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Effect of regenerative braking on energy-efficient train control

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Outline

Effect of regenerative braking on energy-efficient train control

- Introduction
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- Case study no regenerative braking
- Regenerative braking
- Case study regenerative braking
- Conclusions

Introduction

What is the effect of regenerative braking?

- The optimal energy-efficient driving regimes without regenerative braking are well-known
- Modern trains have the ability of regenerative braking
- This ability increases the number of driving regimes
- No exact algorithms have been described yet except for simplifying assumptions
- Different effects are reported in the literature possibly due to simplifying assumptions or heuristic solution methods

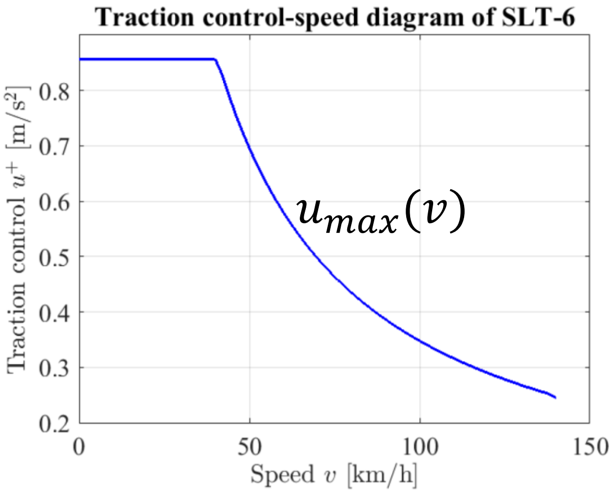
Challenges

- Find the effect of regenerative braking on energy-efficient driving
- Find an efficient algorithm to find all switching times
- First part of the answer: level track with fixed speed limit

No regenerative braking

Optimal control problem

- State variables: time t and speed v
- Control variable: mass-specific force u
- Independent variable: distance x



$$\min_u \int_0^X u^+(x)dx$$ Objective (energy)

$$\frac{dt}{dx} = {}^1/_v$$

$$\frac{dv}{dx} = \frac{u - r(v)}{v}$$ Dynamic equations

$$v(x) \in [0, v_{max}], u(x) \in [-u_{min}, u_{max}(v(x))]$$ Path constraints

$$t(0) = 0, t(X) = 0, v(0) = v(X) = 0$$ Terminal conditions

with $u^+ = \max(u, 0) = F_{Traction}/\rho m$ and $r(v) = r_0 + r_1 v + r_2 v^2$

No regenerative braking

Application of Pontryagin's Maximum Principle

Optimal control structure

$$\hat{u}(x) = \begin{cases} u_{max}(v(x)) & \text{if } \lambda(x) > v(x) \\ u \in [0, u_{max}] & \text{if } \lambda(x) = v(x) \\ 0 & \text{if } 0 < \lambda(x) < v(x) \\ -u_{min} & \text{if } \lambda(x) \le 0 \end{cases}$$

Maximum acceleration
Cruising
Coasting
Maximum braking

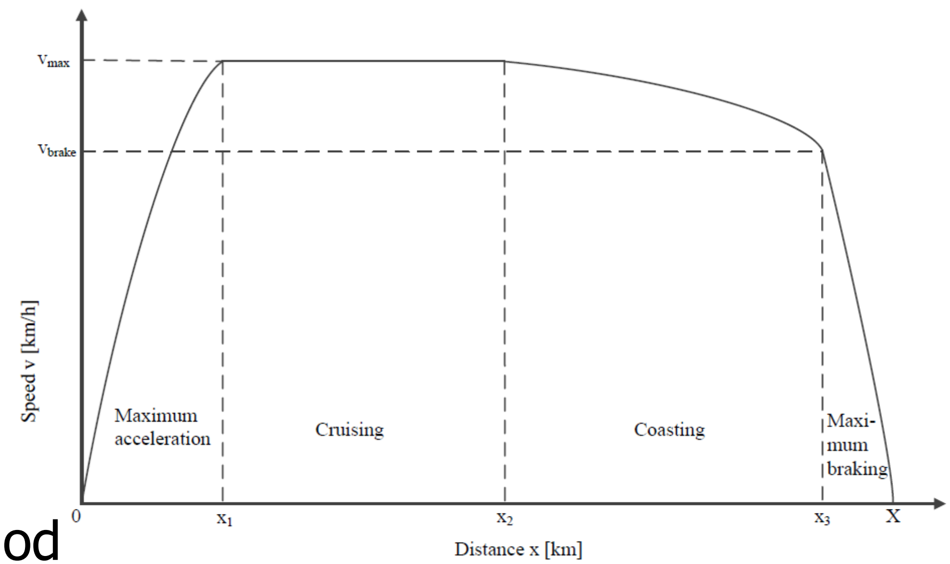
with $\lambda(x)$ a co-state variable

Indirect solution method

- Find switching points between driving regimes

Direct solution method

- Transcribe into NLP
- Solve by Pseudospectral method



Case study no regenerative braking

Scenarios

Solution algorithms

- Indirect method (EZR)
  - Iterative bi-level search algorithm to find optimal cruising speed and coasting point (Scheepmaker and Goverde, 2015)
  - Developed, calibrated and validated for train control
- Direct method (EZ3R)
  - Gauss Pseudospectral Method implemented in GPOPS (Rao et al, 2010)

Optimal train control problems

- Time-optimal train control (TO)
- Energy-efficient train control (EETC)

Case study no regenerative braking

Sprinter 7400 Driebergen-Zeist – Maarn (NL)

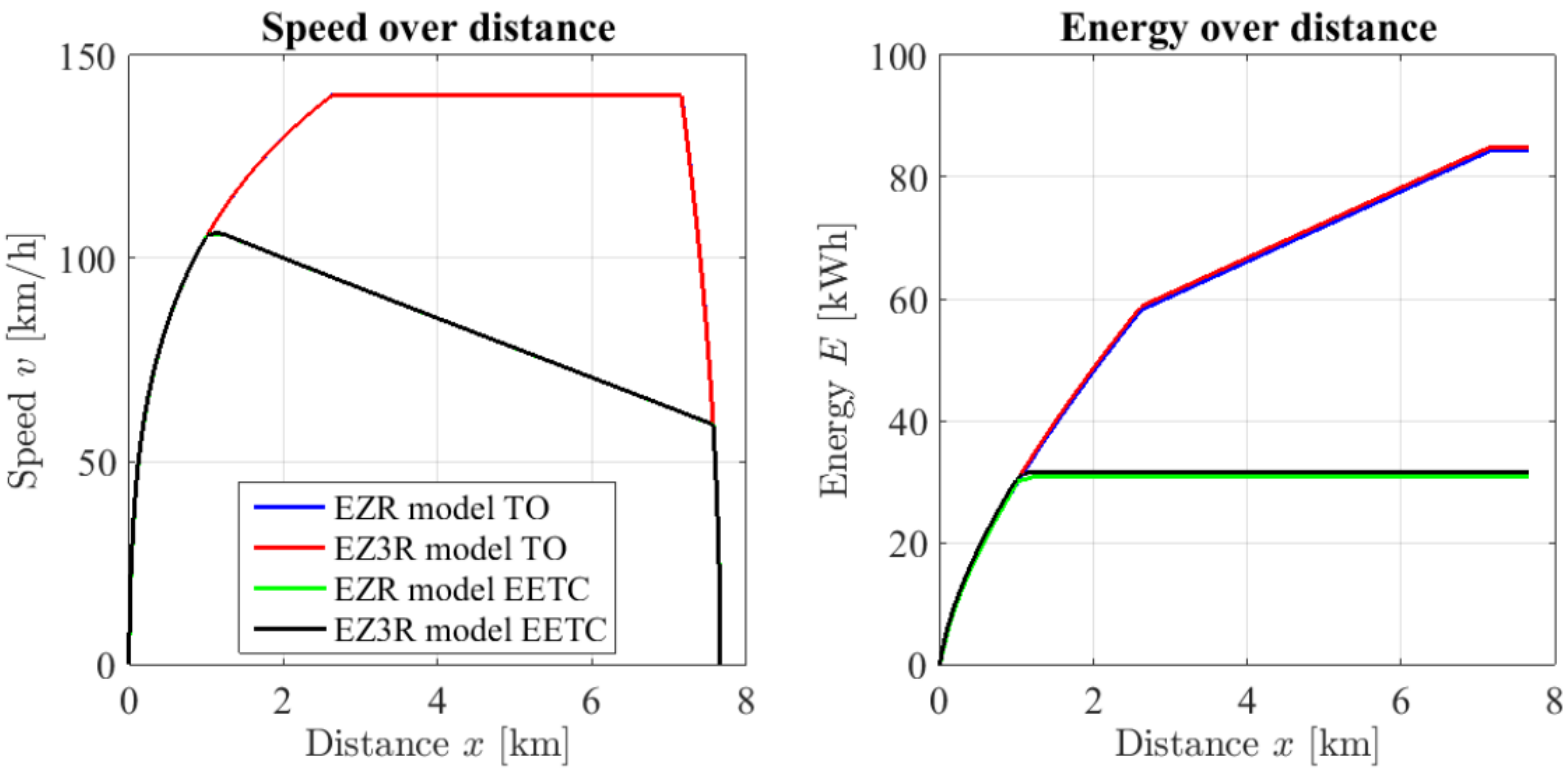
- Distance $X = 7668$ m
- Scheduled running time 6 min
- Rolling stock type SLT-6
- Max speed 140 km/h

Scenarios

- EZR + TO: indirect search method & time-optimal train control
- EZ3R + TO: direct GPOPS method & time-optimal train control
- EZR + EETC: indirect search method & energy-efficient train control
- EZ3R + EETC: direct GPOPS method & energy-efficient train control

Case study no regenerative braking

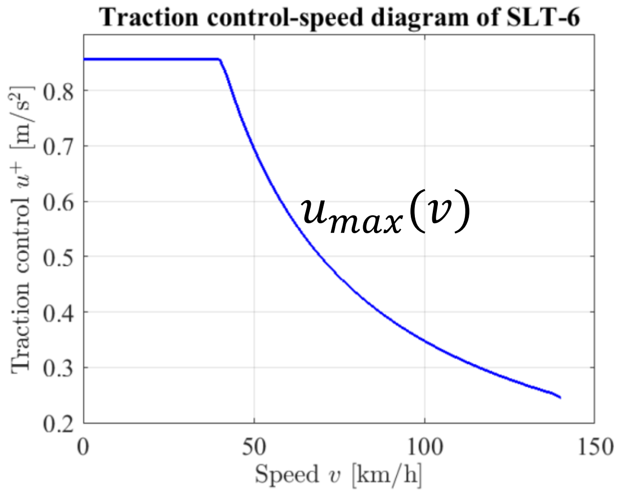
Results



- Computation times EETC models
  - ❑ Indirect algorithm (EZR): 122 s
  - ❑ Direct algorithm (EZ3R/GPOPS): 5 s

Regenerative braking

Optimal control problem



- Control variables
  - Traction force u
  - Regenerative braking force u_r
  - Mechanical braking force u_b

$$\min_{u,u_r,u_b} \int_0^X (u(x) - \eta u_r(x))dx$$ Objective (energy)

$$\frac{dt}{dx} = 1/v$$

$$\frac{dv}{dx} = \frac{u - u_r - u_b - r(v)}{v}$$

Dynamic equations

Path constraints

$$v(x) \in [0, v_{max}], u \in [0, u_{max}(v(x))], u_r \in [0, \bar{u}_r], u_b \in [0, \bar{u}_b]$$

$$t(0) = 0, t(X) = 0, v(0) = v(X) = 0$$ Terminal conditions

With efficiency parameter $\eta \in [0,1]$ and $\bar{u}_r + \bar{u}_b = u_{min}$

Case study regenerative braking

Sprinter 7400 Driebergen-Zeist – Maarn (NL)

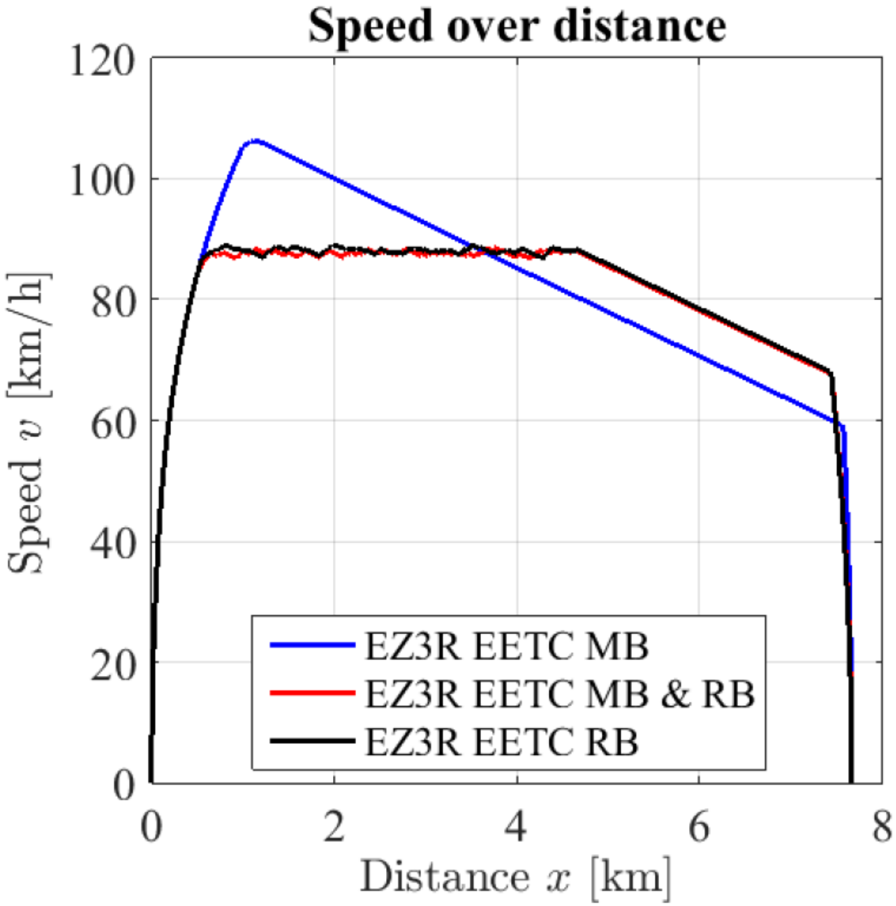
- Distance $X = 7668$ m
- Scheduled running time 6 min
- Regenerative braking efficiency $\eta = 0.87$
- Solver: GPOPS (Gauss Pseudospectral Method)
- Rolling stock type SLT-6
- Max speed 140 km/h

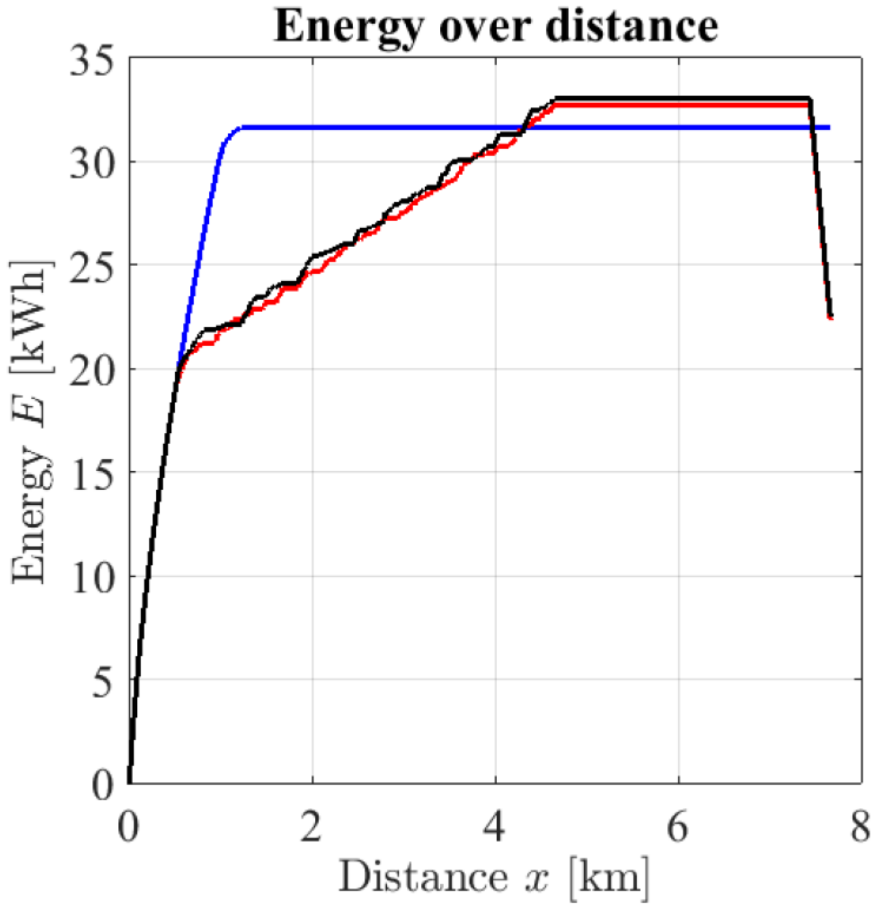
Scenarios

- Mechanical braking only (285.8 kN)
- Mechanical and regenerative braking (135.8 + 150 kN)
- Regenerative braking only (150 kN)

Case study regenerative braking

Results





- Energy saving with regenerative braking: 29%
- Computation times < 20 s

Conclusions

Energy-efficient driving regimes with RB

Results for level track and fixed speed limit

- Lower cruising speed
- Coasting still applied
- Regenerative braking applied in final braking stage
    - Starting earlier at higher speed
    - No mechanical braking used when regenerative braking available
- Case study on an 8 km line shows 29% extra energy saving w.r.t. no regenerative braking

Solution algorithm

- Gauss Pseudospectral Method is fast (< 20 s)
- Issue with singular solution (cruising at less than max speed) which is approximated by a bang-bang control (successive maximum acceleration-coasting)