$E^* = \min\{E_a + E_c - E_r\}$

Optimized Speed Profiles for Sustainable Train Operation with Regenerative Braking

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ABSTRACT

Atmospheric pollution due to fossil fuel consumption has resulted in climate change; and in some cases, the altering of entire ecosystems. In the US rail industry this issue is problematic because a large percentage of electricity consumed is derived from fossil fuel combustion. This research examined the benefits of regenerative braking in reducing the energy consumption of electric rail vehicles and the extended benefits obtained when synergized with coasting. Regenerative braking converts the kinetic energy of the train into electrical energy which is used to power subsequent acceleration cycles. The optimization problem was solved by applying Genetic Algorithms (GA) and it was found that at peak hours with approximately 30% of the total weekly Long Island Rail Road trains running, energy savings totaled 24.5% when coasting and regenerative braking were synergized rather than applied separately. Annual savings were \$5.9 million during peak periods and \$8.1 million at off-peak hours. In addition, the peak hour operation was significantly more efficient consuming 42.64 BTU per passenger mile over the off-peak operation at 95.74 BTU per passenger mile.

Keywords: train; speed profile, energy; sustainable operation; efficiency; regenerative braking; genetic algorithms.

INTRODUCTION

Electric rail vehicles have been known to have high fuel efficiency among various modes of transportation in terms of per passenger fuel consumption and play a leading role in transportation sustainability. However, railroad operations have faced numerous challenges over the years with regards to fuel consumption and Greenhouse Gas (GHG) emissions. Modern railcars are either diesel or electric powered, and although electric trains do not emit pollutants locally, statistics show that 62.7% of the electricity generated in the US was derived from fossil fuels (Energy Information Agency 2017). The figure for the world electricity generation is slightly higher at 66% (World Energy Council 2017). Therefore, electric trains do have significant carbon emissions which can be reduced by optimizing their operation. The objective of this study was to develop a model to minimize the consumption of rail energy through the application of coasting and regenerative braking. The model examined three distinct scenarios, including Baseline run (no energy savings), Coasting only, and Coasting + Regenerative Braking.

All the variables affecting train operation and energy consumption, such as speed limits, schedule, alignment topography, motive power and acceleration were considered. The captured energy was stored in a Wayside Energy Storage System (WESS) consisting of a network of Electric Double-Layered Capacitors (EDLC) to be used in subsequent acceleration cycles. The intention of the model was to reduce the peak power usage of the trains, which is a major determining factor in electrical energy charges. This reduction in consumption using regenerated energy for acceleration averages between 20% and 30% (Walker et al 2002).

METHODOLOGY

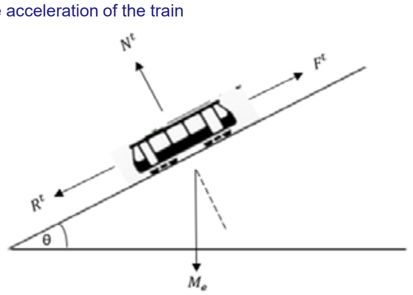
A model consisting of three distinct scenarios was designed to optimize the energy consumption of the train with all axles powered and simulated as follows:

1. Baseline scenario – no energy saving
2. Coasting only
3. Coasting and regenerative Braking

Starting from Newton's second law of motion, kinematic equations were developed and along with the train specifications and alignment parameters:

$$F^t - R^t = M_e \cos\theta . a$$

Where a is the acceleration of the train

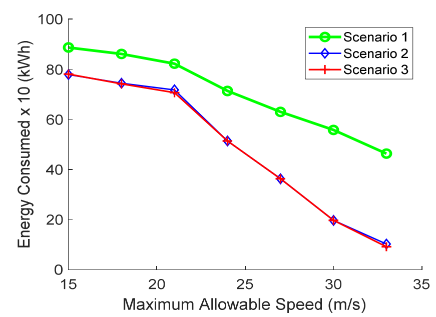


The objective function is $E^* = E_a + E_c - E_r$
Where E^* is the optimized energy consumption
E_a is the energy consumed during acceleration
E_c is the energy consumed during cruising
and E_r is the regenerative braking energy

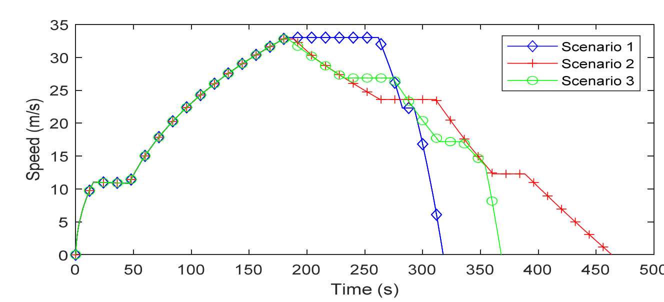
Genetic Algorithms (GA) applied to optimize the energy consumption.

RESULTS AND SENSITIVITY ANALYSIS

- Scenario 1 (Baseline) consumed the most energy of the three, but has the shortest travel time
- Scenario 2 (Coasting only) delivered great savings over the baseline, but the consumption was not optional since regenerative braking was not included.
- Scenario 3 delivered the optimal energy consumption with performance that was superior to all other scenarios

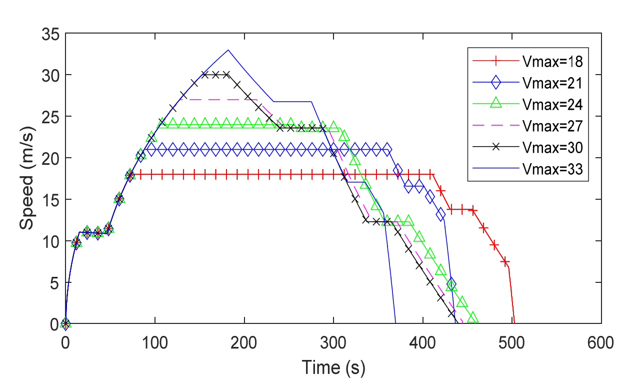


- In scenario 1 there was no coasting and thus travel time was minimized.
- Scenario 2 did not include cruising. It consisted of acceleration, coasting and braking only. Therefore is had the longest duration.
- Scenario 3 included optimal quantities of the cruising, costing and braking regimes. It was the least energy intensive and satisfied the time constraint.



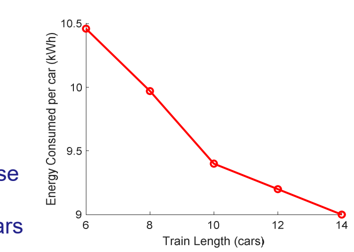
Maximum speed vs. travel time

- Figure shows optimal speed profiles for varying maximum speeds
- As the maximum speed increases, the cruising regime becomes shorter and the train consumes less energy
- Simulations with lower maximum speeds did not include a coasting regime and had higher coasting termination speeds to maximize regenerative braking energy
- The optimal speed profiles for simulations in the middle of the range of speed values tended to resemble scenario 2



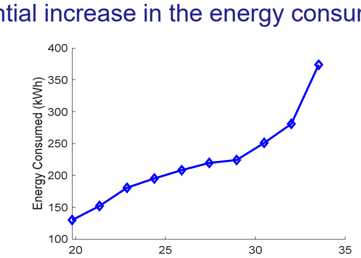
Energy Consumed per Car vs. Number of Cars per Train

- As number of cars increases energy per car decreases
- The operator could benefit from economies of scale by running longer trains
- For this study, the rate of decrease slows after the 10-car mark, so it is advisable to run trains at 10 cars or less unless necessary.



Coasting Termination speed (V_c) vs Energy consumed

- The relationship shows a slow increase in energy consumed as V_c increases up to a V_c value of 27.75 m/s after which there was an exponential increase in the energy consumed



SUMMARY

A model consisting of three scenarios was developed to optimize the energy consumed by an electric railcar.
Scenario 1: Baseline Case (No energy saving strategy applied)
Scenario 2: Coasting only
Scenario 3: Coasting and Regenerative braking

A case study was conducted on section of Long Island Rail Road's Hempstead Branch using an M7 consist of 10 cars and was simulated on a single alignment section subject to the train specifications and alignment parameters. Simulations were conducted at peak, off-peak and zero load factors and for progressively early and late trains.

. The peak hour train consumed more energy than the off-peak or empty train but was more efficient because it consumed less BTU per passenger mile saving costs for the operator and benefitting the environment .

On the issue of late or early trains, it was determined that as long as the maximum travel time allowed is greater than or equal to the travel time experienced in the optimal profile for the particular maximum travel speed, then the resulting simulation and the speed profile generated therein will be identical to the optimal speed profile.

The inclusion of the WESS would benefit the operator by obtaining significant energy savings over time. In the case study it was determined that if the Long Island Rail Road adapted their strategies according to those outlined in this study, their savings could amount to approximately \$14 million annually from their electric fleet.

CONCLUSIONS

- The purpose of this study was to minimize the net energy consumed by the train through coasting and regenerative braking subject to the train specifications and alignment parameters.
- It was found that although when applied separately the strategies delivered some amount of energy saving, it was the combination of the two that really obtained the minimization of the objective function.
- The combination of coasting + regenerative braking delivered a 14.3% off-peak energy saving and 24.5% peak energy saving over the strategy when only coasting was applied. When the maximum allowable travel speed increases, the energy consumed decreases, and when coasting is terminated at higher speeds, the energy that could be regenerated for re-use increases. Although the peak hour train consumed more energy than the off-peak or empty train, it was more efficient because it consumed less BTU per passenger.