Demonstration of a Liquid Natural Gas Fueled Switcher Locomotive at Pacific Harbor Line, Inc.

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Executive Summary

In an effort to reduce air emissions from rail operations within and surrounding the ports of Long Beach and Los Angeles, Pacific Harbor Line, Inc. (PHL) entered into a second amendment to its operating agreement with the ports to deploy lower-emitting technologies and fuels within the PHL fleet of switcher locomotives. A condition of the agreement requires PHL to lease or acquire one switcher locomotive fueled by liquefied natural gas (LNG) to demonstrate the technology's suitability and emissions reduction characteristics. On May 22, 2009, PHL initiated a nine-month demonstration of an LNG-fueled switcher locomotive leased from Burlington Northern Santa Fe Railway (BNSF) at the Port of Los Angeles' West Basin Container Terminal (WBCT). This 1,200 HP LNG locomotive (BNSF 1203) was the primary switcher locomotive used at WBCT during the duration of the demonstration project.

The original objective of the demonstration was for PHL to document operational parameters for the LNG locomotive (e.g., fuel consumption, reliability), and make comparisons to PHL's existing fleet of older, similarly sized diesel-electric switcher locomotives (i.e., the test "baseline" locomotives). As described in this report, PHL was unable to execute the test plan as originally written. By the time the LNG locomotive was ready to be tested, PHL had replaced its entire fleet of older 1,200 HP switcher locomotives with larger, newer technology switchers meeting or exceeding EPA's Tier 2 emissions levels.

A modified test plan was implemented in consultation with the ports. The revised plan called for the test LNG switcher to be <u>operationally</u> compared to PHL's older (phased-out) 1,200 HP diesel-electric switchers, using recent historical data. This provided the most "apples to apples" comparison because the two types of switcher locomotives are similar in size and capabilities. In addition, <u>emissions</u> comparisons were made under the revised plan of the LNG switcher versus both types of diesel-electric locomotives (the older phased out "baseline" switchers, and the new "Tier 2" switchers).

Using the modified demonstration test plan as approved by the ports, the LNG switcher was operated by PHL for a period of 36 weeks. Based on PHL-provided data and observations from the demonstration, the following conclusions are made:

<u>Operational Comparisons</u>

- Overall, the LNG locomotive performed "adequately to well" in railcar switching service. However, logistics and mechanical issues associated with storing and combusting LNG fuel negatively impacted the locomotive's reliability and service capability.
- According to PHL, the level of effort required to support fueling and address fueling-related mechanical issues was unusually high. These mechanical issues with LNG fueling compounded already difficult fueling logistics associated with requirements imposed by the local fire department.

- The average fuel consumption for the test locomotive (including fueling losses and boil off) was 72 diesel-equivalent gallons per day. A comparable (baseline) diesel switcher tested by PHL under a different program[1] consumed about 65 diesel gallons per day. For this comparison, it appears that the newer engine technology of the LNG locomotive roughly offset two inherent inefficiencies of dedicated LNG engines with respect to fuel consumption, which are: 1) the lower thermal efficiency of spark ignition compared to compression ignition; and 2) fueling and boil off losses associated with LNG.
- Despite its apparent higher rate of fuel consumption, the LNG locomotive cost approximately 23% less to fuel on an energy-equivalent basis, due to the lower price paid by PHL per BTU of LNG fuel compared to diesel fuel.

Emissions Comparisons

Based on the use of existing emissions factors rather than actual emissions testing, the following conclusions are made about the relative emissions of the three locomotive types / technologies:

- The LNG switcher locomotive emits an estimated 92% less oxides of nitrogen (NOx) and 76% less particulate matter (PM) compared to the baseline (uncontrolled) diesel locomotives.
- The LNG switcher locomotive emits an estimated 81% less NOx and 57% less PM than PHL's new Tier 2 locomotives.
- It is important to recognize that these three types of switcher locomotives differ significantly in age and emissions control technology, among other factors. This makes it difficult to isolate the emissions reduction contributions of using cleaner-burning LNG fuel in the test locomotive.

[1] GreenGoat™ hybrid locomotive demonstration, conducted by PHL in cooperation with the ports.

1. Introduction

1.1 Project Background

In an effort to reduce air emissions from rail operations within the ports of Long Beach and Los Angeles, the ports entered into a second amendment to Pacific Harbor Line, Inc's (PHL) operating agreements with the ports to deploy lower-emitting technologies and fuels in PHL's fleet of diesel locomotives and investigate various low-emission locomotive technologies, including an LNG-powered locomotive. Requirements for the LNG-locomotive demonstration program were outlined in the second amendment, with details of the program provided by the ports in an oversight capacity.

The LNG locomotive, a 1,200 HP switcher locomotive leased from BNSF Railway (BNSF 1203), entered service at the Port of Los Angeles' West Basin Container Terminal on May 22, 2008 and operated for a period of 36 weeks. West Basin Container Terminal was selected as the location to demonstrate the LNG locomotive due to the stringent permit requirements of the local fire department, which limited the use of the LNG locomotive to a location where fueling[2] of the locomotive would not interfere with other rail or terminal activity.

The test plan called for operation of the LNG engine in tasks normally performed at PHL by similarly rated diesel switchers including tandem and solo modes of operation. As discussed later in this report, PHL was unable to execute the test plan exactly as written, but instead made modifications to the plan in consultation with the ports. Operational parameters including fuel consumption and reliability data were documented by PHL during the demonstration, and are presented in this report.

1.2 Contractual Requirements

The Second Amendment to PHL's Operating Agreements with the ports state that PHL "shall timely lease or otherwise acquire" the use of an "LNG powered locomotive" for use in the ports "to demonstrate the suitability and emissions reductions characteristics of these locomotives." PHL is required to acquire the LNG locomotive within one year of the second amendment's effective date, and to "obtain Owner's (the ports') approval of the specific type and/or capabilities of such locomotives." It further states that the ports will approve the one-year[3] service demonstration.

[2] The LNG locomotive was fueled using a mobile LNG-refueling truck; this "wet fueling" technique is common for demonstrations involving small numbers of LNG test vehicles.

[3] The ports and PHL mutually agreed to terminate the demonstration at nine months given the timing of PHL's turnover of its 1,200 HP switcher locomotives to newer, lower-emitting locomotives.

To demonstrate the suitability and emissions reductions potential of the LNG locomotive technology, PHL was required to document the following parameters during the demonstration:

- Emissions
- Fuel consumption
- Availability
- Reliability
- Service capability
- Maintenance
- Support requirements

2. Pacific Harbor Line Report

2.1 Program Goals

The goal of the demonstration program was to evaluate the LNG-powered locomotive technology under the ports approved test plan within PHL's unique operational demands. In meeting the contractual requirements of the demonstration program, PHL was able to offer valuable data, including PHL staff's expert opinion on the suitability of LNG engine technology as a substitute for conventional diesel-electric switcher locomotives of similar size and usage serving the Ports.

2.2 Test and Control Locomotives

Currently, PHL operates a fleet of 22 diesel-electric locomotives. Sixteen locomotives meet the Environmental Protection Agency's Tier 2 standards for switcher locomotive engines and six are engine-generator, or "gen-set" switcher locomotives meeting Tier 3 standards. Previously, PHL operated five 1,200 HP switcher locomotives referred to as "smurfs" (see Figure 1). These locomotives operated primarily in the Port of Los Angeles' West Basin Container Terminal as single engines, and in intermodal service as tandem units. The LNG locomotive leased by PHL for the demonstration has similar performance characteristics to the "smurfs" as shown in Table 1.

Figure 1. Test Unit (BNSF 1203), Baseline Unit (PHL 32), and Tier 2 Unit (PHL 20)

Table 1. Specifications for the LNG, Baseline, and Tier 2 Switcher Locomotives

Datum / Parameter	Test (LNG) Locomotive	Baseline ("Smurf") Locomotive	Current Fleet (Tier 2) Locomotive
Locomotive Type / Model	MK1200G* Switcher	EMD SW1200 Switcher	Motive Power MP20B Switcher
Locomotive Model Year	1994	1957	2008
Engine / Powerplant	Caterpillar G3516 SITA (Spark-Ignited Turbocharged Aftercooled)	12-567-C Block	MTU-Detroit Diesel 12V4000R33
Fuel Type	Liquefied Natural Gas (LNG)	CARB Ultra-Low Sulfur Diesel[4]	CARB Ultra-Low Sulfur Diesel
Drive System	Series Hybrid-Electric / DC Traction Motors	Series Hybrid-Electric / DC Traction Motors	Series Hybrid-Electric / DC Traction Motors
Locomotive No.	BNSF 1203	PHL 32	PHL 20 / PHL 21
Tractive Horsepower / Max. Weight	1,200 HP / 250,000 lbs.	1,200 HP / 248,000 lbs.	2,000 HP / 289,000 lbs
Tractive Effort (Starting)	68,800 lbs	62,500 lbs	85,000 lbs
Traction Motors	D78B (4)	D77 (4)	D78B (4)
Emissions Certification	None (Prototype)	None (EPA Tier 0)	EPA Tier 2

*For detailed specifications and the history of the Test Locomotive technology, refer to information provided by the manufacturer at http://www.lngplants.com/mk1200G.htm

In basic operation, the LNG-electric powered locomotive is no different than PHL's fleet of old (phased out) or new (Tier 2) diesel-electric powered switchers. Each technology uses electric traction motors powered by electricity generated from on-board steady-state engines that operate within a series of "throttle notches." The major difference is that the test locomotive uses LNG rather than diesel to power its steady-state engine. Because LNG is a clean-burning fuel, this fuel switch can provide significant reductions of PM and NOx emissions. However, many other factors affect emissions levels from these three types of locomotives, including engine age, type of

[4] According to PHL, it transitioned from using CARB low-sulfur to ultra-low sulfur diesel (ULSD, 15 ppm sulfur) in January 2007. See http://www.anacostia.com/pdfs/PHLLowEmissionLoco07.pdf.

combustion process, and existence of emissions control technology (if any). Some of these factors are summarized in Table 1 above.

Operating a locomotive using LNG requires significant changes to the fuel system of the test locomotive. The most significant change is the use of highly insulated fuel tanks that allow LNG fuel to maintain its cryogenic temperatures (approximately -260^{o} F). The increased bulk of the LNG tanks combined with the lower volumetric energy density of LNG[5] results in a locomotive that typically provides less operating time per fueling event than its diesel counterpart (further discussed below).

Table 2. Fuel capacities by fuel type

Datum / Parameter	Test Locomotive	Baseline Locomotive(s)	Tier 2 Locomotive(s)
Fuel Capacity	1,400 gallons LNG	900 gallons Diesel	2,500 gallons Diesel
Diesel Equivalent Gallons	840	900	2,500

2.3 Demonstration Test Plan

Beginning in early August of 2006, PHL began working with the ports to develop a test plan that would capture the necessary data to implement a meaningful LNG locomotive demonstration. The resulting test plan outlined a one year test consisting of two phases. In the first phase the LNG locomotive was to be operated for six months in tandem with a diesel switcher from the PHL fleet. Typically, two 1,200 HP diesel switchers ("smurfs") were used to provide intermodal service. The size and power of the LNG locomotive made it a comparable replacement for one of the diesel smurf units. In the second phase of testing, the LNG locomotive was to operate in "solo" mode providing car switcher service at the Yang Ming yard (shown in Figure 2-2.)

In 2007, PHL began phasing out its 1,200 HP diesel switcher smurfs, replacing them with the newer Tier 2 switcher locomotives. As a result, the tandem operation portion of the original test plan was not conducted. Instead, the LNG locomotive was operated in "solo" mode for the entirety of the demonstration period, and the performance of the LNG locomotive has been compared to historical data of a smurf in the same solo mode of operation.

[5] According to the LNG locomotive's manufacturer, under normal operating conditions a fuel capacity of 1,400 LNG gallons on the LNG switcher would have the energy equivalent of about 900 gallons of diesel fuel on a diesel-powered switcher (1.55 LNG gallons = one diesel gallon). The table above assumes that 1.67 LNG gallons = one diesel gallon.

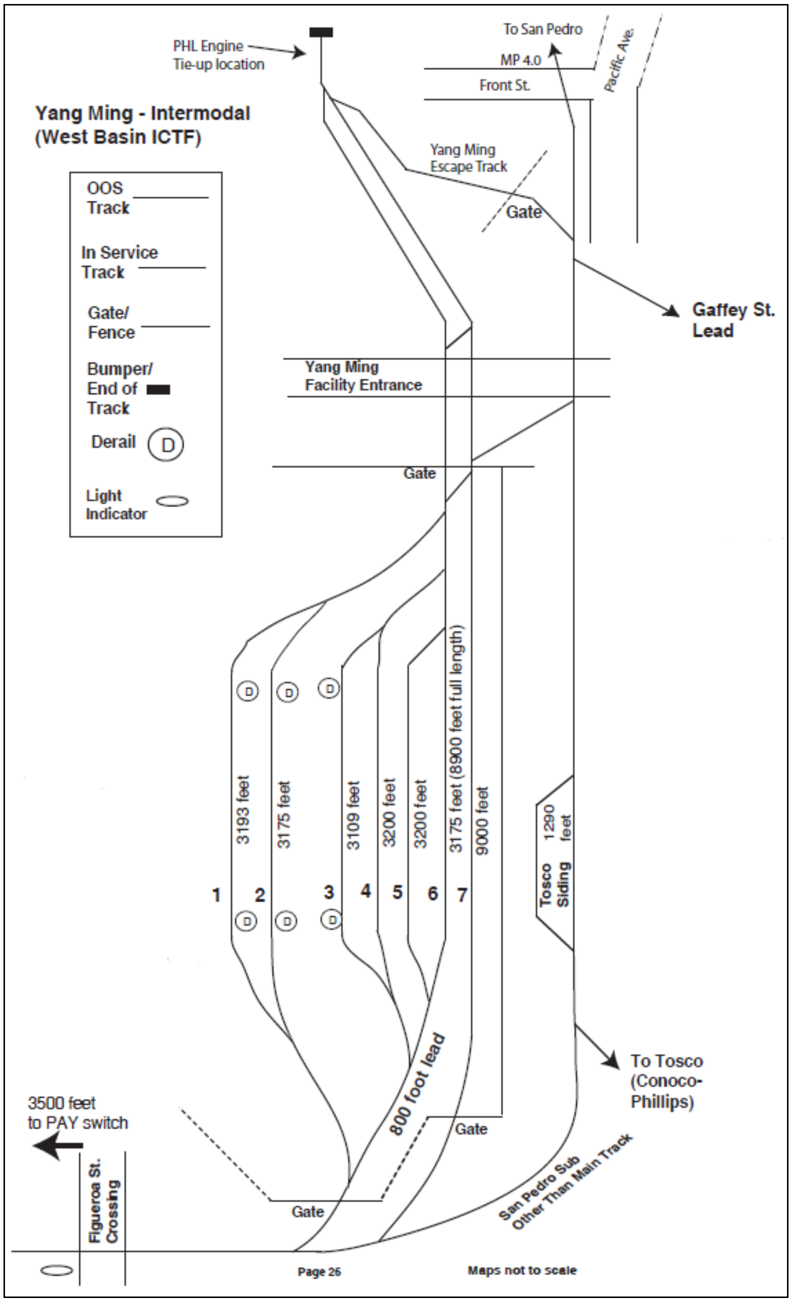

Figure 2-2. Yang Ming Yard Diagram

3. Demonstration Program Results

3.1 Emissions

Due to budget and time constraints, emissions tests were not performed on the LNG or diesel locomotives for this project. As a surrogate, existing emissions data for the LNG and diesel locomotives (both types) were used to derive estimated emissions levels in duty cycle similar to PHL's typical switcher operations. Emissions factors from PHL's diesel fleet are taken from the Port of Long Beach emissions inventory for 2008; these data are used in this report for the baseline diesel emissions rates. LNG emissions rates are taken from a report prepared by BNSF Railway, Union Pacific Railroad, and others as presented to the California Air Resources Board[6]. The emissions data for the LNG locomotive were collected prior to EPA establishing a switcher duty cycle, but they represent the only known emissions rates for the Caterpillar 3516G in a switcher locomotive application. Based on the similarity of the duty cycles between the diesel and LNG locomotives, discussed further in Section 3.5, it is reasonable to assume that emissions from the locomotives would be comparable to the ratios of the emissions rates given in Table 3. Specifically, one would anticipate a 92% reduction in NOx and a 76% reduction in PM from the LNG locomotive compared to the "Tier 0" (uncontrolled) baseline diesel locomotive. Compared to PHL's current fleet of Tier 2 diesel locomotives, one would anticipate an 81% reduction in NOx and a 57% reduction in PM from the LNG locomotive.

It is important to note that this does not represent an "apples-to-apples" comparison suitable to accurately quantify the emission reduction effects of switching a given locomotive from diesel to LNG technology, due to major differences in the engines of the three locomotive types (age, emissions control technology, etc.).

Table 3. Emissions rates for LNG, baseline diesel, and Tier 2 locomotives

Locomotive Type	Fuel	NOx	CO	THC	PM
MK1200 LNG	LNG	1.4	2.2	3.3	0.09
Baseline Diesel	Diesel	17.6	1.83	0.87	0.38
Tier 2 Diesel	Diesel	7.30	1.83	0.52	0.21

Diesel emissions data collected using EPA, 40 CFR Parts 85, 89, and 92, Emission Standards for Locomotives and Locomotive Engines. Values in grams/brake horsepower-hour. Tier 2 Diesel emissions rates taken from Port of Long Beach 2008 Air Emissions Inventory, Table 5.1

[6] An Evaluation of Natural Gas-fueled Locomotives, BNSF Railway et al, 2007. Viewed on the internet at http://www.arb.ca.gov/railyard/ryagreement/112807lngqa.pdf

3.2 Fuel Consumption

The nature of LNG makes the fueling process and fuel consumption measurements significantly different from those involving diesel fuel. LNG must be kept at cryogenic temperatures to maintain its liquid state. Heat leakage into the fuel tanks causes the fuel to slowly boil off over time. As a result, there is a difference in the amount of fuel initially put into the fuel tanks and the amount of fuel that is ultimately available to the engine for combustion and locomotive power. There is also the potential to vent (waste) fuel during the refueling process, resulting in LNG fuel that is recorded as used without ever making it into the locomotive's onboard fuel tank. This venting is ideally minimized using a "vapor collapse", which was utilized when the LNG switcher was refueled. While some benefit was achieved using the vapor collapse process, PHL still noted significant difficulties each time the LNG locomotive was refueled, throughout the demonstration. As a result, significant volumes of LNG were vented / lost during refueling events.

Quantifying the amount of fuel supplied by the vendor during each refueling event (including losses) is relatively straightforward: the fuel vendor provides a metered quantity on its fuel invoices to PHL. However, it is more complicated to separate out the volume of LNG fuel that was subsequently vented (lost) from the locomotive, versus that which was actually consumed by the engine. The approach utilized in this report is based on estimated brake specific fuel consumption, the average duty cycle of the engine, and the total operating hours of the engine. The formula for estimating the fuel consumed is given in the equation below.

$$FuelConsumed = \left(\sum_{idle}^{8} \%DC_i * BHP_i * BSFC_i \right) * T_{operation}$$

where:

- *FuelConsumed* is the total fuel consumed by the engine over the corresponding operating mode (solo or tandem)
- *%DC* is the percentage of time spent at the corresponding notch setting
- *BHP* is the brake horsepower output of the engine at the corresponding notch
- *BSFC* is the brake specific fuel consumption of the engine in lb/HP
- $T_{operation}$ is the total engine on time over the corresponding operating mode
- The summation is for 7 data points: an aggregate of idle, notch 1 and 2; and notches 3 through 8

Once the total fuel consumed during the testing phase is determined, a ratio can be defined to estimate the percentage of fuel consumed by the engine compared to the amount of fuel purchased. This is simply the FuelConsumed/FuelPurchased. Table 4 lists the fuel purchased and the calculated fuel consumption for the LNG switcher in solo mode. Note that the data for LNG fuel consumption in Table 4 represents fuel use for eight months of the nine-month test period. No fueling data are available for the ninth month. Table 5 documents the assumptions made about engine performance data for the Caterpillar G3516 engine. Based on the assumptions in Table 5, it is estimated that approximately 12% of the fuel purchased was lost due to venting that happened during fueling operations and/or through boil-off as the fuel warmed in the tanks. Note that this estimate is highly sensitive to the assumptions in Table 5. However, as no direct measure of fuel used by the engine is available, the above methodology represents a best estimate.

Table 4. LNG Fuel Consumption Data / Calculations

LNG Purchased (Diesel Equivalent Gallons)	LNG Consumed (Diesel Equivalent Gallons)	LNG Vented (Diesel Equivalent Gallons)	Fuel Consumption Ratio
19,673 (vendor provided)	17,343 (calculated)	2,330 (calculated)	88.2%

Table 5. Engine Performance Data Assumptions

Notch	Engine Power HP[7]	Specific Fuel Consumption[8] lb/HP-hr	Duty Cycle Solo
Idle/1/2	106	0.132	76.5%
3	310	0.119	5.9%
4	462	0.111	5.9%
5	640	0.103	4.7%
6	845	0.097	3.1%
7	1,122	0.094	2.0%
8	1,320	0.094	1.9%

In the GreenGoat™ hybrid locomotive demonstration report, PHL reported the average fuel consumption for diesel switcher Number 32 (i.e., the control used in this report) to be 65 gallons per day. Using 19,673 diesel-equivalent gallons of LNG purchased during the nine month demonstration, it is estimated that the daily fuel consumption (including boil off / fueling losses) of the LNG locomotive was 72 diesel-equivalent gallons per day. For this comparison, it appears that the newer engine technology of the LNG locomotive roughly offset two inherent inefficiencies of dedicated LNG engines with respect to fuel consumption, which are: 1) the lower thermal efficiency of spark ignition compared to compression ignition; and 2) fueling and boil off losses associated with LNG. Table 6 summarizes the daily fuel use estimates for the LNG and baseline diesel locomotives. An estimate of the average Tier 2 locomotive fuel use is included based on data from the 2008 Port of Long Beach emissions inventory. Note that the fuel rates are normalized by the total engine horsepower as the Tier 2 locomotives are significantly larger than the LNG or baseline diesel locomotives. As a result of the

7 Based on typical locomotive power vs notch settings, United States Environmental Protection Agency, Office of Mobile Sources, Regulatory Support Document, Locomotive Emission Standards, April 1998

8 Based on Specific Fuel Consumption data for the G3516 LE engine. Caterpillar document number LEHQ6163

increased engine power, PHL now uses one Tier 2 locomotive in services that previously required two of the older, 1,200 HP switcher locomotives.

Table 6. Comparison of fuel consumption rates (diesel equivalent gallons)

Locomotive	Horsepower	Estimated Annual Fuel Use (gal/yr)	Fuel Rate (gal/day)	Normalized Fuel Rate (gal/day/hp)	% Change from Baseline
BNSF 1203	1,200	26,200	72	0.060	11.1%
PHL 32	1,200	23,725	65	0.054	0%
Average PHL Tier 2	2,000	38,125	104	0.052	-3.7%

The average price for a diesel equivalent gallon of LNG was $2.35 during the demonstration, approximately 23% lower than the average diesel price of $3.07 per gallon. It is important to note that the average daily fuel consumption data for the LNG locomotive were collected more than a year after the diesel consumption data were reported. As a result, it is difficult to compare the fuel economy of the LNG and diesel locomotives on a gallons/day basis. However, the 12% of LNG fuel lost through venting (primarily during refueling) offsets roughly half of the 23% cost savings from the lower price of the LNG fuel. Provided the fueling process can be improved to minimize or eliminate venting, then significant fuel cost savings might be realized by PHL.

It is important to note that PHL incurred additional costs associated with fueling that are not reflected in the fuel price, due to fueling logistics and requirements of the LNG fueling permit received from the Los Angeles Fire Department (LAFD). First, PHL provided staff from 2:00 a.m. to 4:00 a.m. on each day fueling was performed, adding labor costs. Second, PHL was required to pay a fee to the (LAFD) Los Angeles County Fire Department to cover the costs of the fire inspector's time to monitor each LNG locomotive refueling event.

3.3 Availability

PHL provides rail operations 365 days per year supporting significant fluctuations in the volume of cargo to be moved on a daily basis. To support such dynamic load demands, PHL needs its switcher locomotives to be ready for work when called upon. Actual "availability" of any given switcher can be defined as:

Availability = (Time Worked) / (Time Requested to Work)

However, PHL does not track "time requested to work" for its locomotives. For the purposes of this report, it is assumed that any PHL switcher locomotive could be requested to work 365 days per year. Further, the "time worked" by any switcher locomotive will be taken as: time requested to work (365 days) minus the number of days out of service. Availability (as used in this report) is then defined by:

Availability = [365 – (Days Out of Service*)]/(365)

*(Days Out of Service) includes both scheduled and unscheduled maintenance

PHL service logs do not include records for the total number of days the LNG locomotive was out of service. Instead, PHL reported the number of mechanical issues the locomotive experienced. In total, PHL reported 11 mechanical issues over the nine-month demonstration period. Without knowing the associated number of service days lost due to these mechanical issues, "Availability" as described above cannot be accurately quantified.

However, PHL staff did provide a relative estimate on availability, indicating that the LNG locomotive was out of service approximately 15-20% more often than the diesel fleet. PHL reports an excellent record of availability (greater than 95%) for most baseline (smurf) switcher locomotives in its fleet. Therefore, a 15-20% increase in downtime for the LNG locomotive compared to the baseline locomotive fleet would equate to an availability of roughly 75% to 80%.

PHL cited two key issues that contributed to decreased availability of the LNG switcher locomotive; 1) failure of LNG-specific subsystems and 2) problems associated with the LNG fueling process. Both issues are discussed further in Section 3.4.

3.4 Reliability

The baseline diesel fleet of smurfs at PHL historically exhibited exceptionally high reliability, considering the average age of the fleet. This can be attributed to several factors including PHL's service personnel, and the general maturity and robustness of diesel technology (especially as applied to rail operations over a long history). PHL found the LNG switcher locomotive's overall reliability to be average, but less than its diesel smurf fleet.

Of the 11 mechanical issues reported by PHL, five were related to LNG-specific components, i.e., those that do not exist on diesel-electric locomotives. These issues and components are summarized in Table 7. Three of the five issues were related to the fueling process for the locomotive. PHL consistently cited fueling as the most difficult aspect of operating the LNG locomotive. In particular, the mobile LNG refueler truck was typically unable to completely fill the locomotive's LNG fuel tanks, due to pressure build-up in the tanks. The resulting partial fills had two effects. First, the resulting reduction in on-board energy diminished the locomotive's operating time capacity. Second, the inside of the vacuum-insulated LNG tanks were not being cooled as much as they would be during a complete fill. This resulted in progressively higher tank temperatures at the beginning of each fueling operation. Prior to rupturing the burst disk in mid-September (see Table 7), the LNG locomotive was only able to be fueled to about one-third of the rated fuel capacity (1,400 LNG gallons).

Table 7. Summary of LNG-related mechanical issues

Issue	Date	Details
Low main air pressure	5/25/05	Engine would not start with low air pressure in the main reservoir, as air pressure is required to operate the LNG fuel valves.
Failed spark plug transformer	6/17/08	Found during 92 day inspection.
Out of fuel	9/9/08	Locomotive only accepted 500 gallons of fuel due to hot fuel tanks. Ran out of fuel while operating.
Out of fuel, heavy venting of fuel	9/13/08	Ran out of fuel. When refueled to 400 gallons, tanks heavily vented LNG fuel.
Blown burst disk	9/14/08	Burst disk ruptured during previous fueling due to a too-rapid fueling event.

3.5 Service Capability

The LNG locomotive acquired for the demonstration program was used in solo operation and compared against historical data from one of PHL's smurf switchers; both cases involved car switcher service at the Yang Ming terminal. Table 8 summarizes the average mileage and time the locomotives were utilized in solo operation while Table 9 summarizes the average duty cycle for each locomotive by notch setting. Figure 3-1 provides a graphical comparison of the average duty cycle by fuel type. It is important to note that the data for the diesel locomotive is limited to a single data set spanning just six days of operation, while the LNG switcher logged nearly nine months of operation. However, it is reasonable to conclude that the test (LNG) and diesel (baseline smurf) locomotives were operated in essentially similar ways, based on the nearly identical average miles traveled per hour of operation (Table 8) and the similar duty cycles shown in Figure 3-1,

Table 8. Time and mileage by locomotive / fuel type in solo operation

Locomotive/ Fuel	Miles per day	Hours per day	Total Miles	Total Hours	Avg. Miles Traveled per Hour of Operation
Test / LNG	10.4	4.6	2,365	1,049	2.25
Baseline (Smurf) Diesel	6.5	2.9	36.9	16.3	2.26

Table 9. Average duty cycle by fuel type for solo operation

Locomotive / Fuel	Idle/ Notches 1 and 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7	Notch 8
Test / LNG	76.5%	5.9%	5.9%	4.7%	3.1%	2.0%	1.9%
Baseline (Smurf) Diesel	73.3%	6.6%	6.9%	4.5%	3.2%	2.4%	3.1%

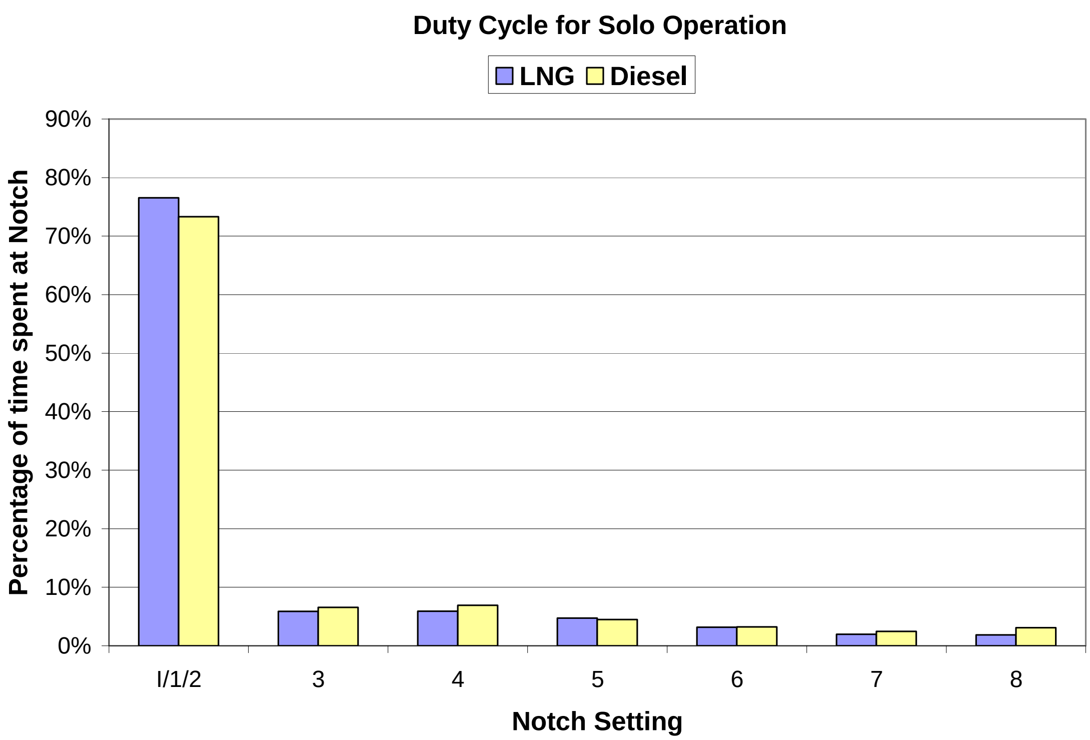

Figure 3-1. Average Duty Cycle for Solo Operation

PHL found that when the LNG locomotive was operating, it had performance similar to the control diesel locomotive. However, PHL reported that "fuel capacity was a big issue" because the LNG locomotive required refueling every three days, compared to the diesel locomotive that was refueled once a week. Additionally, the LNG locomotive lacked a reliable fuel gauge. This necessitated PHL staff to make educated estimates of fuel levels in the LNG locomotive and, on two occasions, contributed to the locomotive running out of fuel.[9]

3.6 Maintenance and Support Requirements

PHL reported that the maintenance and support requirements for the LNG locomotive were comparable to the diesel fleet, with the exception of the fuel system and safety

[9] Greg Peters, Pacific Harbor Lines, email to TIAX's Helena Chiang on October 1, 2010.

monitoring equipment related to the use of the LNG fuel. PHL stated that the number and type of mechanical issues encountered during operation of the LNG locomotive were comparable to the existing diesel fleet, not considering issues specifically related to the LNG fuel system. Table 10 summarizes the number of scheduled and unscheduled maintenance events as well as the number of mechanical issues encountered during the test period. Maintenance events are considered any mechanical repair or inspection that was performed on the locomotive. During the demonstration, the only scheduled maintenance events were federally required 92-day mechanical inspections. It is important to note that two of the mechanical issues were discovered and repaired during scheduled maintenance events and, therefore, did not result in an unscheduled maintenance event.

Table 10. Number of Scheduled and Unscheduled Maintenance Events

Fuel / Locomotive Type	Total # of Mechanical Issues	# of Scheduled Events	# of Unscheduled Events
Test LNG Switcher	11	3	6
Diesel “Smurf” Switcher Baseline (average estimated from PHL fleet)	6	3	3

4. Summary and Conclusions

Pacific Harbor Lines conducted a nine-month demonstration of an LNG-fueled switcher locomotive in service at the Port of Long Beach and Port of Los Angeles. Based on data and observations provided by PHL, the following conclusions are made:

- Overall, the LNG locomotive performed "adequately to well" in car switching service. However, the logistics and mechanical issues associated with fueling negatively impacted the locomotive's service capability.
- Mechanical issues with fueling compounded already difficult fueling logistics associated with the local fire department's requirements.
- Based on the service events for the LNG locomotive in comparison with the diesel fleet, PHL feels the reliability of the LNG locomotive is average but less reliable than the diesel locomotives. This is primarily due to 1) the addition of system components required for the spark-ignited engine and 2) fueling problems.
- Compared to the existing diesel switcher fleet, the LNG locomotive required similar levels of maintenance and facilities support. However, the level of effort required to support fueling and address fueling-related mechanical issues was exceptionally high.
- Emissions from the LNG locomotive were estimated to be 92% lower in NOx and 76% lower in PM, compared to the baseline (uncontrolled) diesel locomotives that PHL has already phased out. Compared to PHL's new Tier 2 locomotives, emissions from the LNG locomotive were estimated to be 81% lower in NOx and 57% lower in PM. However, it is important to recognize that these three types of switcher locomotives differ in age and emissions control technology, among other factors. This makes it difficult to isolate the emissions reduction contributions of using cleaner-burning LNG fuel in the test locomotive.
- The average fuel consumption for the test locomotive (including fueling losses and boil off) was 72 diesel-equivalent gallons per day. A comparable diesel switcher tested by PHL under a different program consumed about 65 diesel gallons per day. It appears that the newer engine technology of the LNG locomotive roughly offset two inherent inefficiencies of dedicated LNG engines with respect to fuel consumption, which are: 1) the lower thermal efficiency of spark ignition compared to compression ignition; and 2) fueling and boil off losses associated with LNG.
- Despite its apparent higher rate of fuel consumption, the LNG locomotive cost approximately 23% less to fuel on an energy-equivalent basis, due to the lower price paid by PHL per British thermal unit (Btu) of LNG fuel compared to diesel fuel.