The Fourth International Conference on Railway Technology
RAILWAYS 2018
3–7 September 2018
Sitges, Barcelona, Spain

Sub-Optimal Non-Linear Optimization of Trajectory Planning for the DLR Next Generation Train (NGT)

Athanasios Iraklis, Holger Dittus, Toni Schirmer*, Ivan Windemut, Joachim Winter
German Aerospace Center (DLR), Stuttgart & Berlin, Germany
Institute of Vehicle Concepts | Vehicle Energy Concepts
Contact: toni.schirmer@dlr.de

04th September 2018
Toni Schirmer
DLR

I am happy for you to photograph or tweet the slides from my talk

DLR

Agenda

1. Motivation
2. Status quo
3. Methodology
4. Use case
    - NGT LINK
    - Reference Scenario
    - Simulation Results
5. Conclusion & Outlook

Motivation
Driving optimization for DLR Next Generation Train (NGT)

Status quo: Trajectory Planning Tool (TPT)

Conventional time optimized trajectory planning method for developing speed profiles

Future

Need for time optimized speed profiles with minimized energy usage and LCC

- Computer-aided calculation of optimal driving style
- Increasing share of electro dynamic braking
- Reduction of wear and lifecycle costs
  - Less usage of friction brakes
- Improving computing time

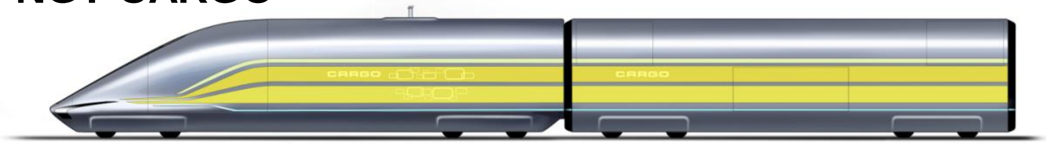
NGT HST

→ Ultra-high-speed train, traction power 16 MW, operational speed 400 km/h

NGT LINK

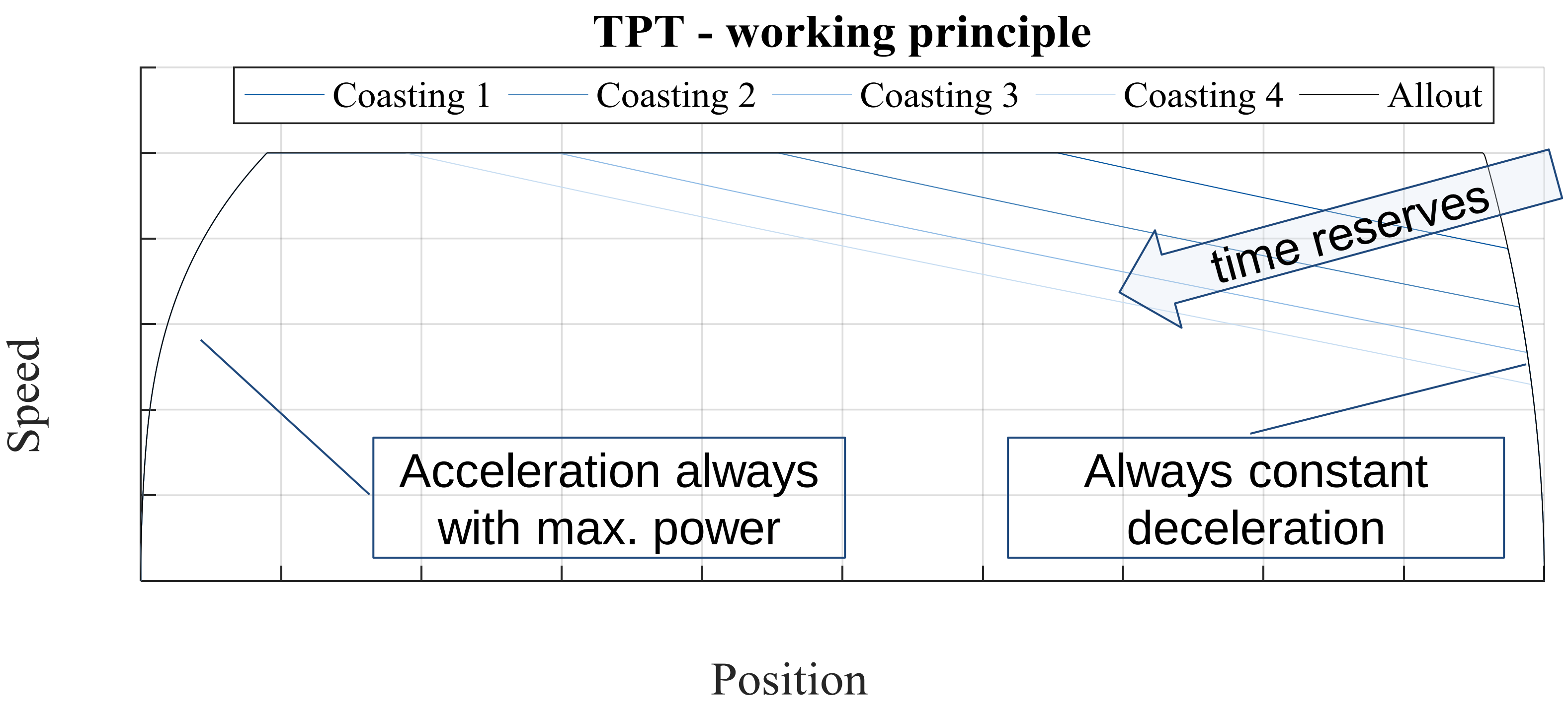
→ feeder train set, traction power 2.5 MW, operational speed 230 km/h

NGT CARGO



→ Autonomous ultra-high-speed railcar freight train, operational speed 400 km/h

Status Quo
Trajectory Planning Tool (TPT)



Methodology:

1. Calculate fastest trajectory (AllOut) as basis
2. Add coasting to fulfil timetable:
   a) Try to cut AllOut trajectory beginning in the right corner
   b) If no solution is found, max. speed will be reduced

- Results are only time optimized
- Trajectory is composed appropriately “per try and error”
- Computing for Coasting is time consuming

Methodology

Sub-Optimal Non-Linear Optimization of Trajectory Planning (OPT)

- Direct Method (DM) for train trajectory generation
  - Solution vector: *x(u,v) = [u(d), v(d)]*
  - Problem domain: *d* ➔ distance
  - Control vector: *u(d)* ➔ notch setting $u(d_i) \in [-11...+8]$ ➔ $P_{wheel(u(d)}$
  - State vector: *v(d)* ➔ vehicle speed constrained within the range [0…*max_line_speed(d)*

Constraints

Total journey time	$T_{TOTAL} \leq T_{TIMETABLE}$
Initial speed	$v(d_0) = 0$ km/h
Stops	$v(d_{stop}) = 0$ km/h
Final speed	$v(d_n) = 0$ km/h
Equation of motion	$\dot{v}(d_i) = (T_{trac\|brk} - T_{res})/(m + m_{rot})$
Maximum motor torque	$\|T(u(d_i)\| \leq T_{MAX}$
Ac-/Deceleration rate	$a(d_i) \leq / \geq a_{MAX}$

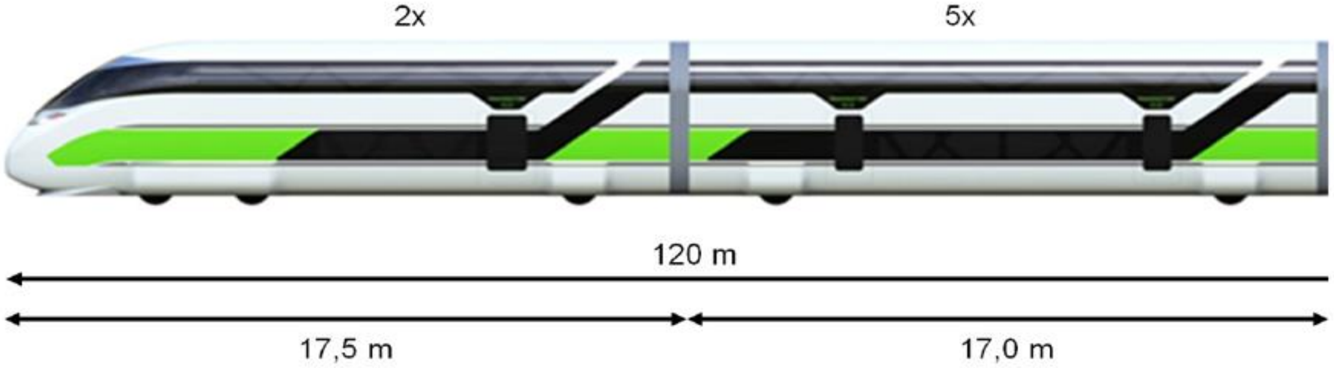
Specification

Target function	$L_s = \min(\sum(C(u(d_i)))$
Gradient of target function	$g_i = \frac{\partial Ls(x(u,v))}{\partial xi}$
Jacobian of constraints	$J_{i,j} = \frac{\partial ci(x(u,v))}{\partial xj}$

- **OPTI** IPOPT NL solver [1,2]

[1] OPTI Toolbox: https://www.inverseproblem.co.nz/OPTI/index.php
[2] Wächter, A. and Biegler, L.T., 2006. On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming. *Mathematical programming*, *106*(1), pp.25-57.

Use case: NGT LINK



- Innovative 16-axle train concept with all-wheel drive as EMU
- Double-decker regional and intercity train
- Serves as basis for comparing TPT and OPT

Relevant specifications

Maximum tractive power at wheel	2500 kW
Maximum tractive and electro dynamic brake force at wheel	412 kN
Maximum Ac-/Deceleration rate	± 1 m/s²
Design mass (fully loaded)	272 t
Rotational allowance	8 %
Auxiliary power P_{Aux}	0 kW
Davis coefficient A	3.9 kN
Davis coefficient B	0.8 kN/m/s
Davis coefficient C	4.6 kN/m/s2

Assumed efficiencies

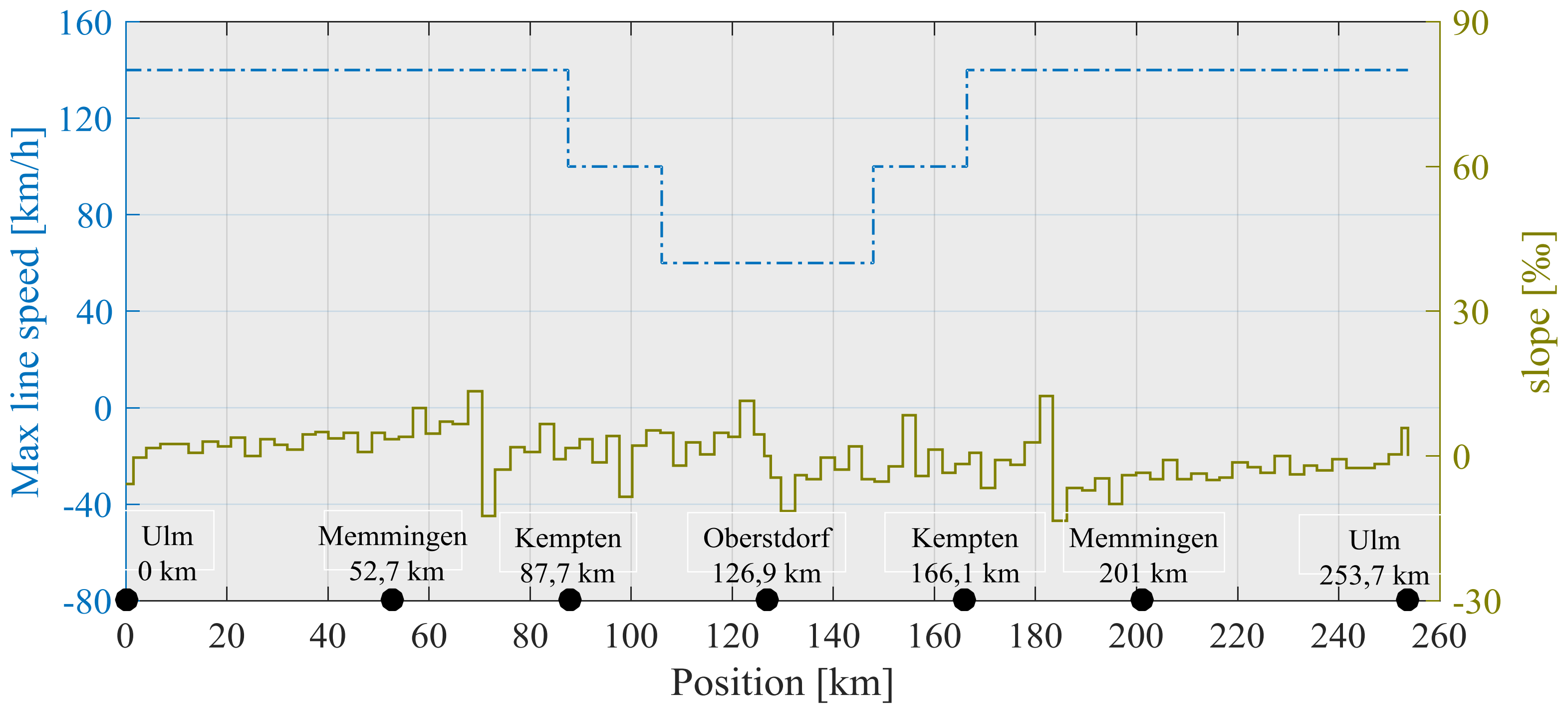
$\eta_{TractionMOT}$	90%
$\eta_{TractionINV}$	98%
$\eta_{Rectifier}$	98%
$\eta_{Transformer}$	95%

Use case: Reference Scenario

- Round-trip Ulm - Oberstdorf – Ulm (Germany) → overall distance 254 km [3]
- Assumption for use case: line is fully electrified
- Three journey times are considered: (1) 150 min, **(2) 166,7 min**, (3) 183,4 min

Energy prices at catenary [4]

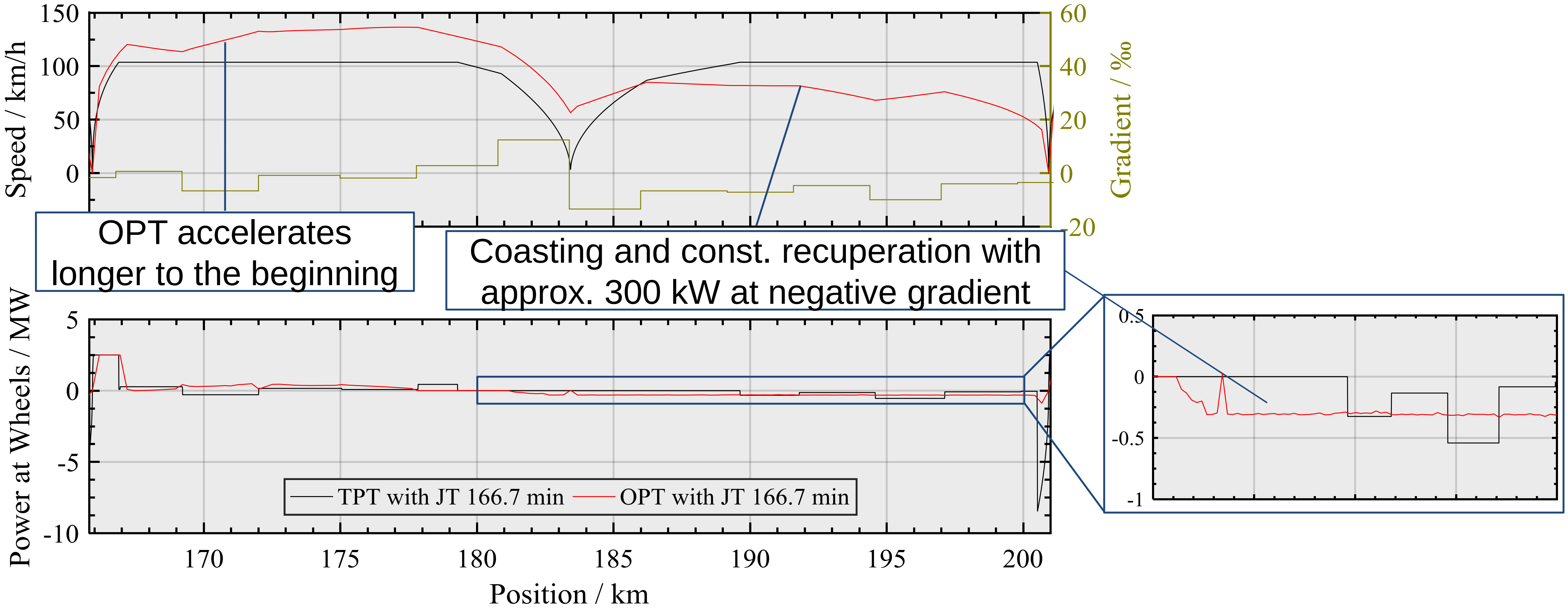
Price for traction	6.94 ct/kWh
Price for recuperation	3.34 ct/kWh



[3] Dittus, H., Hoffmann, M., Streit, S. and Kaimer, S., 2016. Design, Dimensioning and Analysis of a novel, locally emission-free Propulsion Concept for Regional Trains on non-electrified Railway Lines.
[4] DB Energie. 2017. Preisblatt für die Nutzung des 16,7-Hz-Bahnstromnetzes (Bahnstromnetz). Gültig ab 01.01.2017. [Online].

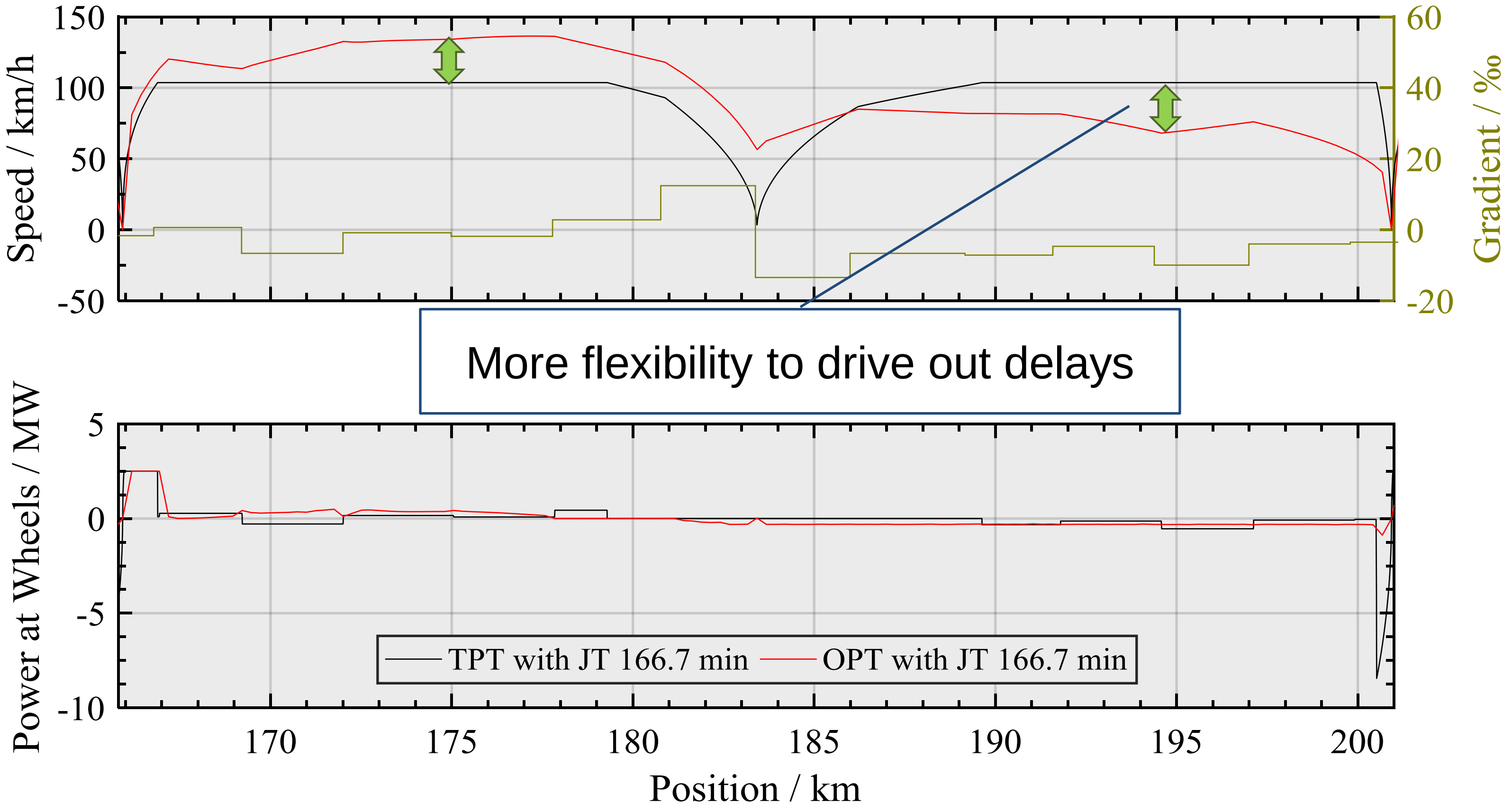
Use case: Results

OPT with better adaption to track boundary conditions than TPT

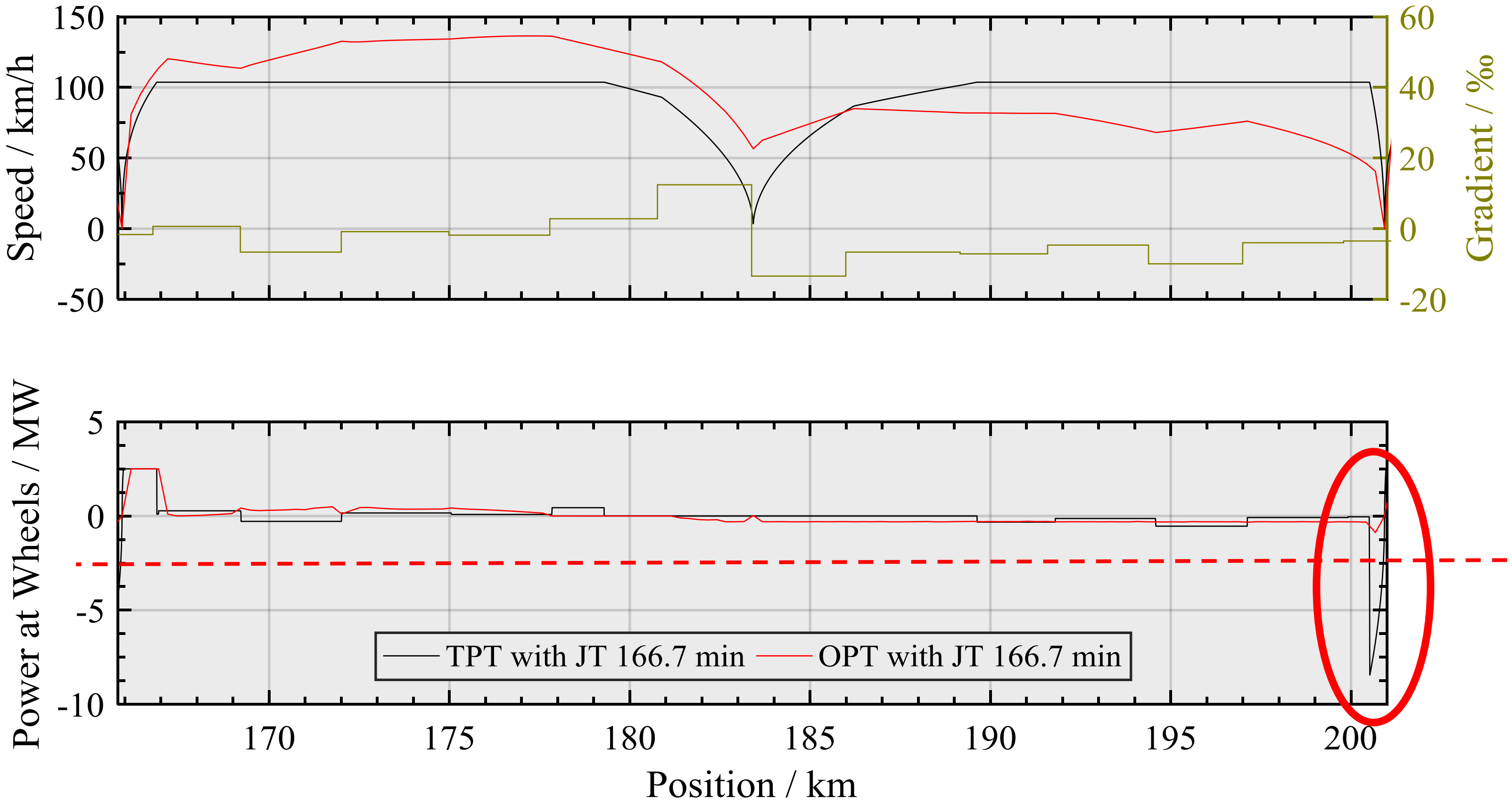


Use case: Results

Here: OPT with more time reserves than TPT due to higher speed at the beginning



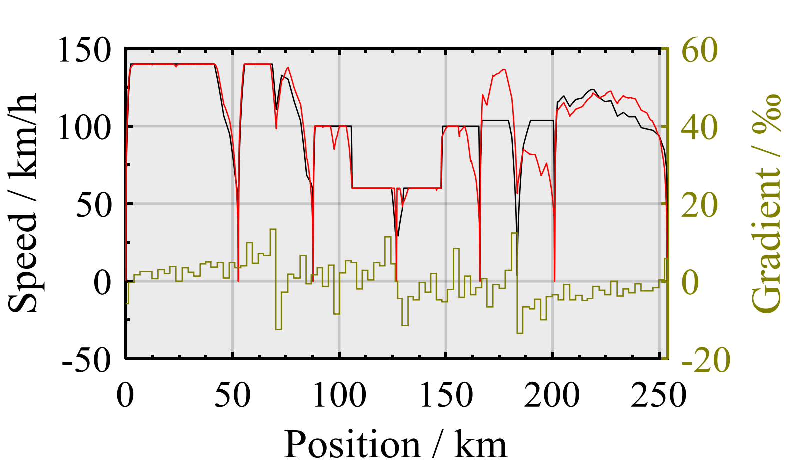
Use case: Results
OPT avoids using mechanical brakes

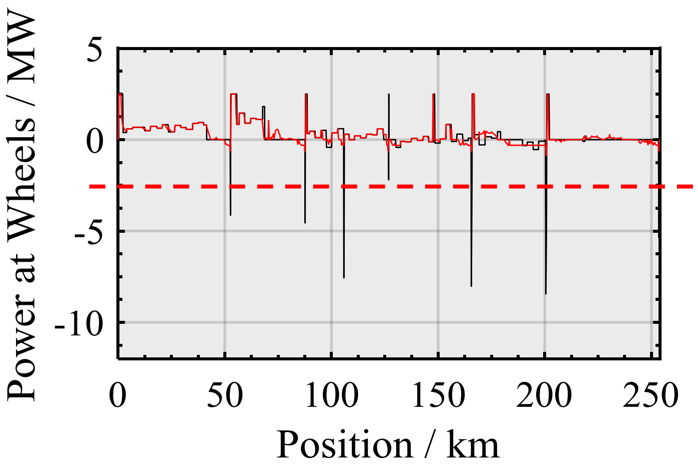


No use of mechanical brakes (< -2,5MW)

Reduction of wear and LCC

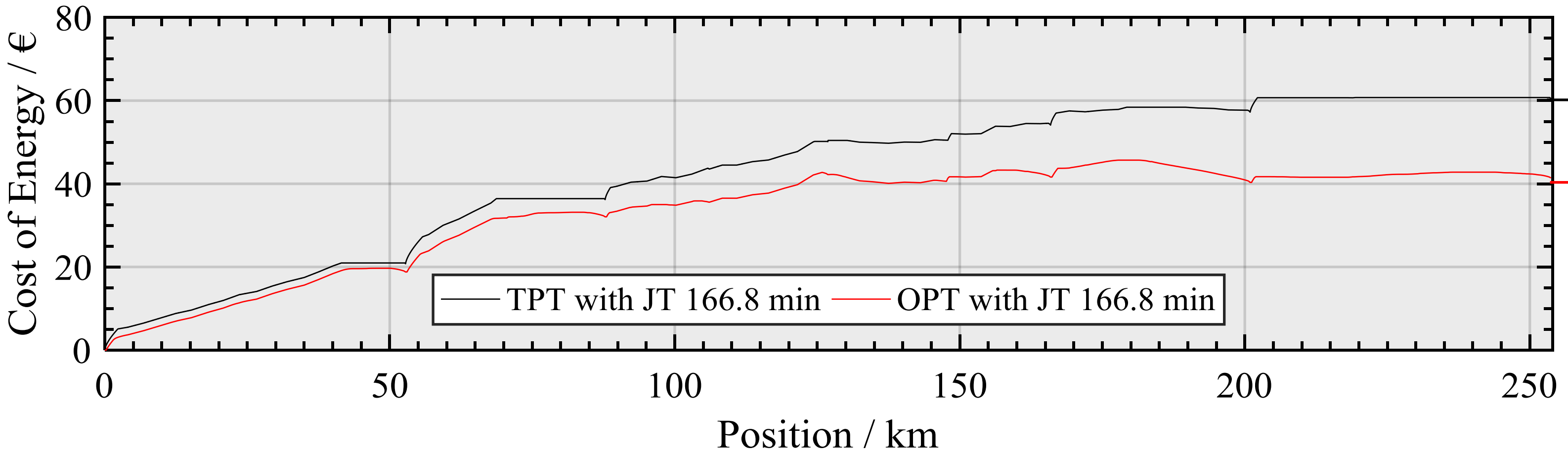
Use case: Comparison of Simulation Results
TPT vs OPT for journey time (JT) 166.7 min





No use of mechanical brakes

Reduction of wear and LCC



32% cost savings

30% for JT 150.0 min
35% for JT 183.4 min

DLR

Conclusion & Outlook

Conclusion

- OPT provides multi-criteria optimization → energy and time, TPT only time
- OPT uses track boundary conditions (gradients) – TPT with “try and error”
- OPT has better usage of electro dynamic braking → avoids mechanical breaks → reducing LCC
- OPT provides significant energy and cost savings when tested on reference scenario (30% – 35%)
- OPT has lower computation time requirements than TPT

Outlook

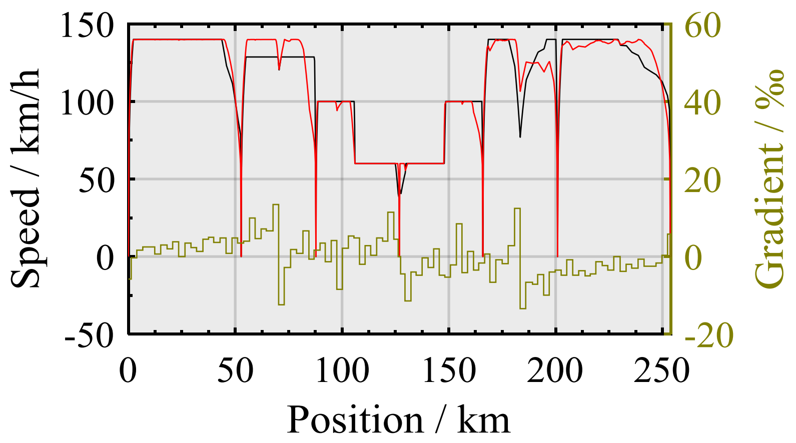
- Potential for integration in Driver Assistance Systems (DAS) or as a feature in Automatic Train Operation (ATO)
- Will be used for development of test cases in NGT projects (LINK, HST, CARGO)
- Integration of OPT tool in opportunity charging [8] of on-board Energy Storage System (ESS) scheme for vehicle concept NGT LINK

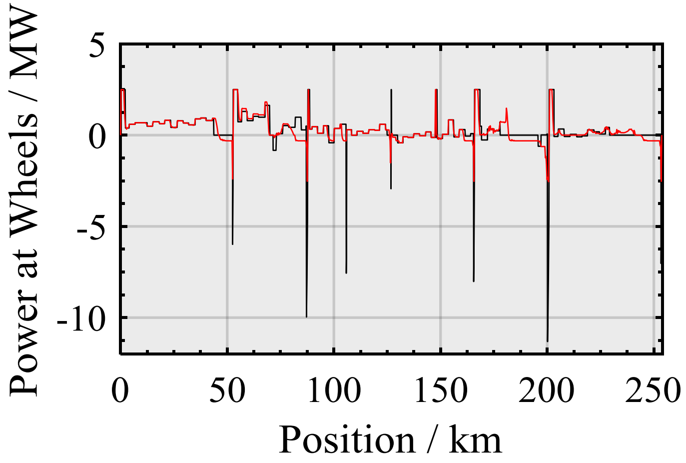
[8] Iraklis, A., Iraklis, C. and Hoffrichter, A., 2017. Catenary Free Battery Electric Operation with Opportunity Charging for Light Rail Networks. *Newsletter*, *2017*.

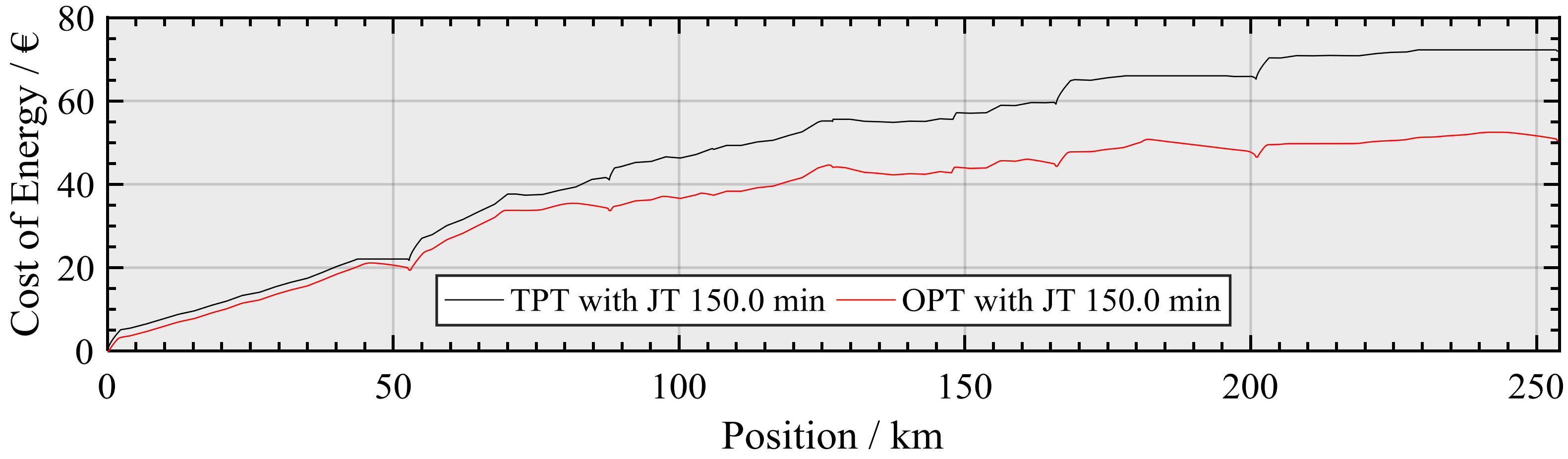
Thank you for your attendance!
Questions?

Toni Schirmer, M.Sc.
Institute of Vehicle Concepts
toni.schirmer@dlr.de

Appendix
TPT vs OPT for JT 150.0 min







Appendix
TPT vs OPT for JT 183.4 min