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Optimizing the Placements of Energy Storage Devices to Maximize the Net Present Value in Rail Transit Operations

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Abstract

Facing unprecedented increases in operational expenses, rail operators are seeking new methods to reduce costs. Traction is their largest expense and despite their low energy intensities, the scale of operations causes large overall energy consumptions. This, coupled with the environmental impact of fossil fuel consumption is cause for concern. Modern railcars are equipped with the regenerative braking feature allowing them to generate electrical energy on braking. The energy can be stored for later use or transmitted directly to an accelerating train to reduce the energy used for acceleration. This study presents an intelligent method for harvesting the kinetic energy of an electric train through coasting and regenerative braking, and optimal positioning of the wayside energy storage system (WESS) units on a multi-segment rail line. Coasting saves energy by maintaining motion with propulsion disabled, and regenerative braking converts the kinetic energy of the train into electrical energy for the powering of subsequent acceleration cycles. The study entails the design of a model that simulates the movement of the train over an existing alignment section while considering alignment topography, speed limits, and train schedule. The main contribution of this research is the optimization of the number and locations of the WESS units using optimized speed profiles to maximize the net present value (NPV) of the energy recovery project. In this study, the optimized speed profiles are obtained with and without WESS installation and used as inputs to a linear programming (LP) simulation model. Hence, the model begins with inputs that are already optimized, ensuring a greater degree of processing speed and accuracy. The decision variables are the number and locations of the WESS units, and the output of the simulator is the optimized NPV. The results can be used for the planning of smart infrastructural

upgrades, the reduction of energy consumption or the mitigation of environmental pollution.

Keywords: rail transit; sustainable operation; energy optimization; regenerative braking; simulation; genetic algorithm; speed profile.

1 Introduction

Increasing operational expenses are causing railroads to seek new methods for sustainability improvement of their operations. Although rail is one of the least energy-intensive modes of transportation, their scale of operation dictates large fuel budgets. In addition, since 25% of all passenger rail is powered by fossil fuels [1], concerns about environmental pollution are warranted.

The optimal placements of energy storage devices play a very important part in the improvement of the receptivity of regenerative braking energy harvested from braking trains. Receptivity in this context refers to the likelihood of the energy storage devices being able to absorb the energy generated in their proximity.

The main contribution of this research is to optimize the number and locations of the WESS units using optimized speed profiles to maximize the net present value (NPV) of the energy recovery project. The NPV is the present value of future cash flows generated by a project at a required discount rate compared to the initial investment. It is capable of finding a balance between the energy saving and the installation costs, which can be a decision maker as to whether or not the project will proceed.

In this study, the optimized speed profiles are obtained with and without WESS installation and used as inputs to a linear programming (LP) simulation model. Hence, the model begins with inputs that are already optimized, ensuring a greater degree of processing speed and accuracy. The decision variables are the number and locations of the WESS units, and the output of the simulator is the optimized NPV.

2 Methods

Speed Profile Optimization

Through the application of a genetic algorithm (GA) similar to that in [1], the speed profile was optimized by minimizing the net energy consumed. The total energy consumed by the train at time t is given by [1]:

$$E_T^{'} = \sum_{t=0}^{T} P^t \frac{t}{3600} . \frac{1}{1.341} \qquad \forall t \tag{1}$$

The total regenerated energy E_R is [4]:

(2)

$$E_R = \sum_{t=0}^{T} \left[0.01072 m\rho \left[\left(v^t\right)^2 - \left(v^{t+1}\right)^2 \right] + 27.25\left(s^{t+1} - s^t\right) mG^t - \left(0.2778 R^t \left(s^{t+1} - s^t\right)\right) \right] \eta_r$$

Thus the net energy consumed is:

$$E_T = E_T^{'} - E_R \tag{3}$$

Optimization of WESS Locations

The NPV was chosen as the optimization output because it considers the real value of money at every year of operation. It includes the interest rate which is usually equal to the rate of inflation [5].

The interest was calculated using the compound interest formula:

$$A_T = P\left(\left(1+r\right)^q - 1\right) \tag{4}$$

where A_T is the total interest ($) to be paid to the lender, P is the principal ($), r is the interest rate as a decimal, and q is the repayment period (years).

For the calculation of the average annual cost shown in Table 2, the cost per unit was added to the interest accrued over 15 years at 2.5% interest. The result was divided by the payback period (e.g., 15 years) and then added to the annual maintenance cost.

Cost per unit ($)	**Interest over 15 years ($)**	**Yearly cost per unit ($)**	**Maintenance ($/year)**	**Annual cost ($/year)**
979,738	439,214	94,596	28,921	123,517

Table 1**:** Costs per WESS unit

The yearly cash flow for the line is the value of energy saved using WESS. Therefore:

$$CF = C_E - C_{E'} \tag{5}$$

where CF is the cash flow and $C_{E'}$ and C_E are energy costs with and without WESS respectively. C_E is determined by the train frequencies and operation in periods with different electricity rates. Thus,

$$C_E = \sum_{j=1}^{M} (e_{ij})(f_N r_N + f_1 r_1 + f_2 r_2) \quad (6)$$

where M is the number of track segments on the line, e_{ij} (kWh/year) is the energy consumed by train i on section j without WESS, f_N, f_1 and f_2 are the annual train frequencies during off-peak, summer-peak, and winter-peak electric consumption periods, respectively, while r_N, r_1 and r_2 represent the corresponding unit costs.

$$C_{E'} = \sum_{j=1}^{M} (e_{ij}(1-y_j) + e'_{ij} y_j) f_N r_N + (e_{ij}(1-y_j) + e'_{ij} y_j) f_1 r_1 + (e_{ij}(1-y_j) + e'_{ij} y_j) f_2 r_2 \quad (7)$$

where e'_{ij} (kWh/year) is the energy consumed by train i on section j with WESS installed and y_j is an index for WESS installation on segment j; if y_j is 1, then a WESS is installed. Else, if y_j is 0, then no WESS is installed.

The objective function is therefore:

$$\text{Max: } NPV = \left[\sum_{t=1}^{T_L} \frac{C_E - C_{E'}}{(1+r)^t} - C_M \right] - \mathrm{C}_I \quad (8)$$

$$\text{st:} \quad C_I + C_M \le B \quad (9)$$

$$\sum y_i \le M \quad (10)$$

Where B is annual budget allowance, T_L is the lifecycle time of the WESS, r is the discount rate.

3 Results

Numerical Example

A multi-segment section of track on Long Island Rail Road's Babylon branch shown in Figure 1 below was chosen to verify the methods outlined in this study.

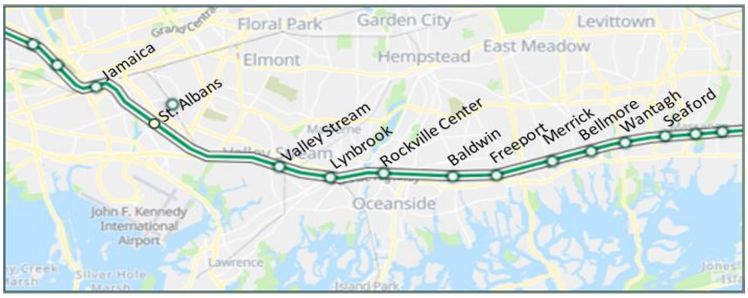

Figure 1: Study alignment section.

The lengths of the segments and the average gradients [6] are listed in Table 1.

Jamaica – St. Albans	3541.04	0.7
St. Albans – Valley Stream	6517.76	0.002
Valley Stream – Lynbrook	804.66	0.36
Lynbrook – Rockville Center	4707.31	0.03
Rockville Center – Baldwin	3459.97	0.02
Baldwin – Freeport	2051.89	0.1
Freeport – Merrick	2856.57	0.08
Merrick – Bellmore	2011.67	0.07
Bellmore – Wantagh	1770.25	0.13
Wantagh – Seaford	2132.36	0.014

Table 2: Segment lengths and average gradients.

Optimization

A linear programming optimization was performed to determine the number and locations of WESS units to maximize the NPV. The results indicate that placing two units on Segments 2 and 5 would maximize the NPV as shown in Table 3 below, giving a value of $120,242.

Segment ID	**Segments**	**WESS index***
1	Jamaica – St. Albans	0
2	St. Albans – Valley Stream	1
3	Valley Stream – Lynbrook	0
4	Lynbrook – Rockville Center	0
5	Rockville Center – Baldwin	1
6	Baldwin – Freeport	0
7	Freeport – Merrick	0
8	Merrick – Bellmore	0
9	Bellmore – Wantagh	0
10	Wantagh – Seaford	0

** 1 = WESS installed; 0 = no WESS installed*

Table 3: Optimized WESS placements

Sensitivity Analysis

Electricity costs vs. optimal NPV

The electricity rates for each period was increased in 20% increments and the optimal locations and NPV was computed. Figure 3 shows that as rates increase, the NPV for each segment increases.

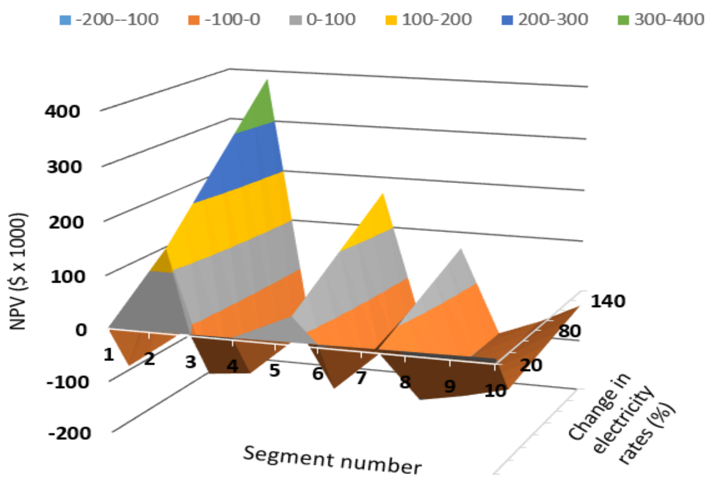

Figure 1**:** Increases in electricity rates vs. NPV for each segment.

Table 4 shows that as rates are increased, an additional optimal location was available for increases above 40%.

Percent rate increase (%)	**Optimal locations**	**Optimized net present value ($)**
20	2,5	170,809
40	2,5	234,668
60	2,5,7	308,620
80	2,5,7	387,015
100	2,5,7	465,407
120	2,5,7	543,779
140	2,5,7	622,171
160	2,5,7	698,880

Table 4: Percent electricity rate increase vs. optimal WESS locations and optimized NPV.

Train Frequency vs. NPV

The train frequencies were varied in 10% increments and the optimal unit locations and NPV were computed. Figure 4 shows that the NPV for each segment varies proportionally with train frequency.

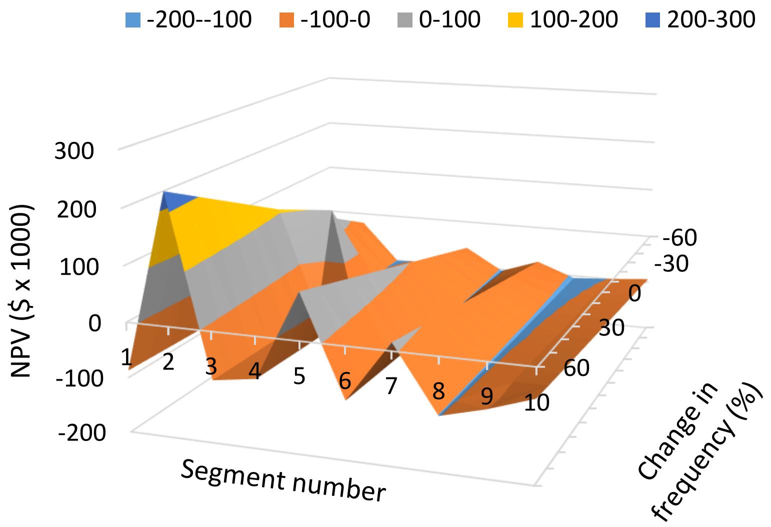

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Figure 2: Train frequency vs. NPV

Interest Rate vs. NPV

For the project to be profitable, the NPV must be positive. In this section, the interest rate was varied and the NPV determined. As seen in Figure 4, as the discount rate increases, the NPV decreases rapidly.

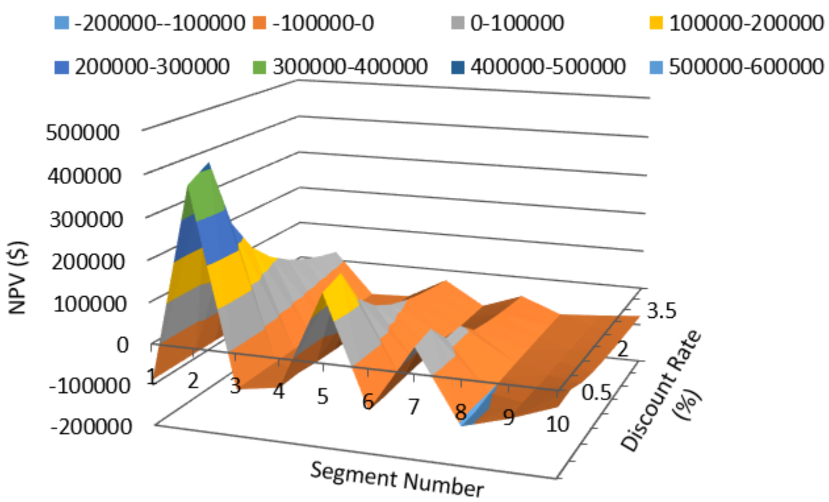

Figure 3: Change in discount rate vs. NPV

4 Conclusions and Contributions

The aim of this study was to optimize the placements of the energy storage devices used to capture the regenerative braking energy by maximizing the net present value (NPV) of the project. A linear programming optimization algorithm was used in the determination of the number and locations of WESS units to maximize the NPV. The results indicate that placing two units on Segments 2 and 5 would maximize the NPV giving a value of $120,242 with the initial values of interest on capital, train frequency and electricity rates.

Sensitivities conducted found that as electricity rates increase, the NPV for each segment increases with additional WESS units becoming necessary for larger percentage rate increases.

For variations in train frequencies, it was observed that the NPV varied proportionally, indication a linear relationship between the two variables.

The discount rate, which is the cost to acquire funding, causes the NPV to rapidly decrease as it increases and results in a decrease in the number of WESS units needed to re-optimize the system.

The optimization methods outlined in this study could accurately determine the optimal placements and number of WESS units to maximize the NPV and were made even more efficient by prior optimization of the speed profiles. This double optimization results in faster execution of the commands and therefore would be ideal for driver advisory systems and other energy optimization infrastructural improvements.

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