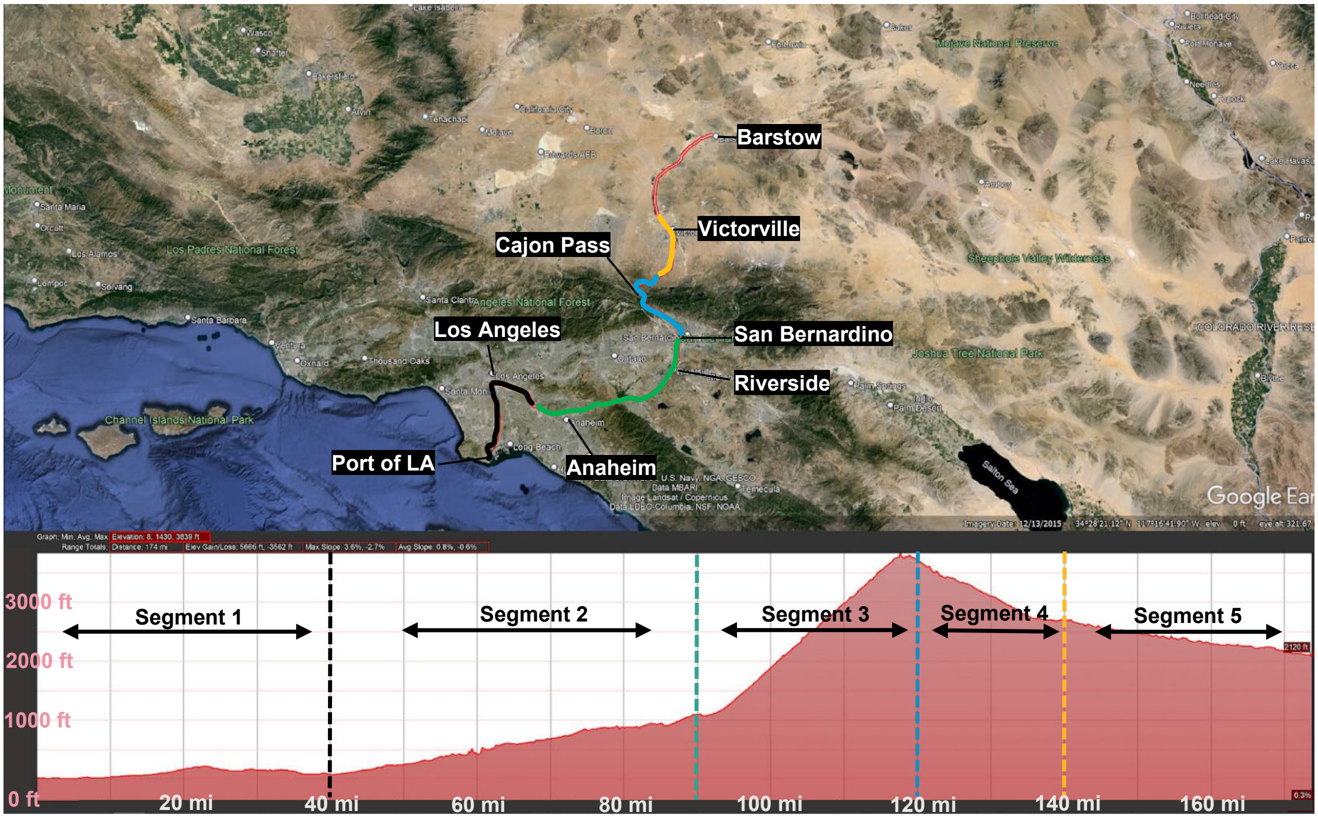
Feasibility Analysis: Zero Emission Train from the Port of Los Angeles to Barstow

Staff analyzed the feasibility of using current battery electric and hydrogen fuel cell zero emission (ZE) locomotive technologies from the Port of Los Angeles (POLA) to Barstow, a high-traffic freight route in California. For a train to complete a trip from POLA to Barstow, there must be sufficient power and energy supplied from the locomotives throughout the trip. To determine the number of current ZE locomotives required to pull 130 double stacked railcars from POLA to Barstow, power and energy required to complete the trip needed to be calculated while taking into account length of trip, track grade, rolling resistance, and drag. Once the power and energy required to complete the trip were calculated, staff were able to determine the minimum number of ZE locomotives required to supply the power and energy needed. The ZE locomotive models being evaluated in this analysis are Wabtec's FLXdrive Heavy-Haul battery electric locomotive, Progress Rail's SD70J-BB battery electric locomotive, and CPKC's hydrogen fuel cell locomotive with a tender car to carry hydrogen fuel. These models were chosen as they are rated for line haul operation and could be used by Class I railroads.

Route from Port of LA to Barstow

Figure 1: Typical Class I Route from Port of LA to Barstow (Google Earth Pro)



The route from POLA to Barstow is approximately 174 miles with elevation as low as 17 ft and as high as 3,800 ft above sea level. The analysis splits the route into five segments as shown in Figure 1. The five segments were defined based on significant differences in elevation change. For example, Segment 1 has no elevation change, while Segments 2 and 3 have elevation changes with hill grades of 0.6% and 2.2%, respectively. Segments 4 and 5 are downhill portions of the route. Details about each segment can be found in Table 1 below.

Table 1: Characteristics of Route Segments

Segment	Distance (mi)	Elevation Change (ft)	Grade (%)	Speed (mph)
1	40	0	0	50
2	50	1020	0.6	50
3	30	2740	2.2	20

Segment	Distance (mi)	Elevation Change (ft)	Grade (%)	Speed (mph)
4	20	-1140	-1.55	50
5	34	-580	-0.5	50

Note: Elevation change is relative to the previous segment (i.e. elevation change of Segment 3 is the altitude at the end of Segment 3 minus the altitude at the end of Segment 2). Negative elevation change and grade indicates downhill portion of route. Track grade in Segments 3 and 4 were found using published data while the track grades in the rest of the segments were estimated using Google Earth Pro due to a lack of publicly available information.[1] Train speed for each segment was estimated based on speed data from BNSF's Zero-and Near Zero-Emission Freight Facilities Project report.[2]

Power and Energy Requirements

The power and energy required to travel along each segment of the route from POLA to Barstow were calculated. Power (P) (Eq. 1) was calculated by finding the net force (F_{net}) required for the locomotives to pull the train multiplied by the train's velocity (v). The net forces (Eq. 2) calculated along each segment considers the force to overcome a hill against gravity $(F_{gravity})$, drag force (F_{drag}), and rolling resistance (frictional forces) (F_{rr}). Drag force calculations assumed a coefficient of drag value of 2.1 (entire train treated as a rectangular box) as a means to simplify the calculation and due to a lack of drag coefficient data for locomotives.[3] It is important to note that Eq. 2 is used for flat ground and uphill travel only. Going downhill, the net force (F_{net}) calculation uses Eq. 3. Energy (E) requirement (Eq. 4) was calculated by multiplying power by the time (t), it takes to travel along that segment based on the train's velocity.

$$P = F_{net} \times v$$

Eq. 1

$$F_{net} = F_{gravity} + F_{rr} + F_{drag}$$

Eq. 2

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[1] Trains Magazine, Cajon Pass as you've never seen it, 2011, accessed April 12, 2024. (Weblink: https://www.trains.com/wp-content/uploads/2020/10/trnm0811_acajonpass.pdf).

[2] CARB, BNSF ZERO-AND NEAR ZERO-EMISSION FREIGHT FACILITIES PROJECT, May, 2021, accessed April 5, 2024. (Weblink: https://ww2.arb.ca.gov/sites/default/files/2022-11/zanzeff-bnsf-belreport.pdf).

[3] The Engineering Toolbox, Drag Coefficient, 2004, accessed April 15, 2024. (Weblink: https://www.engineeringtoolbox.com/drag-coefficient-d_627.html).

$$F_{net} = F_{rr} + F_{drag} - F_{gravity}$$

Eq. 3

$$E = P \times t$$

Eq. 4

The mass of the 130 double stacked railcars, with each container weighing 19 tons, used in the analysis was calculated using the methodology found in CARB's Truck vs. Train Emissions Analysis.[4] The total mass of the train is equal to the sum of the railcar mass with cargo and locomotive mass.

To determine the number of ZE locomotives required to complete a trip from POLA to Barstow, a minimum energy and power requirement was determined. Staff found that Segments 1-3 require the use of energy from the locomotive, while Segments 4-5 do not. Therefore, the minimum energy required to complete the trip is the sum of the energy needed in Segments 1-3. As energy is only required in Segments 1-3 (flat and uphill track only), staff determined that regenerative braking did not need to be modeled. When braking, the locomotives can convert some of their kinetic energy back into electricity through regenerative braking to charge the batteries. This regenerative braking would only occur in Segments 4-5 (downhill track) where no energy is needed to power the locomotives. Furthermore, a minimum power requirement was determined by determining the most power required by a segment. Segment 3 has the largest power requirement due to its steep grade, so the Segment 3 power requirement was set as the minimum power requirement for the train to complete the trip from POLA to Barstow.

Table 2: Power Required, Energy Required, and Energy Regained in Each Segment provides information regarding estimated power and energy required for each segment of the route from POLA to Barstow. The table presents the estimated power and energy requirements as a range of values rather than fixed values to account for variability in ZE locomotive models.

Table 2: Power Required, Energy Required, and Energy Regained in Each Segment

	Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 5**	**Total**
Power Required (MW)	2.27 – 2.30	14.50 – 14.75	18.77 – 19.09	0	0	Not Applicable
Energy Required (MWh)	1.82 – 1.84	14.50 – 14.75	28.16– 28.63	0	0	44.48– 45.22

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[4] CARB, Truck vs. Train Methodology, September 23, 2020, accessed April 5, 2024. (Weblink: *https://ww2.arb.ca.gov/sites/default/files/2024-02/Truck%20vs%20Train%20Methodology%209-23-2020_0.pdf*).

It is important to note that the power and energy requirements calculated for this analysis are estimates and not exact. More detailed data such as exact track grade throughout the route, measurement of track curvature, exact dimensions of the locomotives, and specific efficiencies of each locomotive model are required to produce a more accurate analysis. Aerodynamic drag and rolling resistance were modeled in a simple manner. Staff understand that additional refinements can be made to the aerodynamic and rolling resistance factors in force calculations, however, when compared to the force required to overcome gravity when travelling along uphill portions of the route (Segments 2-3), the effect of drag and rolling resistance is small. Therefore, refinements in aerodynamic drag and rolling resistance will not significantly impact the overall power and energy requirements.

Staff also considered the effects of track adhesion to ensure that there will not be any wheel slip from the locomotive while pulling the railcars. Coefficient of friction between the track and the wheel may be as high as 0.7.[5] However, various contamination on the track surface may reduce the coefficient of friction to as low as about 0.05 that can cause wheel slip. Sand is a commonly used method to enhance adhesion on locomotive wheels, which can provide a coefficient of friction of up to 0.4. Staff assessed the friction between the locomotive wheel and the track assuming a coefficient of friction of 0.4, and compared it to the required adhesion at the steepest segment of the route. The analysis determined that wheel slip will not occur as there would be enough adhesion between the wheels of the locomotive and the track.

Analysis Results

Table 3 shows the minimum number of ZE locomotives required to complete the trip from POLA to Barstow for different locomotive types and models. An efficiency value of 90% was used for battery electric locomotives, and 60% for hydrogen fuel cell locomotives.[6,7] Table 3 also presents the number of locomotives required to complete the trip using typical diesel locomotives with an efficiency of 35% (tank to wheel) to create a comparison with ZE locomotives.[8] The analysis also compares the number of locomotives required for different factor of safety (FOS) values to account for errors (up to 20%) in power and energy calculations. It is important to note that usable energy capacity is not determined by traction power, rather usable energy capacity and traction power are independent of each other.

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[5] Federal Railroad Administration, A Survey of Wheel/Rail Friction, September 2017, accessed April 17, 2024 (Weblink: *https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/17468/A%20Survey%20of%20Wheel-Rail%20Friction.pdf*).

[6] Progressive Railroading, With all-battery electric locomotive purchase, Newburgh & South Shore Railroad serves as OmniTRAX's 'guineapig' in green power initiative, March 23, 2022, accessed April 5, 2024. (Weblink: *https://www.progressiverailroading.com/RailPrime/Details/With-all-battery-electric-locomotive-purchase-Newburgh-South-Shore-Railroad-serves-as-OmniTRAXs-guinea-pig-in-green-power-initiative--66191*).

[7] Office of Energy Efficiency & Renewable Energy, Fuel Cells, accessed March 24, 2024. (Weblink: *https://www.energy.gov/eere/fuelcells/fuel-cells*).

[8] Environmental and Energy Study Institute, Electrification of U.S. Railways: Pie in the sky, or Realistic Goal?, May 30, 2018, accessed April 9, 2024. (Weblink: *https://www.eesi.org/articles/view/electrification-of-u.s.-railways-pie-in-the-sky-or-realistic-goal*).

Table 3: Number of Locomotives Required for Different Models

Locomotive Model	**Type**	**Weight per locomotive (MT)**	**Traction Power per locomotive (MW)**	**Usable Energy Capacity per locomotive (MWh)**	**Minimum Number of Locomotives Required**	
					FOS: 1	**FOS: 1.2**
Typical Diesel Locomotive[9]	Diesel	218	3.2	65.2	7	8
SD70J-BB[10]	Battery Electric	245	5.7	13.05	4	5
FLXdrive Heavy-Haul[11]	Battery Electric	189	3.2	7.65	6	8
CPKC Line-Haul (with tender car)[12,13]	Hydrogen Fuel Cell	167	3.3	55.8 (per hydrogen tender car)	6	8

Note: For the CPKC Line-Haul hydrogen fuel cell locomotive to sustain 3.3 MW of traction power, battery augmentation would be required as the fuel cell stack itself only provides 1.2 MW of sustained power (Appendix C Technical Support Document: Zero Emission Locomotive Conversion, p. 15-16). Staff determined that in each hydrogen locomotive in the analysis of POLA to Barstow, a battery size of 6.9 MWh is needed to provide the rest of the power required to sustain 3.3 MW.

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[9] BNSF, BNSF Locomotives, accessed April 9, 2024. (Weblink: https://www.bnsf.com/about-bnsf/virtual-train-tour/locomotive.html).

[10] Progress Rail, EMD Joule Battery-Electric Locomotive, accessed April 5, 2024. (Weblink: https://s7d2.scene7.com/is/content/Caterpillar/CM20231020-d404c-92873?_gl=1*h81skd*_ga*MjA0MTg3Nzc2Ny4xNzAwMDAxOTQ5*_ga_FMYNPMTMYT*MTcxMjMzNjEwOC4zMC4wLjE3MTIzMzYxMDguNjAuMC4w&_ga=2.139680507.955966259.1712179450-2041877767.1700001949).

[11] Wabtec, FLXdrive Battery-Electric Locomotive Technology, accessed April 5, 2024. (Weblink: https://www.wabteccorp.com/FLXdrive-Battery-Electric-Locomotive?inline).

[12] CARB, Appendix C Technical Support Document: Zero Emission Locomotive Conversion, accessed April 5, 2024. (Weblink: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/15dayappc.pdf).

[13] Railway Age, Zero/Low-Emission Locomotive Global Roundup (Updated), June 7, 2023, accessed April 5, 2024. (Weblink: https://www.railwayage.com/mechanical/locomotives/zero-low-emission-locomotive-global-roundup/).

Key Takeaways

The major limiting factor that impacts the number of locomotives required to travel from POLA to Barstow is traction power. Due to the steep inclines along the Cajon Pass, a locomotive with higher traction power is favorable. The analysis concludes that for a train consisting of 130 double stacked railcars, an equal amount or fewer ZE locomotives are required complete the trip compared to diesel locomotives, which further demonstrates the capability of ZE locomotives along routes like POLA to Barstow.

Progress Rail's SD70J-BB battery electric locomotive will require the least number of locomotives (4 locomotives with factor of safety of 1) to travel from POLA to Barstow as it offers the highest traction power compared to the other locomotive models. When using typical BNSF diesel locomotives, 7-8 locomotives are required to complete the trip. CPKC's hydrogen fuel cell locomotive and Wabtec's FLXdrive Heavy-Haul have a similar power output, and thus the number of locomotives required are similar between the two models.

Staff also estimate that the analysis result is scalable to heavier or lighter trains. That is, a 50% increase in the number of double stacked railcars will result in approximately 50% more locomotives required for all three zero-emission models (when factor of safety is 1 and not including combinations of different types of locomotives within a train). While the relationship between train mass and number of locomotives needed is not exactly linear, the trend generally holds. The weight of railcars and containers contribute most to the power required to complete the trip, thus affecting the number of locomotives needed.

The CPKC hydrogen fuel cell locomotive has similar traction power to Wabtec's FLXdrive, however, the total range that the CPKC locomotive can travel is considerably more. Hydrogen carries more energy than current batteries and a fuel cell locomotive utilizing a tender car can carry even more hydrogen along its route to extend the locomotive range. CPKC's fuel cell locomotive utilizing a tender car can carry more than four times the amount of energy of Progress Rail's SD70J-BB battery electric locomotive. Utilizing a hydrogen fuel cell locomotive with a tender car may be beneficial to some operators if they intend on traveling distances further than Barstow and do not want to stop to refuel, or recharge, in the case of battery electric locomotives.

Operators may choose to utilize existing diesel locomotives with battery tender cars. This can result in less fuel usage and emissions benefits as the locomotives can use energy from the batteries rather than the diesel generator. New battery lithium ferrous phosphate battery technology can allow for a 14 MWh battery to reside within a single boxcar[14]. Staff estimates that 7 diesel locomotives with 4 battery tenders are required to complete the trip from POLA to Barstow when the factor of safety is 1, and 9 diesel locomotives with 5 tender cars when the factor of safety is 1.2.

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[14] Natalie D Popovich, et al. Nature Energy, Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric, November 11, 2021, accessed April 12, 2024. (Weblink: https://www.nature.com/articles/s41560-021-00915-5).

Overhead Catenary Systems

The use of overhead catenary systems (OCS) can reduce the number of locomotives required to complete the journey from POLA to Barstow if an operator only has access to locomotives with less energy capacity. For this analysis, if OCS is implemented along Segments 2 and 3 (Anaheim to the peak of Cajon Pass), an operator would only need two OCS-compatible locomotives and two battery electric locomotives to complete the trip. This is assuming that the OCS-compatible locomotives can produce at least 6.4 MW of traction power, such as the Siemens Vectron, a European freight locomotive.[15]

Conclusion

The use of ZE locomotives along the route from POLA to Barstow is feasible with the ZE rail technology available today.

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[15] Siemens, Vectron AC/DC/MS – the locomotive that’s forging new paths, accessed April 5, 2024. (Weblink: *https://www.mobility.siemens.com/global/en/portfolio/rolling-stock/locomotives/vectron/ac-dc-ms.html*).