Quick-Charging Battery-Electric Locomotives for Zero Emission Switching and Shortline Rail Operations

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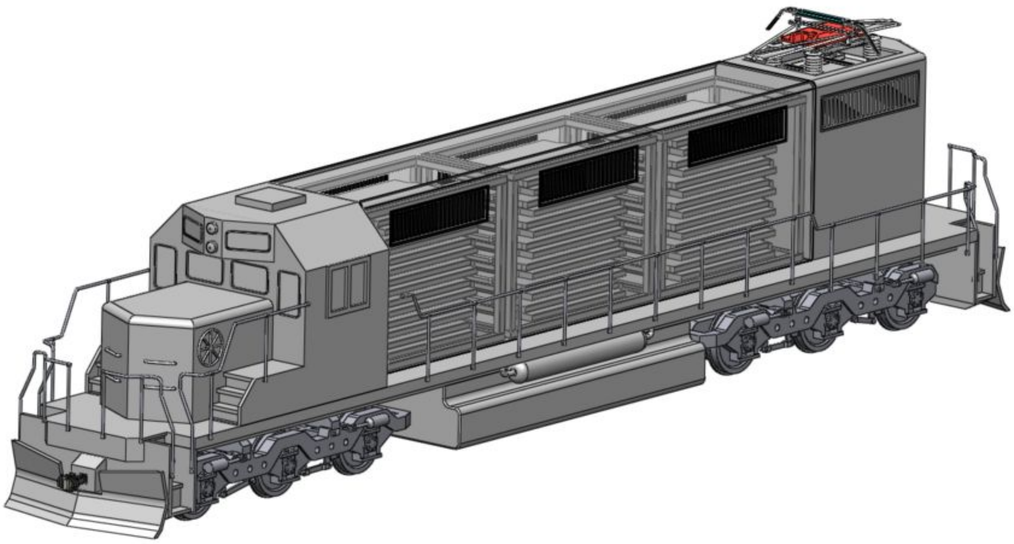

Pilot Project Executive Summary

We propose to refit an existing diesel-electric locomotive by replacing the diesel engine and generator with 33 high-energy, commercially available battery packs to create a true battery-electric locomotive which is functionally equivalent to existing diesel-electric locomotives currently used in the Ports of Los Angeles and Long Beach. The prototype locomotive (the "PL1") would be used in switching operations within the Ports, and transferring freight between the ports and near-dock railyards (the ICTF) and more distant railyards located some 50 miles east of Los Angeles. The quick-charging capability of PL1 would ensure minimal recharging time (<1 hour per day).

The proposed 4 year pilot project is still at the concept stage, but it is estimated that it would require nearly $3M in equipment and prototype build costs. However, this project would provide a critical proof of concept for the use of battery-electric locomotives for moving freight in and around the ports, providing substantial operations data on which to base future technology decisions for Sustainable Freight.

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Location

In conjunction with Pacific Harbor Line (PHL), the proposed pilot study would conduct rail freight operations in and around the Port of Los Angeles (POLA) and Port of Long Beach (POLB). On Within Port property (i.e."on-dock"), the proposed Battery-Electric Locomotive (the "PL1") would be used by PHL employees for switching operations, moving rail cars between marine terminals, and building trains for linehaul operators. The PL1 locomotive would also be used to transfer rail freight between the ports and near dock facilities like the Intermodal Container Transfer Facility (ICTF), and also between the Ports and more distant off-dock railyards located east of Los Angeles.

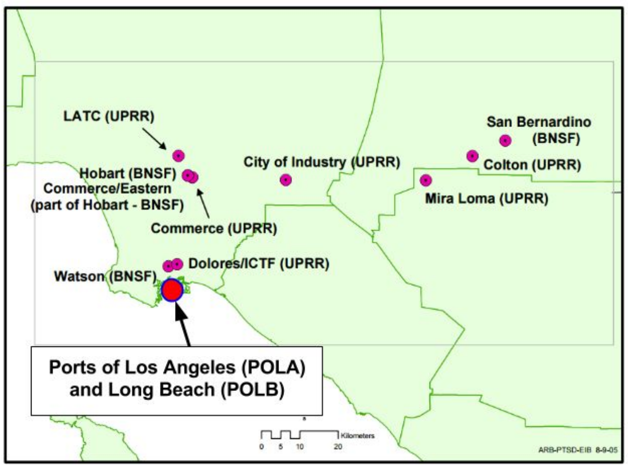

Figure 1. Operations area of the PL1 battery electric locomotive pilot project.

Detailed Description

Background

Southern California's Ports are facing a crisis in freight logistics and environmental sustainability. The volume of freight expected to pass through the Ports of Los Angeles and Long Beach is expected to double by the year 2035 to more than 45 million TEUs per year. Despite extensive upgrades to the rail infrastructure at the Ports, it is clear that the ability to handle the increased traffic will not be met solely by increasing the number of on-dock linehaul trains. Already, the Ports struggle to build outbound trains for mainline destinations to the East. The rise of multi-line mega-vessels carrying in excess of 18,000 TEUs necessitates an ever increasing amount of on-dock switching which will not be operationally sustainable as the Ports progress towards their projected TEU volumes.

More and more emphasis is now being placed on processing trains (especially trains travelling to the smaller, second-tier eastern destinations) at near-dock railyards such as the Intermodal Container Transfer Facility (ICTF) and the proposed Southern California International Gateway (SCIG). In this case, containers coming off ships would be transferred unsorted from the Ports to the near-dock facilities either by truck or by switcher locomotives.

Additionally, planners are again considering the concept of using smaller Inland Ports whereby containers would be transferred unsorted by truck or short-haul rail to facilities 50 miles or more to the east of Los Angeles. If the majority of containers are transferred to Inland Ports by truck, as many envisage, then truck congestion and pollution within Los Angeles and Orange Counties will increase unacceptably as total Port throughput increases.

To meet its goal of minimizing pollutants (including, particulates, NOx, SOx, etc.) and greenhouse gases (GHGs), California must commit to maximizing the amount of freight that travels within the South Coast Air Basin by green, sustainable rail. While California has already made good progress in decreasing pollutants and GHGs from diesel-electric locomotives, there are still substantial gains to be made by phasing out the use of diesel engines altogether for switching and shortline operations. The time is right for California to consider freight rail electrification for some operations.

Traditionally, electrification of freight-rail systems has meant the large-scale installation of electrification infrastructure such as catenary power lines, transformers, and expensive substations. A recent study looking at electrification of the Southern California freight rail system estimated the cost of freight rail electrification to be at least $7 Billion, not including the cost of replacing the current stock of diesel-electric locomotives with European-style full-electric locomotives. This model is not appropriate for Southern California. It is too expensive and would cause too much disruption to the existing freight transportation system.

Recent advances in battery technology, however, have opened up a third path that is separate from the two traditional paths of diesel-electric motive power and grid-tied electric motive power. Battery-electric locomotives have several advantages over competing technology, including:

Table 1: Advantages of Battery-electric Locomotives

	Diesel-electric	Grid-electric	Battery-electric
No GHG emissions		✔	✔
No particulates		✔	✔
No NOx emissions		✔	✔
Optimized Tractive Effort		✔	✔
No engine idling		✔	✔
No engine noise		✔	✔
No overhead wires	✔		✔
Minimal new infrastructure	✔		✔
Minimal new EIR/EIS	✔		✔
Reduced Failure Modes	✔		✔

Although battery-electric locomotives are not a new idea, having been first conceived and built in the mid 19th century, it is only with the recent commercialization of mass-market electric vehicles by the automotive industry that battery technology and production costs have improved to the point where battery-electric locomotives are now a viable alternative to diesel-electric locomotives in switching and shortline applications. Modern lithium-ion battery packs are high energy density (250 kWh/kg), quick charging (80% recharge within 50 minutes), and increasingly affordable (less than $300 per kW-hr). This means that it is now possible to build battery-electric locomotives that are not only cost-competitive with diesel-electric, but also store enough energy for high-duty cycle rail applications.

Pilot Study

Objectives

- Modify a used SMD45 locomotive with existing Commercial Off The Shelf (COTS) battery packs and inverters to create a battery-electric locomotive capable of matching or exceeding performance and reliability of existing diesel-electric switching and shortline locomotives
- Conduct one year of testing to measure hauling performance, energy usage, emissions offset, noise abatement, charging performance, operator satisfaction, and compare data with traditional diesel-electric locomotives

Locomotive Refit Period

Our pilot battery-electric locomotive, the “PL1” (figure 2), is designed to be functionally equivalent to a modern switching and shortline locomotive (e.g., the NRE N-ViroMotive 3GS-21C). The PL1 is based on the same EMD SD45 platform and matches or exceeds the NRE locomotive in terms of equivalent horsepower and torque.

Working with a nationally recognized locomotive remanufacturer, we will adopt industry standard methods to tear-down a used EMD SD45 locomotive to its core platform, removing major components like the diesel engine, alternator, inverter, and radiators, while keeping key components such as the frame, wheel trucks, and traction motors. Removing the unnecessary components from the SD45 will create enough free space to house three battery modules under the locomotive cowling. Each battery module consists of 11 commercially-available, high-energy battery packs. and stores nearly 1.25 MWh of energy. A total of 3.75 MWh of energy will be available for freight hauling operations.

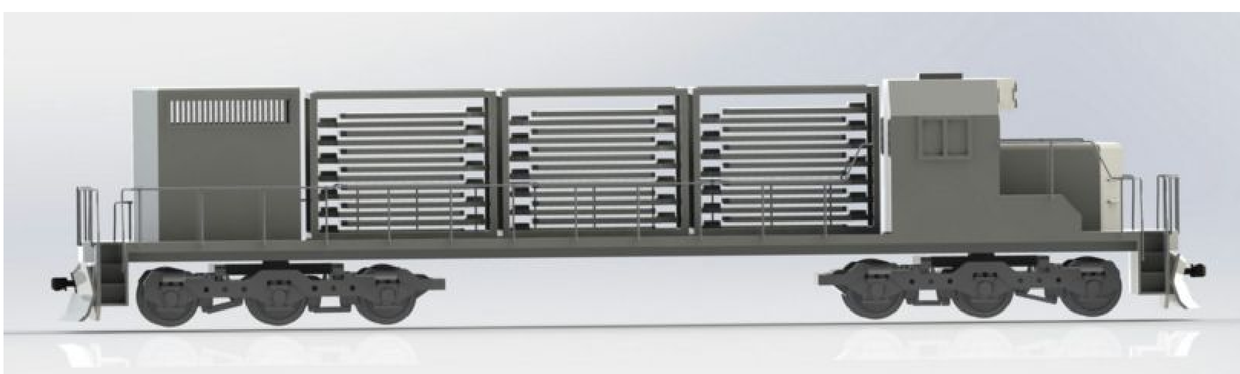

Figure 2. Side view of the PL1 battery-electric locomotive showing location of the 3 battery modules in place of the traditional engine and generator.

Additionally, a charging pantograph will be added to the locomotive which can be raised during charging periods (e.g. at charging stations at locomotive service yards) Commercially purchased quick-charger electronics will be added to the system to ensure maximum availability of the locomotive for operations.

We also plan to build a control stand and user interface equivalent to existing locomotives so that operators will not require extensive training prior to use of the PL1.

Finally, before entering into operations, the resulting battery-electric locomotive will then be subject to a suite of hardware and software systems tests to ensure that all components are performing within specification.

Pilot Operations Period

The PL1 locomotive will be extensively tested and evaluated during a 12 month period in three types of operations: on-dock switching, near-dock hauling (e.g. between the Port and the ICTF), and rail shuttle operations transferring freight between the Port and an inland railyard at least 50 miles from the port.

The goal during this period is to maximize active operations time for the PL1 locomotive in order to characterize the suitability of battery-electric locomotives for freight operations within and around the Port. Our hope is that we will be able to work closely with PHL and POLA to achieve this goal.

Final Evaluation and Reporting

After the one year operations period, all data would be compiled into a final report and submitted for independent review to the participating California agencies and private project partners.

Project Partners

This pilot project is still in the concept stage. We are exploring possible partnerships with the following entities.

1. Pacific Harbor Lines, LLC
2. Tesla Motors, Inc.
3. Port of Los Angeles and Port of Long Beach

Technology

Locomotive platform

The EMD SD45 series (SD45 and SD45-2) locomotive is one of the most successful freight platforms ever produced, with thousands of SD45 and SD45-2 diesel-electric locomotives built between 1965 and 1974. Many are still in operation, and many more have been refurbished with newer gensets. For example, many of the Ultra Low Emission Locomotives currently used by PHL in the Ports are NRE N-ViroMotive 3GS-21C series locomotives that are remanufactured from the SD45 platform.

Battery Technology

Battery power (tables 1 and 2) for the proposed PL1 locomotive is provided 33 Tesla P85 battery packs arranged into 3 modules consisting of 11 battery packs each. The use of a commercial off-the-shelf product like the P85 battery pack provides several advantages: first, the P85 battery pack is already a mature technology that has been extensively tested under more extreme conditions than would ever be experienced in a locomotive application; second, the P85 battery pack as it currently exists is already in a form factor that would allow easy integration into the SD45 platform; third, since the P85 battery pack is now produced in volume for the Tesla Model S electric car (>40,000 per year), the production costs for the P85 battery pack are already low compared with other battery manufacturers.

Table 1: Tesla Battery Packs

Tesla P85 Battery Pack Storage (Nominal)	85 kWhr
Conservative storage estimate	60 kWhr
Weight of pack	1200 lbs

Table 2: Train Pack and Power

Train Power	1490 kW
Tesla packs	33
Energy of all packs	1,980 kWhr
weight of all packs	39,600 lbs
Cost perTesla pack	$22,000
$ kWhr	$367
Battery cost	$726,000

Although, Tesla's battery production costs are not advertised, they are widely believed to be significantly lower than $300 per kilowatt-hour, and the costs are expected to fall as new production capacity comes online. Our conservative estimate for the cost of batteries for the prototype PL1 locomotive is $726,000, which is comparable to the cost of a genset for a modern tier 3 locomotive. Battery costs will continue to drop with time, however, as the market for battery electric locomotives grows, and as the scale-up of battery production plants continues apace.

Battery Performance and Charging

For switching and shorthaul operations to nearby inland railyards, the PL1 locomotive will be capable of running for long periods without recharging (Table 3). In switching operations, standard locomotives spend almost 80% of their time idling. In contrast, the PL1 can "idle" indefinitely without wasting energy or emitting pollutants. Also, when not idling, standard switching locomotives barely throttle above notch 2, spending another 15% of the time in either notch 1 or notch 2. In other words, for switching operations, locomotives spend only 5% of their time in notch 3 or higher. Thus, it seems likely that the PL1 could continue switching operations for up to 24 hours without recharging.

For shorthaul operations from the Ports to either near-dock railyards or inland railyards located in San Bernardino county, actual hauling times are relatively short. Even for an inland railyard located 70 miles east of the POLA or POLB, the PL1 would likely be running in notch 3 or lower most of the time, allowing the PL1 to complete its round trip journey with plenty of margin.

Table 3. PL1 locomotive runtime between charges

With Regeneration			Without Regeneration		
Load	Notch	Hours	Load	Notch	Hours
100%	8	1.3	100%	8	1.7
88%	7	1.5	88%	7	1.9
75%	6	1.8	75%	6	2.2
63%	5	2.1	63%	5	2.7
50%	4	2.7	50%	4	3.3
38%	3	3.5	38%	3	4.4
25%	2	5.3	25%	2	6.6
13%	1	10.6	13%	1	13.3

Furthermore, the PL1 locomotive can be rapidly recharged. Requiring only 50 minutes to reach 80% recharge, and 95 minutes to reach 100% charge, the PL1 can top off its battery charge whenever it is convenient.

During charging, the PL1 pulls into the charging location and raises its pantograph to contact a standard 25 kV overhead wire. Unlike full-electric trains which require a continuous electrification of the train's route, however, the PL1 only requires a short section of overhead wire at charging locations. This greatly simplifies the deployment of charging infrastructure for battery-electric systems versus full-electric systems, and also reduces expense and permitting times.

Expected advantages of mass adoption of battery-electric locomotives

1. **Improved Operations -** Compared with conventional locomotives, battery-electric locomotives require almost zero maintenance, saving time and money. They also do not require a diesel fueling center, which can be a point source for pollution and requires additional regulatory oversight. The mechanical advantages of battery-electric locomotives also lead to better operational efficiency. Battery-electric locomotives can respond to wheel-slip faster than traditional locomotives, and therefore can operate with improved tractive effort. Also, unlike diesel engines which operate most efficiently only within a narrow band of its power range, the battery-electric locomotive operates at near peak efficiency across its entire power range. This means battery electric locomotives can accelerate faster to clear a railyard. It also means that, in some cases, a rail operator might choose to pull a load with one battery-electric locomotive operating at a higher throttle setting whereas he might instead be forced to use two traditional locomotives.

2. **Zero Emissions** - Traditional locomotives, even those using the latest pollution control technologies, still produce significant quantities of particulates, NOx, and SOx emissions. For example, in 2014 locomotives emitted 18% of all port-generated Diesel Particulate Matter - 26 tons of DPM. In contrast, battery-electric locomotive emit zero pollutants.

3. **Greenhouse Gas Reductions** - If charged using electricity derived from renewable energy sources (wind or solar), the PL1 locomotive is carbon neutral. Widespread use of battery-electric locomotives will help California meet its greenhouse gas commitments.

4. **Improved Public Health** - Ports and railyards have traditionally been associated with poor air quality. For example, the California Air Resources Board found that cancer risk around some Southern California railyards was extremely high with 3300 excess cancer cases per million residents over a seventy year period. Another study found that particulate matter from diesel emissions (from all sources) resulted in 2200 premature deaths annually within California.

5. **Uses Existing Infrastructure** - Full electrification of the Southern California Freight rail system with build-out of continuous overhead catenary lines, substations, and an adequate number of full-electric locomotives would be prohibitively expensive (> $7 Billion) and also be disruptive to existing freight rail and passenger rail service. Because battery-electric locomotives, charge their batteries at specific locations and don't require extensive

electrification infrastructure, battery-electrics could achieve the same goal reducing emissions and greenhouse gasses for a fraction of the cost.

6. **Minimal EIR/EIS required** - Similarly, due to minimal new infrastructure requirements, the use of battery-electric locomotives would face much less review than traditional full-electric locomotives. Also, since battery-electric locomotives only charge their batteries at suitable locations in nonresidential areas, there would be less concern about unsightly catenary wires, or possible public concern about electromagnetic interference or health effects.

Project Cost

These are best-guess, preliminary cost estimates for the major anticipated equipment and associated labor costs. At this time, the proposed project is at the concept stage only, and has not secured governmental or private funding. Also, personnel and project management costs are not included in the costs below. A 50% overhead/contingency fee has been added to all costs.

Locomotive Refit

Item	**Cost**	**with 50% contingency**
Used SD45 locomotive	$200K	$300K
Cost of batteries	$726K	$1.1M
Cost of prototype control electronics and user interface	$100K	$150K
Labor cost of locomotive refurbishment and integration (5000 man-hours at average $65/hr)	$625K	$1.0M
		Total: $2.55M

Charging Infrastructure (for two charging stations)

Item	**Cost**	**with 50% contingency**
20 feet section of standard 25 kV catenary equipment	$75K	$113K
Power extension and breaker boxes	$100K	$150K
Charging controller	$50K	$75K

Onsite construction costs (400 man-hours)	$26K	$39K
		Total: $377K

Timeline

- Phase 1 - Project planning - 18 months
- Phase 2 - Locomotive refit- 12 months
- Phase 3 - Operations testing - 12 months
- Phase 4 - Final evaluation and reporting - 6 months

- Total project time: 4 years

Measuring Progress

Key data recorded during the pilot study would include:

Performance	Operations	Financial	Environmental
• max carloads • equivalent “notch” profile versus conventional power locomotive • tractive effort versus conventional power locomotive	• operator labor hours • percent up-time • charging time • active pulling time • carloads carried over course of period	• operations and maintenance costs over period • electricity costs versus equivalent fuel costs over period • Estimated lifecycle costs and total cost of ownership	• particulates, NOx, other pollutants avoided • greenhouse gases avoided • gallons of fuel saved • noise abatement

These data would be reported monthly via a website dashboard and database application.

Interagency Partners

The PL1 pilot study is still at the formative stage. As such, the authors wish to express their willingness and enthusiasm to explore this proposal further in discussions with the appropriate agency partners. The major governmental stakeholders would include the California Department of Transportation, The California Air Resources Board, the Ports of Los Angeles and Long Beach, and the county and municipal governments representing Los Angeles and Long Beach.

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Authors goals

The authors are submitting this proposal with the hope that the State of California will recognize the many advantages of using battery-electric locomotives for switching and shortline freight operations. Although we have begun reaching out to potential business partners, this project is still in the concept stage. If California sees merit in this idea, we hope that the various agency program managers will work with us to help bring this concept to fruition.

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