Simulation and Optimization Approach to Identify Routes Maximizing the Diesel Energy Savings Potential of Battery Electric Locomotives

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Introduction

The battery-electric locomotive (BEL) is one example of an alternative energy source for railway locomotive powertrains. A BEL is a self-contained locomotive that produces tractive effort using electric power from onboard batteries. The batteries onboard the BEL are recharged from energy captured through regenerative braking, or from external electric power at terminal facilities. To help foster the economic success of BELs in North American mainline heavy haul service, strategic decisions need must be made to identify optimal routes for initial BEL deployment such that diesel fuel and emissions savings is maximized. Unfortunately, given that each US Class I railroad operates more than 30,000 km of mainline routes linking hundreds of origins and destinations with thousands of possible train runs, identifying optimal BEL assignments via brute force simulation of each possible train is impractical. Thus, research on new techniques to quickly identify promising BEL routes is needed so that practitioner resources can be focused on detailed simulation and evaluation of the best candidate corridors and train runs. This paper makes a novel contribution by proposing a network screening approach to meet this need.

Experimental work

The proposed framework for identifying the best BEL routes from within a large network is shown in Figure 1. Simulation data is generated and used as performance matrix input to find an ideal optimized grade profile for a set of BEL operating parameters. One US Class I railroad network is then systematically searched to identify realistic deployment segments that closely match the optimal BEL grade profile and should maximize fuel savings benefits. The set of optimized grade profiles for different BEL and train operating configurations also provide insights regarding different parameters' impact on optimal vertical alignment for diesel saving.

Results

Optimal vertical alignments were found for all factorial combinations of battery size, train length, and train configuration in the experimental design. Figure 3 illustrates optimal vertical alignments for a 4.8 MWh BEL with 80% loaded and 20% empty railcars and three different train lengths. With increasing train length (and weight), the grade selection tends to favor shallower gradients. This pattern arises because the shorter (lighter) train needs a steeper grade to require the same regenerative braking force from the BEL as the longer (heavier) train.

Figure 4 shows the optimal vertical alignments for the 80% loaded train with 150 total cars and a range of BEL sizes. The "wavelength" of undulation in the optimal grade profile is observed to increase with increasing battery size; the smaller BEL can only handle short segments of constant grade before the battery storage is either filled or depleted and an inflection point is needed to change the BEL use state.

To illustrate the results of the network search and profile matching approach, consider the optimal vertical alignment associated with 120 loaded 30 empty railcars using the 2.4 MWh BEL. Table 1 lists the top five crew districts out of 110 from within the 40,283 km Class I railroad study network along with the MSE for their respective best segment. Figure 5 compares the actual grade profile of these segments to the theoretical optimal vertical alignment of alternating +1.0% and -0.5% segments.

To determine how well a low MSE corresponds to larger diesel savings, and how the identified corridors performed relative to optimal, each crew district segment and the optimal profile were simulated with ALTRIOS to determine diesel energy savings (Table 2). The energy consumption results from ALTRIOS shown inconsistent energy saving performance across the five identified corridors. The simulation result from Sweetwater to Temple (route 2) exhibits similar percent savings as the theoretical optimal vertical alignment, while the others provide far less.

Conclusions

In general, the optimization results indicate that there is no universally optimal freight railroad vertical alignment that maximizes BEL diesel savings. Energy performance across different patterns of upgrades and downgrades is highly sensitive to different train lengths and configurations. The optimal grade profile is flatter for heavier trains, and steeper grades are required for short or light trains to achieve maximum BEL regeneration potential and energy savings.

The BEL battery size influences the optimal "wavelength" of the grade profile corresponding to the distance between inflection points and how frequently the grade changes sign. As battery capacity increases, a BEL can regenerate energy over longer downhill distances and support longer uphill discharges (i.e. a longer wavelength).

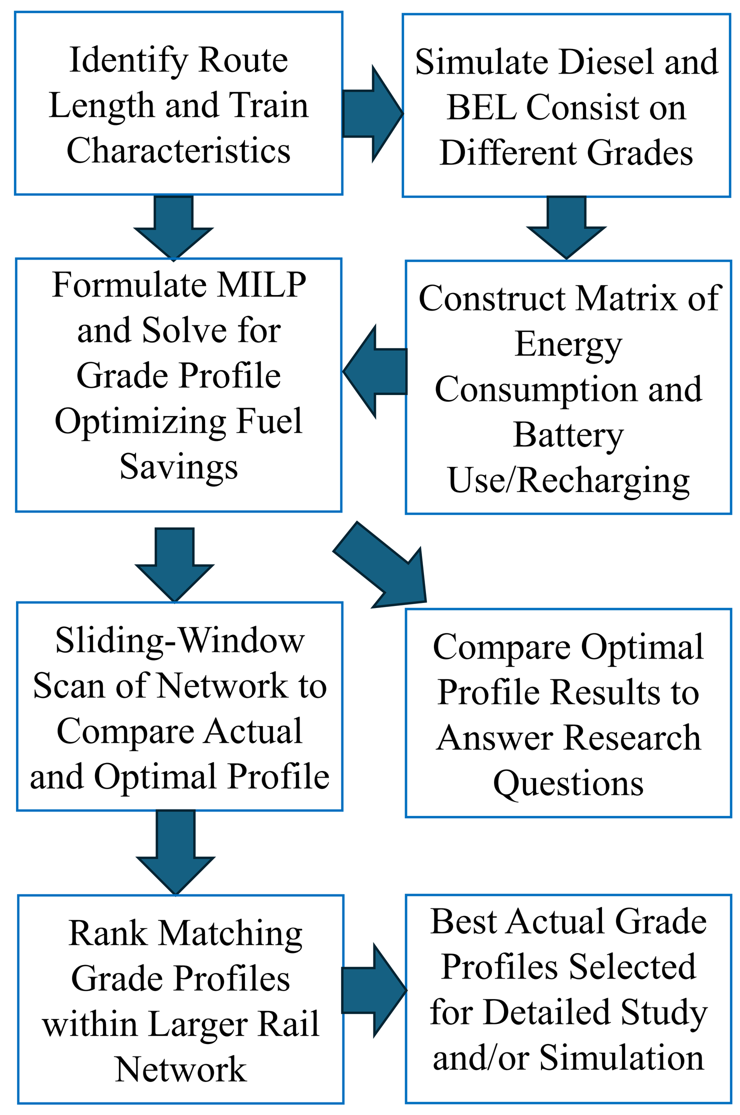

Figure 1. Optimal BEL route screening framework

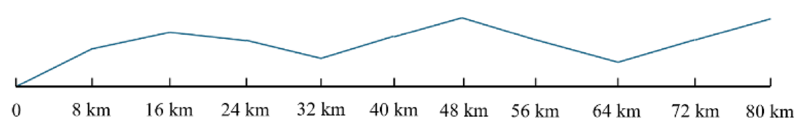

Figure 2. Example track vertical profile for 80-km corridor

The objective function is formulated to maximize diesel saving while considering diesel consumption and number of grade changes in decreasing order:

$$\max \sum_{i=1}^{2N} (R_i - \beta_1 D_i - \beta_2 C_i) \quad (1)$$

s.t.

$$S_i \geq 0,\ i \in [1,2N] \quad (2)$$
$$S_i \leq B,\ i \in [1,2N] \quad (3)$$
$$G_{ij} = [0,1],\ \forall i,j \quad (4)$$
$$\sum_{j=1}^{J} G_{ij} = 1,\ \forall i \quad (5)$$
$$\alpha_{ij} \geq 0,\ \forall i,j \quad (6)$$
$$\alpha_{ij} \leq G_{ij},\ \forall i,j \quad (7)$$
$$S_i = S_{i-1} + \alpha_{ij} \Delta S_j,\ \forall i,j \quad (8)$$
$$G_{ij} = G_{(2N-i)(J-j)},\ \forall i,j \quad (9)$$

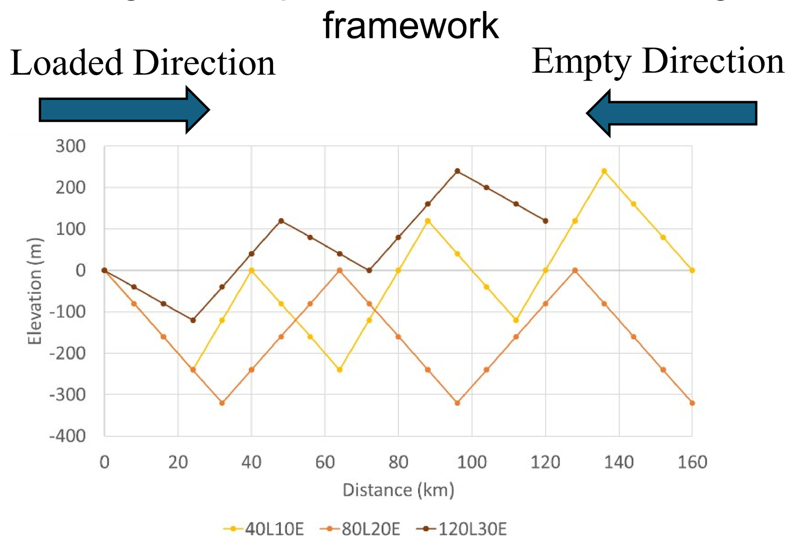

Figure 3. Optimal vertical alignments for 80% loaded train with 4.8 MWh BEL

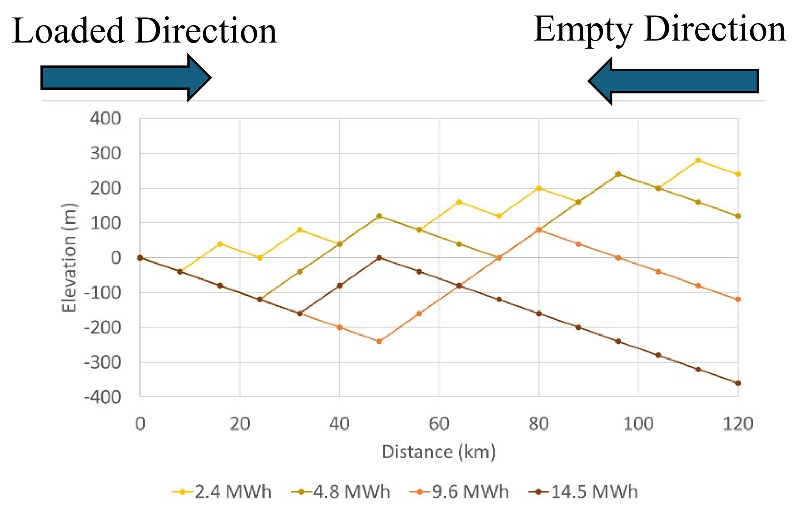

Figure 4. Optimal vertical alignments for 120 loaded 30 empty railcars with different battery sizes

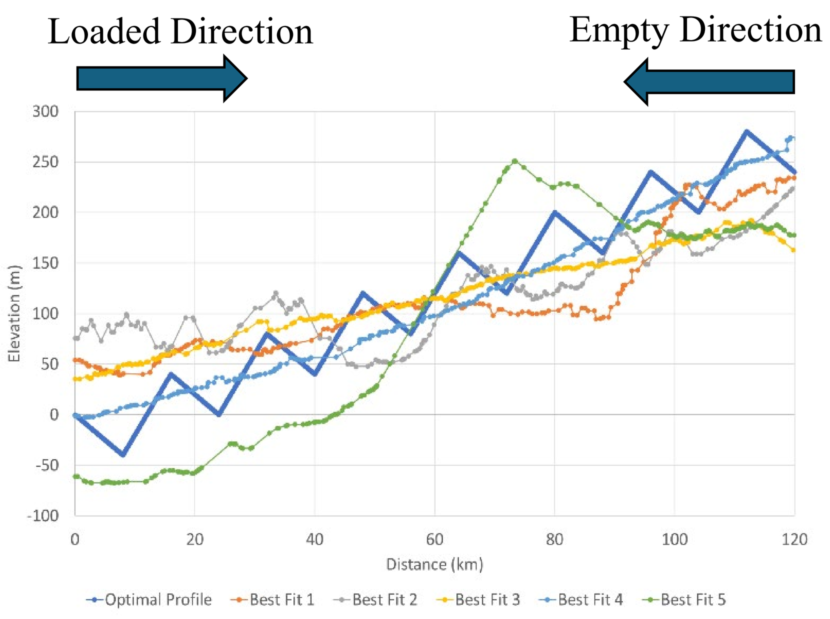

Figure 5. Actual profile of five crew district segments with lowest MSE in comparison to optimal vertical alignment for train of 120 loaded and 30 empty railcars with 2.4 MWh BEL

Crew District Name	MSE
Clovis to Carlsbad	50.86
Sweetwater to Temple	116.03
McCook to Lincoln	422.58
Winslow to Belen	453.37
Aberdeen to Wilmar	489.41

Table 1. Top crew district profile segments ranked by MSE relative for 120 loaded 30 empty railcars using 2.4 MWh BEL

Corridor Grade Profile	Baseline Diesel (MWh)	Diesel with BEL (MWh)	Diesel Saved (MWh)	Diesel Saved (%)
Optimal	105.89	74.97	30.92	29.20%
1	74.88	63.55	11.33	15.13%
2	90.10	68.71	21.38	23.74%
3	67.91	61.35	6.56	9.66%
4	74.44	69.13	5.30	7.12%
5	86.07	74.85	11.22	13.04%

Table 2. Energy savings of optimal and identified top crew districts for 120 loaded 30 empty railcars using 2.4 MWh BEL

Acknowledgments

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