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Heavy-Duty PHEV Yard Tractor: Controlled Testing and Field Results

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Abstract

Diesel powered tractors are used to shuttle cargo trailers from point to point within the confines of a port facility, terminal or warehouse yard. Such operations are similar to those in ground support applications at airports and in industrial warehouses with lift trucks, in that the vehicles are used as tools to move goods in a semi-regular pattern. Southern California Edison Company (SCE) and the Electric Power Research Institute (EPRI) have partnered to help electrify vehicle operations in both of those venues with great success and see good prospects for the same at port operations. However, current port operations might require large investments in infrastructure and operational changes to implement electric drive all at once. To help demonstrate the benefits of electric drive without requiring large-scale changes, a plug-in hybrid electric vehicle (PHEV) yard tractor design was proposed by EPRI and member utilities as a means to reduce operational emissions and diesel fuel use. Four member utility companies with large port customers in their service area (SCE, Southern Company, CenterPoint Energy, and New York Power Authority) agreed to work with EPRI to study the benefits and impacts of a PHEV yard tractor. In 2007 the Electric Power Research Institute (EPRI) contracted US Hybrid Corporation (USH) to design and construct a unique PHEV yard tractor. SCE agreed to test and evaluate the PHEV yard tractor for EPRI.

To properly evaluate the benefits realized by the yard tractor in comparison to unmodified conventional yard tractors as well as other alternative fueled tractors, SCE had to test the tractor in controlled conditions with realistic loads in addition to field testing. SCE developed test procedures for controlled testing and for field evaluation. The field testing was conducted in four ports across the United States, each with different operating conditions and climate: Long Beach, California; Houston, Texas; Savannah, Georgia; and New York City.

SCE designed a test procedure that simulates an accelerated duty cycle of cargo operations. The accelerated duty cycle has multiple starts and stops and little idle time. SCE measured the idling fuel consumption separately so it can be inserted to match the duty cycle of any particular port. The test cycle was performed with the vehicle both unloaded and loaded to profile the effects of load on system

efficiencies. SCE also tested the battery and charger performance of the PHEV, and as a comparison, tested an unmodified yard tractor.

In the accelerated testing, SCE found the PHEV fuel savings were as high as 60% (on a per-cycle basis) when compared to a stock diesel Kalmar tractor, and up to 35% fuel savings versus operating the PHEV tractor as a hybrid (i.e, not charging it), In charge sustaining operation, the fuel savings are as high as 40% compared to the stock vehicle. On a daily-operation basis, the projected fuel savings on a duty cycle similar to the SCE test cycle could be as low as 35% but as high as 60% with significant amounts of idling and low speed operation.

The field test results show good fuel economy but are complicated by reliability issues that reduced the operational time of the prototype PHEV vehicle. Also, it was difficult to get fleet fuel use data. It was the intention in the project to compare the test vehicle's results with the fleet average fuel use per unit time. These results will be discussed in the body of the paper. Port operators, in general, appreciated the engine-off mode's reduced noise and exhaust.

The US Hybrid prototype PHEV yard tractor has the potential to significantly reduce fuel consumption, as demonstrated in the SCE tests. Performance issues with the prototype prevented full duty in the field tests. Further testing, with a more reliable vehicle incorporating the key system improvements learned from this project, is worth pursuing to determine if the potential fuel savings can be fully realized in larger scale. Furthermore, the techniques and testing methods described can be used for other alternatively-fueled yard tractors.

Keywords: Southern California Edison, EPRI, non-road, yard tractor, PHEV

1 Introduction

1.1 Background

The diesel-powered tractors that pull containers and cargo are used extensively in ports, warehouses, and other applications where it is necessary to shuttle cargo trailers from point to point within the confines of a specific facility, terminal or yard. Often called yard tractors, yard hostlers, or terminal tractors, this equipment is of a specific design with a single driver compartment and a fifth wheel that has the ability to be raised and lowered. These widely used yard tractors are unique to the cargo industry.

Seaports are under increasing pressure to reduce operational emissions. Some ports and their tenants are beginning to take significant steps in reducing emissions from various aspects of their operations, from lower sulfur fuels in vehicles and equipment to electric power for ships docked in port. Many emission reduction efforts focus on cargo handling equipment such as the yard tractor due to this sector's share in port emissions and concerns over oxides of nitrogen (NOx) and particulate matter (PM) emissions that result from this equipment. Electric technology can play an important role in this target sector by significantly reducing equipment emissions.

This project, managed by the Electric Power Research Institute (EPRI), with participation by Southern California Edison (SCE), CenterPoint Energy, New York Power Authority, and Southern Company, began in earnest in 2007 when EPRI contracted for the design and construction of a first of a kind PHEV yard tractor. SCE provided oversight of the development of the prototype vehicle, developed vehicle evaluation procedures, conducted tests, and collected and analyzed the field data under a subcontract to EPRI.

1.2 Vehicle Characteristics

The goal of the EPRI project was to develop a vehicle that could demonstrate the fuel economy benefits and emissions reductions of electrifying a major source of off-road emissions in port areas, without compromising vehicle functionality in those areas that had not installed charging infrastructure to a large extent. The US Hybrid prototype PHEV yard tractor is a post-transmission parallel hybrid system installed on a Kalmar Ottawa yard tractor. The original engine and transmission are unmodified with the US Hybrid 125 kW, 1000 newton-meter electric motor installed between the transmission and the axle. The PHEV yard tractor has a nominal 32 kWh LTC/Gaia lithium-ion battery pack. The motor controller, charger, and battery are integrated on the right-hand side of the vehicle, outboard of the frame rails, and aft of the cab and forward of the wheels. The added weight of the hybrid system is approximately 2,100 pounds, for a total weight of 17,300 pounds,. The gross combined vehicle weight rating of the PHEV yard tractor is unchanged at 96,000 pounds. The maximum speed of the vehicles is just under 20 mph.

2 Controlled testing procedures

SCE decided that a controlled test similar to real world conditions could simulate the port environment better than a dynamometer test.

To test on a dynamometer, two different coast down profiles would have been needed, loaded and unloaded. Then when testing, the operator would have to alter the weight and horsepower profiles between cycles, and it would be difficult to simulate accurately the trailer pickup and drop-off maneuvers.

2.1 Vehicle Drive Loop Efficiency Tests

SCE designed a test loop that was flexible enough to simulate all sorts of duty cycles. The test cycle used was designed to simulate a near 100% duty cycle with short pauses between cycles. With this method, which is efficient in terms of test time, other duty cycles could be simulated by measuring the idling and creeping fuel consumption and interjecting various amounts of idle time between the actual test loops.

In dynamometer testing, a driver typically follows a trace screen to recreate speeds in a given sequence. Since this is difficult to perform in use, with the complex tasks of picking up and dropping off containers, SCE decided to use a space-oriented approach rather than a speed oriented approach.

The drive loop tests are designed to test the yard tractor under conditions similar to actual yard tractor operations. SCE initially looked at dynamometer cycles developed by CALSTART [1] but decided that these wold be too difficult to implement on a repetitive course. Instead, SCE used a simplified cycle similar to the duty cycles the PHEV manufacturer used in the original proposal for modelling. The test course was designed such that the distances matched a speed profile used by the manufacturer in simulations.

2.1.1 Vehicle Drive Loop Course

The test course was designed with two sections to simulate two types of operation. The inner loop was designed to emulate stop-and-go movement and queuing, while the outer loop was designed to give the operator a chance to develop speed. The course is laid out as shown in Figure 1 The course has an inner loop (A-B-C-D-E-A) and an outer loop (A-F-C-D-G-E-A). The points labeled A through G are marked with traffic cones. The cones denote the inner portion of the drive path.

2.1.2 Driving the Course

The driver starts at position A without trailer, drives to B and comes to a complete stop and pauses 5 seconds. The driver then proceeds to C,

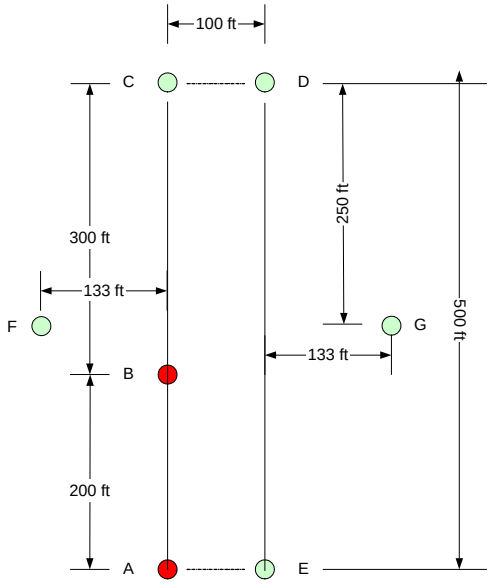

Figure 1 Layout for Yard Tractor Test Loop

D, and then E, turning at each, and comes to a full stop at A and pauses 5 seconds. Repeat three more times, for a total of four loops for this sequence. The driver then drives the outer loop from A to F to C to D to G to E to A non-stop for a total of three times and then comes to a complete stop at A. The driver then connects a trailer (if applicable) and starts the second cycle of seven loops with the trailer, completed by unhooking the trailer (if applicable) at A. In brief, the sequence is:

- 4 times: AB(stop) CDEA(stop)
- 3 times: AFCDGEA (stop)
- Stop, Hook/Unhook trailer
- Repeat

The driver records the number of loops driven. After each set of seven loops the driver records fuel consumption, state of charge, and time. This sequence of seven loops constitutes one complete test cycle, covering an overall distance of 8800 ft, or 1.7 miles (2700 m), with 45 seconds idling for unloaded cycles, and approximately 90 seconds idling for each trailer change, for a total of three minutes, forty-five seconds idling for loaded cycles.

In EV mode, the test was done without a trailer and then again with a loaded trailer to obtain clear metrics on the electrical energy consumption (AC kWh/mi). In the hybrid and diesel modes, the testing was performed as described above.

2.2 Controlled Test Results

The first test conducted by SCE was the electric vehicle (EV) range test. This was performed in the EV-only mode with no engine operation until the minimum SOC level was reached, and the engine started. The EV1 test (unloaded) was done with no trailer or payload and the EV2 test (loaded) was done with the trailer and payload included.

The PHEV yard tractor completed an average of nine drive cycles (with one cycle being seven loops, two miles total) during EV1 testing before the system turned the engine on to recharge the battery (Table 1). SCE found the SOC data unreliable and it is not included in this report. The USH-reported SOC difference was not correlated well with recharge energy. Reported SOC sometimes dropped from 20% to 4% between key off and back on. After charging, a difference in ending SOC from 10 to 12 % was not uncommon. This indicates recalculation of SOC by the LTC battery management system during key-on. For further information about this issue see [2].

Table 1 EV mode, unloaded

Cycles Electric	AC kWh Recharge	AC kWh/Cycle	AC kWh/mi
9.0	29	3.2	1.9

During EV2 testing, with loaded trailer, the vehicle completed an average of 3.2 drive cycles (Table 2) before engine start – a 64% reduction in EV range. The data shows a 159% increase in energy use per cycle for the loaded test.

Table 2 EV mode, loaded

Cycles Completed	AC kWh Recharge	AC kWh/Cycle	AC kWh/mi
3.2	27	8.3	5.1

The next test conducted was the diesel mode test in which the PHEV was operated solely in the diesel mode with no electric-powered operation. This means that it was operating like a conventional diesel tractor, with the difference of the extra 2000 pounds of the PHEV system and additional rotating losses of the electric machine. SCE conducted three tests with test periods of approximately one, two, and three hours respectively. The results (Table 3) showed an average diesel fuel consumption of 0.8 gallons/cycle, with an uncertainty of +6%, -7%. In terms of comparative energy use, 0.8 gallons of diesel fuel converts to approximately 29 kWh/cycle (assuming 125,000 BTU per gallon) which is 250% or 3.5 times the energy per cycle used in EV mode (EV2 test). [3]

Table 3 PHEV Tractor in diesel mode

gal/cycle	Gal/hr	Gal/mi	mpg
0.8	3.1	0.3	3

SCE conducted tests of a conventional unmodified Kalmar Ottawa diesel tractor on two occasions, for about three hours each. The results showed an average diesel fuel consumption of 0.74 gallons/cycle (Table 4). This shows an approximate increase in fuel use in the PHEV with electric drive disabled of about 3% to 8%, due to weight and losses. The gallons per cylce in table 3 show lower precision because of the higher variability of the PHEV results during testing.

Table 4 Unmodified Kalmar Ottawa

gal/cycle	gal/hr	gal/mi	mpg
0.74	4.3	0.4	3

The PHEV hybrid mode loaded test consists of two modes of operation, the charge depleting mode and the charge sustaining mode. In the initial portion of the test the PHEV operates in the charge depleting mode (electric power only) until the battery is discharged to the point at which the diesel engine starts to begin maintaining the battery state of charge. The number of cycles achieved in this mode is recorded as "electric" cycles. Then the PHEV operated in the charge-sustain mode (electric and engine power).

During the charge-depleting parts of the tests the vehicle completed 3.4 and 3.1 electric cycles (similar to EV2 test) before the engine came on (Table 5). During the charge sustaining portion of testing, the vehicle completed 6.6 charge sustaining cycles before a red light ended the first test and 10.1 charge sustaining cycles in the second test. The two tests showed an average diesel fuel consumption of about 0.3 gallons/cycle, but it must be remembered that this result is only valid for the test length presented. Plug-in hybrid fuel economy is not linear, but starts at infinity and declines on a curve to some charge-sustaining band for the remainder of the drive. Therefore, the fuel efficiency results are presented here, and are valid only, for the “10 to 13 Cycle Test.”

Table 5 Hybrid mode, loaded

Date of test	11/25/2009	11/30/2009
Duration (h:min)	3:28	2:57
Cycles Electric	3.4	3.1
Cycles CS	6.6	10.1
Cycles total	10.0	13.3
Recharge AC kWh	28.03	30.41
Diesel gal	3.52	4.00
Diesel gal/cycle	0.35	0.30
Diesel gal/hr	1.02	1.36
Diesel gal/mi	0.19	0.15
mpg	5	6

In June of 2010, SCE had a brief opportunity to retest the PHEV yard tractor. In the intervening time, US Hybrid had devoted engineering time to improve the data accuracy. Over the four-hour lab retests, the US Hybrid iDrive underreported the fuel by 5.4%.

Table 6 June retest

Date of test	6/9/2010	6/10/2010
Duration (h:min)	3:31	4:04
Cycles Electric	5.3	5.3
Cycles CS	10.7	13.7
Cycles total	16	19
Recharge AC kWh	25.13	29.18
Diesel gal	6.36	8.87
Diesel gal/cycle	0.40	0.47
Diesel gal/hr	1.81	2.18
Diesel gal/mi	0.23	0.25
mpg	4	4

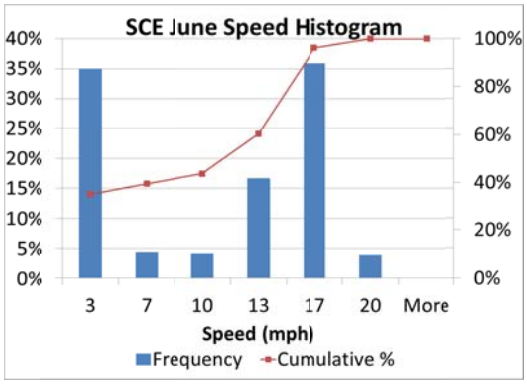

Figure 2 SCE Testing Speed Histogram

A histogram of the speeds used in the June re-test is shown in Figure 2. The distribution is weighted toward low speeds (creeping and trailer change operations) and the fully developed speed.

3 Field Trials

The field tests took place in four ports across the United States. The sites were in the service territories of the four participating utilities (Southern California Edison, CenterPoint Energy, New York Power Authority, and Southern Company) with operators that were interested in reducing fuel use and emissions. These operators had different facilities, operating cycles, and weather conditions. The PHEV yard tractor was initially placed with the Long Beach Container Terminal in Southern California Edison’s service territory in the Port of Long Beach. The PHEV then went to the Port of Houston Barbours Cut, a CenterPoint Energy customer. The next operator was the Georgia Ports Authority at the Port of Savannah, which is in the service territory of Georgia Power, an operating company of Southern

Company. The final placement was at the New York Container Terminal, a New York Power Authority Customer. [4]

3.1 Long Beach Container Terminal

Table 7 LBCT Results

	February (Diesel Only)	March & April (PHEV)
Hours of Operation	60	85
Miles	315	457
Fuel (gal)	95	100
mpg	3.3	4.6
Gal/engine hour	1.6	1.2
kWh	0	386
kWh/mi	0	1.2

Table 7 shows the results from the Long Beach Container Terminal (LBCT) field trial. In February, the operator switched off the hybrid mode when the hybrid system displayed a warning light, resulting in a month of diesel mode data. The key metric is the gallons of fuel per engine hour, which shows that the yard tractor in PHEV operation had 25% fuel savings improvement with more regular hybrid operation.

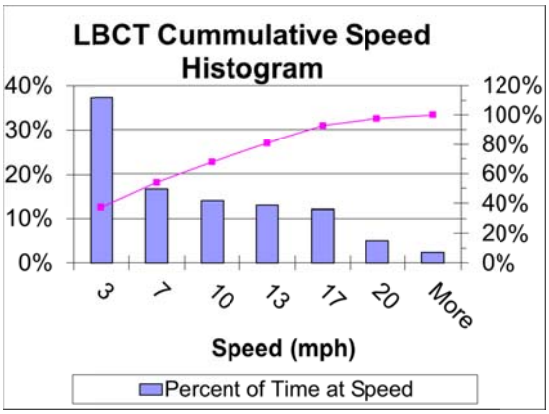

Figure 3 Long Beach Speed Histogram

The speed histogram in Figure 3 shows that the PHEV spent a lot more of its operational time in creeping or idling and low speed operation than during the SCE testing. ,

3.2 Port of Houston

The key results from the Port of Houston demo are:

- 63 hours of operation
- 336 miles
- 59 gallons of fuel
- 5.7 mpg overall
- 1 gallon/hr average
- 340 AC kWh, 1.0 AC kWh/mi overall

GPS logging enabled SCE to capture the speed profile of the operations at the Port of Houston, as shown in Figure 3. Note that this speed profile is closer to the SCE test profile than the profile at LBCT. (Figure 4).

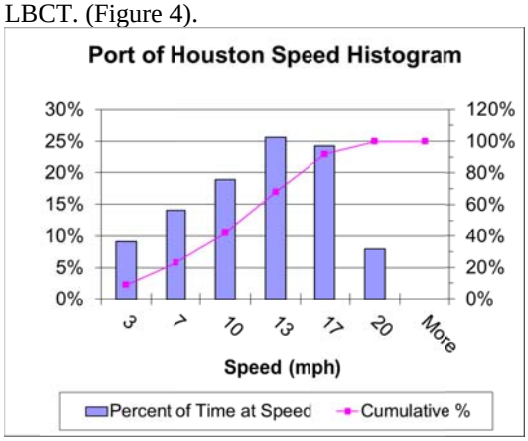

Figure 4 Port of Houston Speed Histogram

3.3 Port of Savannah

The Garden City container terminal at the Port of Savannah was situated in a location where the cell phone remote data collection was not reliable. In addition, the facility operator determined that the top speed of the US Hybrid PHEV yard tractor did not suit their needs and declined to operate it. The results shown in Table 8 are from one week of operation.

Table 8 Savannah Results

Fuel consumed - gal	22.2
Miles net	73
Operational hours	26
Results mpg	3.3
Fuel consumption gal/hr	0.85

4 Real World Correlation

Although it was intended to represent the real world, the question is, how will it compare to real world results that will come in from the field trials? In a port application there is often considerable time spent idling and creeping along at low speed. As stated previously, the valid way to judge the field trial results will be to compare

the PHEV test vehicle fuel economy to the fleet average, as no two vehicles can be guaranteed to be doing the same thing at the same time. We will see how well that can be done, given fleet data collection practices. However, we know that the metrics used to make that comparison will not involve fuel or energy on a test cycle basis, as was done in the lab tests, as in the field the unit of work cannot be held constant. So, the field test results will be based on fuel and energy on a per hour and per mile basis, since those are the metrics available.

In order to validate our test procedure, we compared the results from the first two field placements to the controlled test results. The results from the Port of Long Beach showed an average daily drive distance of 27 miles with the PHEV tractor in a rail duty application at LBCT, with an average maximum speed of 20 mph and an average speed of 8 mph. The average distance of our 10-13 cycle test was approximately 20 miles, with an average speed of 7 mph. Assuming the 27 miles was completed over an 8-hour work shift, compared to 20 miles for 3.25 hours, results in a duty factor of approximately 2. In terms of distance, our test course was about 75% of a day, and in terms of time it was about 40% of a day.

In terms of fuel consumption, early results show that at LBCT delivered 4 mpg on average with the PHEV, and Houston delivered 5 mpg. Our 10-13 cycle test results showed approximately 5 mpg.

Therefore, on a per-mile basis, the lab test may correlate well to real-world results. On a unit time basis, the lab results should differ by a factor of two. On an engine hour basis, they may correlate well, but this is dependent on the idle time. With charging every day, we estimate our 10-13 cycle test will resemble a full day of real work at the port. That is, we expect to save 30% to 60% of the fuel used by a conventional tractor.

5 Reliability Issues and Lessons Learned

One of the advantages of controlled testing versus dynamometer testing is that the vehicle is exposed to realistic conditions and loads which will reveal issues that dynamometer testing may not. In SCE's testing, the PHEV yard tractor was operated at or near the limit of its abilities, much like in actual port operation, while typical practice on a dynamometer is set in a repeatable, achievable, representative speed pattern. In addition, although SCE's testing location was paved, it was a moderately rough pavement that represented the paving conditions of the ports. This exposed the PHEV yard tractor to vibrations that would not have been experienced on the smooth rollers of a dynamometer. Combined, these factors allowed SCE and US hybrid to identify and rectify issues before deployment to ports for field trials. A breakdown of early issues with the PHEV prototype is given in Figure 5

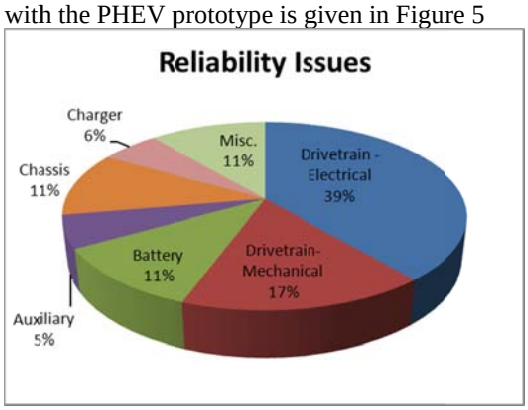

Figure 5 Early Reliability Issues

The majority of the issues experienced in the controlled testing were related to the electrical portion of the drivetrain, and the majority of these issues were controller related. Early identification of these issues allowed US Hybrid to make mechanical and software changes to the PHEV prototype that eliminated these problems in the field deployment.

The mechanical drivetrain issues were related to the OEM transmission. One issue was corrected under the manufacturer warrantee and the other was corrected by the installation of larger capacity electrically driven pump for the transmission fluid.

The battery issues were minor and addressed promptly. One of the battery issues identified by SCE was contamination by dirt and water, an issue unlikely to be revealed on a dynamometer. SCE made recommendations that US Hybrid implemented by redesigning the battery box.

The battery box was also the source of the only chassis related issues. SCE's testing led to a redesign of the battery box support, after the battery box started to tilt, based on higher than anticipated vertical loads in operations on the

rough test course. Another issue didn't show up in SCE testing but only with the first deployment. The battery box was originally situated level with the rear load platform of the yard tractor. When used with a real load at the Long Beach Container Terminal, the battery box interfered with movement of the trailer. US hybrid lowered the battery box by a scant ½ inch to remedy the problem. With all these lessons learned implemented, the key investigators in this program are proposing to conduct a second phase PHEV yard tractor demonstration to prove the capabilities, effectiveness, and savings of this promising technology.

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