Train Trajectory Optimization with Signalling Constraints (PPT)

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Publication date
2015

Document Version
Final published version

Citation (APA)
Wang, P., & Goverde, R. (2015). *Train Trajectory Optimization with Signalling Constraints (PPT)*. 13th international conference on advanced systems for public transport, Rotterdam, Netherlands.

Conference on Advanced Systems in Public Transport

Train Trajectory Optimization with Signalling Constraints

Delft University of Technology

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July 20, 2015

Outline

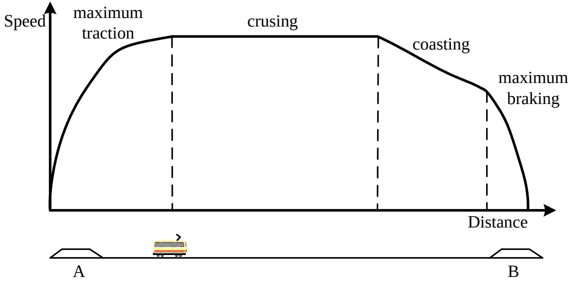
Introduction

What is the train trajectory optimization?

Introduction

What is the train trajectory optimization?

- speed trajectory
- energy-saving, on-time, safe, riding comfort. . .

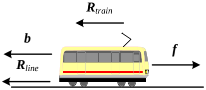


Train Dynamic Movement Model

Dynamic constraints:

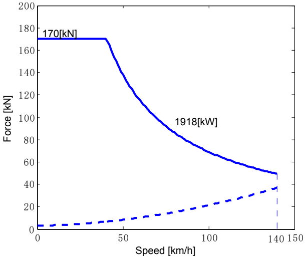
$$\frac{dv}{ds} = \frac{dv}{dt}\frac{dt}{ds} = \frac{a}{v} = \frac{\theta_1 f - \theta_2 b - R_{train}(v) - R_{line}(s)}{\rho \cdot m \cdot v}$$

$$\frac{dt}{ds} = \frac{1}{v}. \qquad \theta_1, \theta_2 \in \{0, 1\}$$



Path constraints:

$$\begin{cases} 0 \le f \le F_{\max} \\ 0 \le b \le B_{\max} \\ 0 \le f \cdot v \le P_{\max} \\ 0 \le v \le V_{\max} \\ A_{\min} \le \dfrac{dv}{dt} \le A_{\max} \end{cases}$$



Train Dynamic Movement Model

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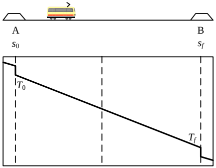

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Boundary conditions:

$$v(s_0) = 0, \quad v(s_f) = 0$$
$$t(s_0) = T_0, \quad t(s_f) = T_f$$

Objective function:

$$\text{Minimize } E = \int_{s_0}^{s_f} f \, ds$$

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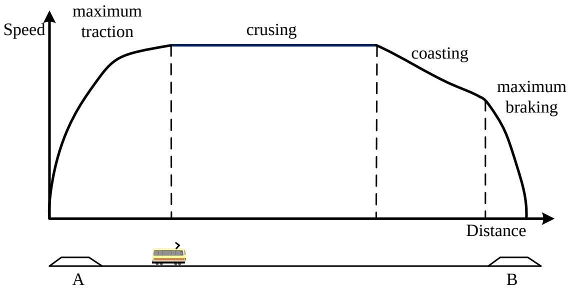
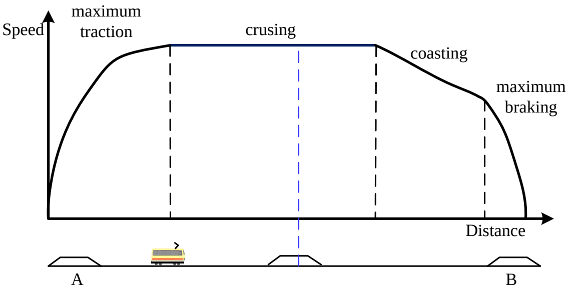
Train Trajectory Optimization

- optimization approach: Maximum principle
- More constraints should been taken into account:



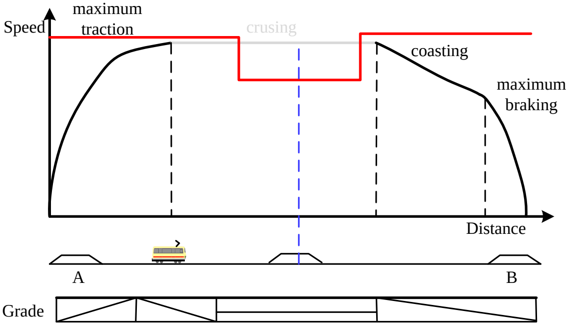
Train Trajectory Optimization

- optimization approach: Maximum principle
- More constraints should been taken into account:
  - time constraints



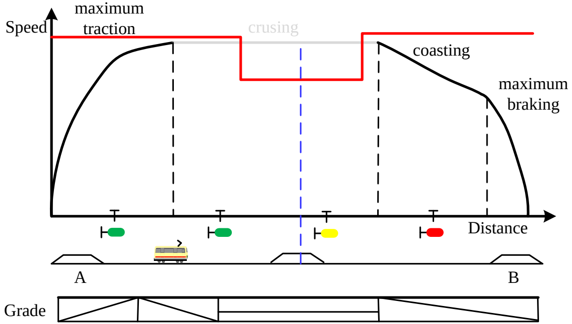
Train Trajectory Optimization

- optimization approach: Maximum principle
- More constraints should been taken into account:
  - time constraints
  - speed limits, grades and curves



Train Trajectory Optimization

- optimization approach: Maximum principle
- More constraints should been taken into account:
  - time constraints
  - speed limits, grades and curves
  - signaling system



Train Trajectory Optimization

More constraints should been taken into account:

- time constraints
- speed limits, grades and curves
- signaling aspects

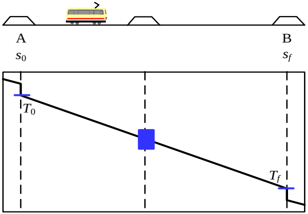
In this paper:

- Train Path Envelope
- Multiple phase train trajectory optimization model
- Optimization strategies in consideration of the influence from signaling system

Train Path Envelope

Train Path Envelope

- a series of time and speed allowances available in real operation



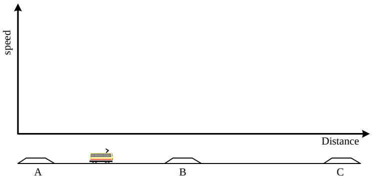
The TPE contains two kinds of targets:

- Mandatory target points, (p, t, v)
- Flexible target windows, $(p, [t_{\min}, t_{\max}], [v_{\min}, v_{\max}])$

Multiple-phase Train Trajectory Optimization Model

Multiple-phase optimal control model:

- divide the train trajectory into several phases by several linkage points;
- each phase has its own cost function, dynamic model, path constraints and boundary conditions;
- two adjacent phases are linked by linkage conditions.



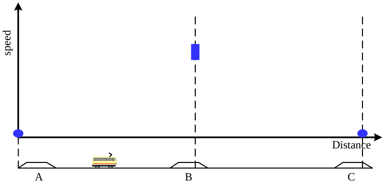
Multiple-phase Train Trajectory Optimization Model

Multiple-phase optimal control model:

- divide the train trajectory into several phases by several linkage points;
- each phase has its own cost function, dynamic model, path constraints and boundary conditions;
- two adjacent phases are linked by linkage conditions.

The linkage points can be:

- the TPE target points



Multiple-phase Train Trajectory Optimization Model

boundary conditions:

at mandatory target points:

$$v(s_0^{(r)}) = V_0^{(r)}, \quad t(s_0^{(r)}) = T_0^{(r)} \text{(initial boundaries)}$$
$$v(s_f^{(r)}) = V_f^{(r)}, \quad t(s_f^{(r)}) = T_f^{(r)} \text{(terminal boundaries)}$$

for flexible target windows:

$$V_{0,\min}^{(r)} \leq v(s_0^{(r)}) \leq V_{0,\max}^{(r)}, \quad T_{0,\min}^{(r)} \leq t(s_0^{(r)}) \leq T_{0,\max}^{(r)} \text{(initial boundaries)}$$
$$V_{f,\min}^{(r)} \leq v(s_f^{(r)}) \leq V_{f,\max}^{(r)}, \quad T_{f,\min}^{(r)} \leq t(s_f^{(r)}) \leq T_{f,\max}^{(r)} \text{(terminal boundaries)}$$

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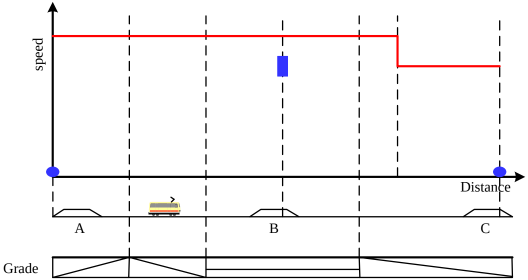
Multiple-phase Train Trajectory Optimization Model

The linkage points can be:

- Target positions of the TPE
- Critical points of speed limits or gradients and curves



Multiple-phase Train Trajectory Optimization Model

cost function:

$$J^{(r)} = \int_{s_0^{(r)}}^{s_f^{(r)}} f^{(r)}\, ds$$

dynamic model:

$$\frac{dv^{(r)}}{ds} = \frac{\theta_1 f^{(r)} - \theta_2 b^{(r)} - R_{train}(v^{(r)}) - R_{line}^{(r)}(s)}{\rho \cdot m \cdot v^{(r)}}$$

$$\frac{dt^{(r)}}{ds} = \frac{1}{v^{(r)}}$$

path constraints:

$$\begin{cases} 0 \le f^{(r)} \le F_{\max} \\ 0 \le b^{(r)} \le B_{\max} \\ 0 \le f^{(r)} \cdot v^{(r)} \le P_{\max} \\ 0 \le v^{(r)} \le V_{\max}^{(r)} \\ A_{\min} \le \dfrac{dv^{(r)}}{dt^{(r)}} \le A_{\max} \end{cases}$$

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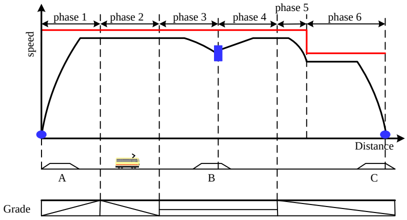
Multiple-phase Train Trajectory Optimization Model

linkage conditions:

$$s_f^{(r)} - s_0^{(r+1)} = 0,$$
$$v(s_f^{(r)}) - v(s_0^{(r+1)}) = 0,$$
$$t(s_f^{(r)}) - t(s_0^{(r+1)}) = 0.$$



Multiple-phase Train Trajectory Optimization Model

- Gauss Pseudospectral methods can be applied for solving multiple-phase optimization problems.
- The optimization objective is to minimize the sum of the cost functions of all phases.

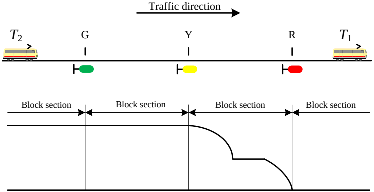
Solver:

- GPOPS
- PROPT
- DIDO

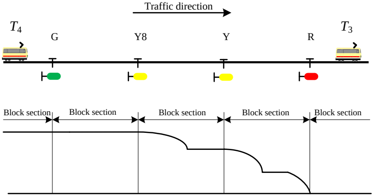
Next Subsection

Dutch Signalling System

Example of Dutch signalling system (a):



Example of Dutch signalling system (b):



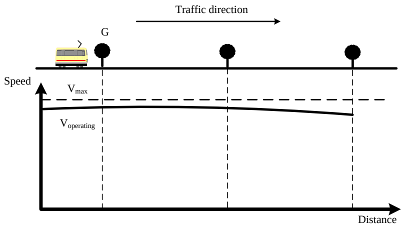
Train Trajectory Optimization Strategies

Two cases of information about the signaling system available:

- Case I: Limited information about the signal aspect ahead only.
- Optimization strategy is to rapidly respond to signaling aspects.

Green:

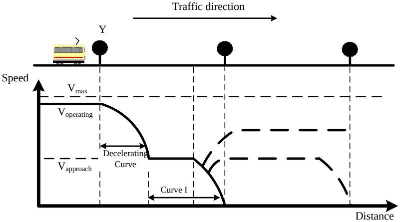
- calculate the optimal trajectory from the current position to the next timetable point



(a)

Train Trajectory Optimization Strategies

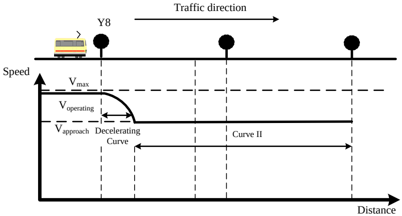
Yellow:



(b)

- Decelerating curve
- Curve I

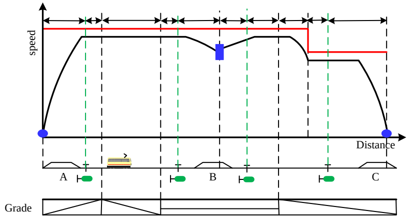
Yellow 8:



- Decelerating curve
- Curve II

Train Trajectory Optimization Strategies

- Case II: Full information about the entire train trajectory of the preceding train
- Optimization strategy: Green wave policy
- $$t(p_s) \geq T_{p_s,\min},$$
  $T_{p_s,\min}$ is the predicted time that the signal changes from yellow to green.



Train Trajectory Optimization Strategies

If the remaining running time is insufficient,

- increase the remaining running time

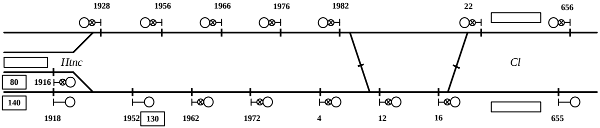
  The time boundary condition of the arrival event is changed from $t(s_f^{(r)}) = T_f^{(r)}$ to $T_f^{(r)} \leq t(s_f^{(r)}) \leq T_f^{(r)} + T_{add}$.

- the cost function is designed as

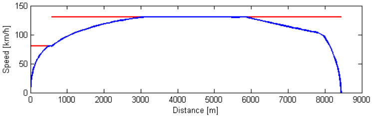
$$J^{(r)} = t(s_f^{(r)}) + \omega \int_{s_0^{(r)}}^{s_f^{(r)}} f^{(r)} \, ds$$

Computational Experiments - Data

Infrastructure: from *Htnc* to *Cl*

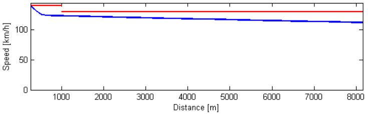


Train: one Intercity, one Sprinter (Local train), and the Sprinter train runs ahead of the Intercity.



running time: 300 s SPR

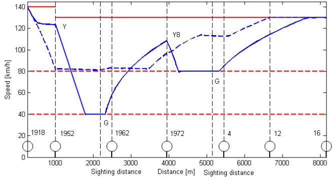
240 s IC



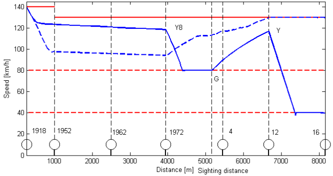
Computational Experiments - Results

the train trajectories of the IC train with four different departure headways after the SPR train at station *Htnc*. (solid line–Case I, dashed line–Case II)

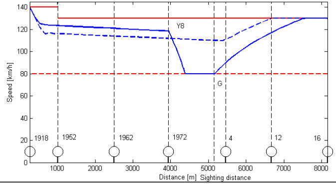
Headway 120 s



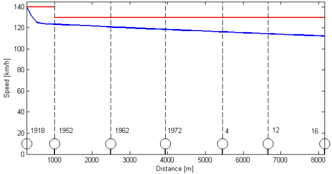
Headway 140 s



Headway 160 s



Headway 180 s



Computational Experiments - Results

	Headway [s]	Energy Consumption [J]	Running time [s]	Delay [s]
I	120	3.3609×10^8	285	45
	140	1.1878×10^8	282	42
	160	1.7640×10^8	255	15
	180	0	240	0
II	120	1.8624×10^8	283	43
	140	1.4541×10^8	263	23
	160	1.4652×10^8	243	3
	180	0	240	0

Table: Results of the IC train operation optimization for different departure headways.

Conclusions

- Train path envelope is a useful formulation of the time constraints for the train operation.
- The multiple-phase optimal control model and the Gauss Pseudospectral Method can been used for the train trajectory optimization problem.
- The influences from the signalling system on train operations should be taken into consideration. More information about signaling system and green wave policy result in better optimal solutions.

Thank you for listening!