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

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DLR
I am happy for you to photograph or tweet the slides from my talk
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: $d \rightarrow$ distance
  • Control vector: $u(d) \rightarrow$ notch setting $u(d_i) \in [-11...+8] \Rightarrow P_{wheel}(u(d))$
  • State vector: $v(d) \rightarrow$ vehicle speed constrained within the range $[0...max\_line\_speed(d)]$

Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Constraint Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total journey time</td>
<td>$T_{TOTAL} \leq T_{TIMETABLE}$</td>
</tr>
<tr>
<td>Initial speed</td>
<td>$v(d_0) = 0 \text{ km/h}$</td>
</tr>
<tr>
<td>Stops</td>
<td>$v(d_{stop}) = 0 \text{ km/h}$</td>
</tr>
<tr>
<td>Final speed</td>
<td>$v(d_n) = 0 \text{ km/h}$</td>
</tr>
<tr>
<td>Equation of motion</td>
<td>$\dot{v}(d_i) = (T_{trac</td>
</tr>
<tr>
<td>Maximum motor torque</td>
<td>$</td>
</tr>
<tr>
<td>Ac-/Deceleration rate</td>
<td>$a(d_i) \leq / \geq a_{MAX}$</td>
</tr>
</tbody>
</table>

Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target function</td>
<td>$L_s = \min(\sum(C(u(d_i))))$</td>
</tr>
<tr>
<td>Gradient of target function</td>
<td>$g_i = \frac{\partial L_s(x(u,v))}{\partial x_i}$</td>
</tr>
<tr>
<td>Jacobian of constraints</td>
<td>$J_{i,j} = \frac{\partial c_i(x(u,v))}{\partial x_j}$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum tractive power at wheel</td>
<td>2500 kW</td>
</tr>
<tr>
<td>Maximum tractive and electro dynamic brake force at wheel</td>
<td>412 kN</td>
</tr>
<tr>
<td>Maximum Ac-/Deceleration rate</td>
<td>$\pm 1$ m/s$^2$</td>
</tr>
<tr>
<td>Design mass (fully loaded)</td>
<td>272 t</td>
</tr>
<tr>
<td>Rotational allowance</td>
<td>8 %</td>
</tr>
<tr>
<td>Auxiliary power $P_{Aux}$</td>
<td>0 kW</td>
</tr>
<tr>
<td>Davis coefficient A</td>
<td>3.9 kN</td>
</tr>
<tr>
<td>Davis coefficient B</td>
<td>0.8 kN/m/s</td>
</tr>
<tr>
<td>Davis coefficient C</td>
<td>4.6 kN/m/s2</td>
</tr>
</tbody>
</table>

### Assumed efficiencies

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{TractionMOT}$</td>
<td>90%</td>
</tr>
<tr>
<td>$\eta_{TractionINV}$</td>
<td>98%</td>
</tr>
<tr>
<td>$\eta_{Rectifier}$</td>
<td>98%</td>
</tr>
<tr>
<td>$\eta_{Transformer}$</td>
<td>95%</td>
</tr>
</tbody>
</table>
Use case: Reference Scenario

- Round-trip Ulm - Oberstdorf – Ulm (Germany) \( \rightarrow \) 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]

<table>
<thead>
<tr>
<th>Price for traction</th>
<th>6.94 ct/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price for recuperation</td>
<td>3.34 ct/kWh</td>
</tr>
</tbody>
</table>


[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
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

Thank you for your attendance!
Questions?

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Appendix

TPT vs OPT for JT 150.0 min

![Graphs showing speed, gradient, power, and cost of energy for TPT and OPT for JT 150.0 min.](image-url)
Appendix
TPT vs OPT for JT 183.4 min

[Graphs showing speed, gradient, power at wheels, and cost of energy versus position for TPT vs OPT.]