7	68.7	61.4	7.3	99.0	28.0	2.14
201410300816.csv	DPT_P1&P2	2.01	1135	0.637	28.3	2.48	1.14	0.782	0.358	2.0	1.7	0.3	1.8	1.6	0.20	70.3	0.8	2.63
201410300846.csv	DPT3	23.24	4230	27.323	55.6	45.44	62.49	53.40	9.091	64.0	57.0	7.0	66.1	58.6	7.5	70.2	27.6	2.09
201410301006.csv	DPT_P1&P2	2.03	1135	0.645	56.3	2.49	1.14	0.78	0.351	2.0	1.6	0.4	1.8	1.5	0.25	43.4	0.9	2.48
201410301028.csv	CD_55MPH	50.17	1461	20.359	76.6	102.84	43.27	41.736	1.537	41.0	39.1	1.9	41.4	39.9	1.4	42.5	23.3	1.92
																23.0		
						Totals	**171.8**	**151.1**	**20.8**	**175.0**	**158.7**	**16.3**	**179.8**	**163.2**	**16.6**			
										Charge [2]	**173.6**							

[1] **Drive**, Net and Regen power as measured by the chassis dynamometer, Hioki power meter, and the Vehicle CAN network system. The Drive power is the power absorbed by the chassis dyno during accelerations or supplied by the battery system to move the vehicle forward. Net power is the sum of the Drive – the Regen power (ie the overall energy usage). Regen power is the power absorbed by the chassis dyno during decelerations or supplied to the battery system (ie enegy recovery). [2] **Charge** was measured as the total net energy delivered back to the battery systems to bring the batteries to full 100 % SOC. Charging occurred after each day of testing. [3] **Drive** energy for the chassis appeared to be in error due to some values exceeding Hioki drive system. As such, the Chassis Drive values are colored blue and are suspect. Additional investigation is being considered to understand the Chassis Drive results. [4] **SOC** is the vehicle state of charge measurement from the dashboard and the CAN network. The dashboard and vehicle CAN network measurements were in agreement and the CAN network data was used for the report.

Table D2 calculated data summaries for duplicate port cycles

TEST NAME	Cycle	Ave Speed	Test Duration	Distance		Ave Wheel Power	Drive [1,3] Energy	Net [1] Energy	Regen [1] Energy	Drive Energy	Net Energy	Regen Energy	Drive Energy	Net Energy	Regen Energy	start SOC [4]	delta SOC [4]	Hioki Energy Rate
n/a	n/a	mi/hr	sec	mi/cycle	accum mi	kW	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	%	%	kWhr/mi
201410300645_1_2.csv	DPT_P1&P2	2.08	1135	0.662		2.60	1.18	0.821	0.358	2.0	1.8	0.2	3.9	3.3	0.6	98.91	1.59	2.72
201410300645_5.csv	DPT_P5	31.41	3096	27.674		62.24	62.61	53.530	9.076	64.0	57.4	6.6	64.7	58.0	6.7	97.32	26.36	2.08
201410300846_1_2.csv	DPT_P1&P2	1.97	1135	0.626		2.40	1.01	0.756	0.250	2.0	1.6	0.4	1.7	1.5	0.1	70.25	0.66	2.54
201410300846_5.csv	DPT_P5	31.04	3096	27.323		61.21	61.48	52.640	8.841	62.0	55.4	6.6	64.4	57.1	7.3	69.58	26.96	2.03

TEST NAME	Cycle [2]	Ave Speed	Test Duration	Distance	Ave Pos Wheel Power	Drive [1,3] Energy	Net [1] Energy	Regen [1] Energy	Drive Energy	Net Energy	Regen Energy	Drive Energy	Net Energy	Regen Energy	start SOC [4]	delta SOC [4]	Hioki Energy Rate
n/a	n/a	mi/hr	sec	mi/cycle	kW	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	kWhr	%	%	kWhr/ mi
n/a	PDT1	6.33	3051	5.38	11.89	10.44	7.39	3.04	13.00	10.88	2.12	13.26	10.90	2.36		4.8	2.03
n/a	PDT1	6.89	3051	5.85	13.58	11.86	8.15	3.70	14.70	11.90	2.80	14.80	12.21	2.59		5.7	2.09
n/a	PDT2	9.51	3367	8.92	21.51	20.48	13.51	6.97	23.70	18.28	5.42	24.20	18.42	5.78		9.1	2.07
n/a	PDT2	9.55	3367	8.95	22.10	21.02	13.62	7.39	24.00	18.80	5.20	25.26	19.00	6.26		9.3	2.12
n/a	PDT3	23.52	4231	28.31	46.21	63.75	54.31	9.43	66.00	59.11	6.89	66.50	59.61	6.89		27.2	2.11
n/a	PDT3	23.26	4231	27.97	45.46	62.62	53.42	9.19	64.00	56.99	7.01	66.23	58.65	7.58		27.9	2.10
n/a	UDDS	19.2	1061.0	5.67	54.5	16.1	10.2	5.9	17.6	13.6	4.0	18.7	14.2	4.5		6.2	2.50
n/a	UDDS	19.0	1061.0	5.62	53.2	15.7	10.1	5.5	17.1	12.8	4.3	17.8	13.2	4.6		6.4	2.35
n/a	7% Grade	35.9	602.0	6.01	201.3	33.7	33.4	0.2	38.9	38.7	0.2	40.2	40.0	0.2		19.3	6.65
n/a	7% Grade	32.8	411.0	3.75	199.8	22.8	22.6	0.2	26.9	26.7	0.2	27.8	27.6	0.2		13.7	7.37
n/a	55 mph Cruise	50.2	1461.0	20.4	102.8	43.3	41.7	1.5	41.0	39.1	1.9	41.4	39.9	1.4		23.3	1.96

[1] **Drive**, Net and Regen power as measured by the chassis dynamometer, Hioki power meter, and the Vehicle CAN network system. The Drive power is the power absorbed by the chassis dyno during accelerations or supplied by the battery system to move the vehicle forward. Net power is the sum of the Drive – the Regen power (ie the overall energy usage). Regen power is the power absorbed by the chassis dyno during decelerations or supplied to the battery system (ie enegy recovery). [2] **These** test results calculated from individual phases from the port cycles phase 1, 2, 3, 4, and 5. PDT1 = PDT_P1&P2+P3, PDT2 = PDT_P1&P2+P4, PDT3 = PDT_P1&P2+P5. [3] **Drive** energy for the chassis appeared to be in error due to some values exceeding Hioki drive system. As such, the Chassis Drive values are colored blue and are suspect. Additional investigation is being considered to understand the Chassis Drive results. [4] **SOC** is the vehicle state of charge measurement from the dashboard and the CAN network. The dashboard and vehicle CAN network measurements were in agreement and the CAN network data was used for the report.

Table D3 UCR daily test log

Date	Test Time	Vehicle Name	Vehicle ID	Project	Dyno Cycle	File ID	Operator	Hp@50	Vehicle Weight	A	B	C	Comments
10/29/2014	6:43:09 AM	1FUBCYBS4HT9041	9E47564_65	2014_TransPower	Warm up	201410290643							
10/29/2014	7:25:17 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	SG-1	201410290725	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	7:52:28 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	SG-2	201410290752	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	8:24:08 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	UDDS	201410290824	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	9:28:07 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P3	201410290928	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	10:04:33 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P4	201410291004	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	10:54:50 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	UDDS	201410291054	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	12:07:30 PM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P3	201410291204	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/29/2014	12:54:27 PM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P4	201410291254	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	Abort Dyno Issue
10/29/2014	12:58:21 PM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P4	201410291258	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/30/2014	6:45:35 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT3	201410300645	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/30/2014	8:16:58 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P1&P2	201410300816	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/30/2014	8:46:01 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT3	201410300846	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/30/2014	10:06:10 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	DPT_P1&P2	201410301006	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	
10/30/2014	10:28:45 AM	3HSDJSJR6EN792183	2014_005	2014_TransPower	CD_55MPH	201410301028	Ed/Don	128.6	71960	511.0913	2.83E-15	0.1814335	

Table D4 Vehicles tested as part of the comparison testing results

Description	Conventional	Hybrid-Diesel	Elec_2011	Elec_2014
Vehicle curb Weight (lb)	15,000	16,000		24,000
Towing capacity (lb)	65,500	64,000		56,000
Motor power rating (kW)	280-335	280		300
Automated Manual Transmission				Need information
Energy Stored (kWh) (Usable)	n/a	39		215 maximum 172 usable (20% reserve)
Electric drive motor (kW)	n/a	50 DC		250 kW continuous 300 kW peak
Inverter/Charger	n/a	n/a		70 kW 208VAC, 200A 3-phase conductive charging on-board
Batteries	n/a	$LiFEPO_4$		384 VDC, 400 Ah. 154 kWh total usable
Recharge time using onboard charger (hrs)	n/a	n/a		<2 hours from 20% to 95%
Loaded range (miles)	400	450		75 based on 2.3 kWh/mi
Loaded range @ 50 mi/day (days)	8	9		1.5
Exhaust emissions	not zero conventional	not zero conventional		Zero at point of

Table D5 Test log and notes for the Class8_2014 testing on 10/29/2014 and 10/30/2014

Test #	Test Day	Dyno ID	Cycle	Starting SOC	Odometer	Test Weight	TransPower ID	Comments
0	0	n/a	Warm up					
1	1	201410290725	SG-1	96.0		71960	DynoRunSG1_1(0)	First run of the day with cold batteries simulating climb up the Gerald Desmond bridge from a running start
2	1	201410290752	SG-2	77.0		71960	DynoRunSG2_1(0)	Simulating climb up Gerald Desmond bridge from 0 speed
4	1	201410290824	UDDS	64.0		71960	EDD2DynoRunUDDS_1(0)	
5	1	201410290928	DPT_P3	57.0		71960	EDD2DynoRunDPT_3_1(0)	SpeedMatchFailFault during Shift from 2 to 1. Fault did not reset itself. Had to stop and cycle key.
5	1	201410291004	DPT_P4	52.0		71960	EDD2DynoRunDPT_4_1(0)	
6	1	201410291054	UDDS	44.3		71960	EDD2DynoRunUDDS_2(0)	
7	1	201410291204	DPT_P3	37.0		71960	EDD2DynoRunDTP3_2(0)	
8	1	201410291258	DPT_P4	31.9		71960	EDD2DynoRunDPT4_2(0)	
	1	201410291600	Vehicle chargning connected to the grid					
1	2	201410300645	DPT3	99.1		71960	EDD2DynoRunDPT3Complete_1(0)	Long Haul Port Cycle
2	2	201410300816	DPT_P1&P2	71.0		71960	EDD2DynoRunDPT1+2_1(0)	Creep at port cycle
3	2	201410300846	DPT3	70.0		71960	EDD2DynoRunDPT3_2(0)	ShiftMotorOverspeedFault and SpeedMatchFailFault at low speeds downshift. The truck self recovered.
4	2	201410301006	DPT_P1&P2	42.0		71960	EDD2DynoRunDPT1+2_2(0)	
5	2	201410301028	CD_55MPH	41.7		71960	EDD2DynoRunCD_1(0)	Ramp up to 55 MPH and drive till we reach 23% SOC

[1] Charging of battery was completed overnight. Chassis augmented braking is off. Class 8 tractor weight is 4,000lb heavier than conventional, thus loads reflect this in the assigned GVW for test weight

Appendix E – Hioki Power Measurements

The measurement specifications of the Hioki meter are provided in the following list (Hioki user manual). This instrument was used to measure the total vehicle energy, power, and current usage in addition to on vehicle CAN measurement provided with the vehicle.

High accuracy over a broad range

- Basic accuracy is ±0.05% rdg. ±0.05% f.s. at DC and from 0.5 Hz to 150 kHz.
- Precise measurements over a broad range of inverter carrier frequencies: ±0.2% rdg. ±0.1% f.s. at 10 kHz, and ±1.5% rdg. ±0.5% f.s. at 100 kHz.

Provides both fast data processing and high accuracy

- While maintaining high accuracy, power measurements and harmonic analysis updates every 50 ms.
- During low-frequency measurements, data is automatically updated in sync with frequency, so no refresh (data update rate) switching is needed when changing from low to high rotation rates.

Extensive data analysis functions are included as standard features

- Simultaneously measure RMS, mean, AC and DC components, and fundamental waveforms.
- Perform harmonic analysis up to the 100th order and inverter noise (FFT) analysis up to 100 kHz.
- Display high-speed waveforms sampled at up to 500 kS/s.
- Perform multifaceted analysis with X-Y graph functions.

Simultaneous analysis of all parameters

- Simultaneously analyzes harmonics and noise while performing integration and displaying waveforms.