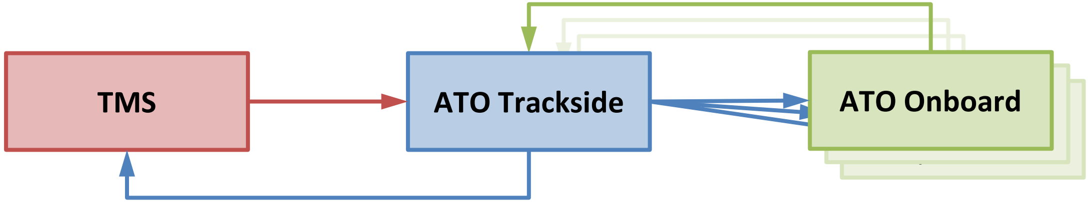
Eisenbahntechnologisches Kolloquium ETK 2025
Darmstadt, September 14-25, 2025

Aligning railway traffic management and automatic train operation



Prof. Dr. Rob Goverde
Digital Rail Traffic Lab
Department of Transport and Planning
Delft University of Technology
www.tudelft.nl/drtlab, r.m.p.goverde@tudelft.nl

Digital Rail Traffic

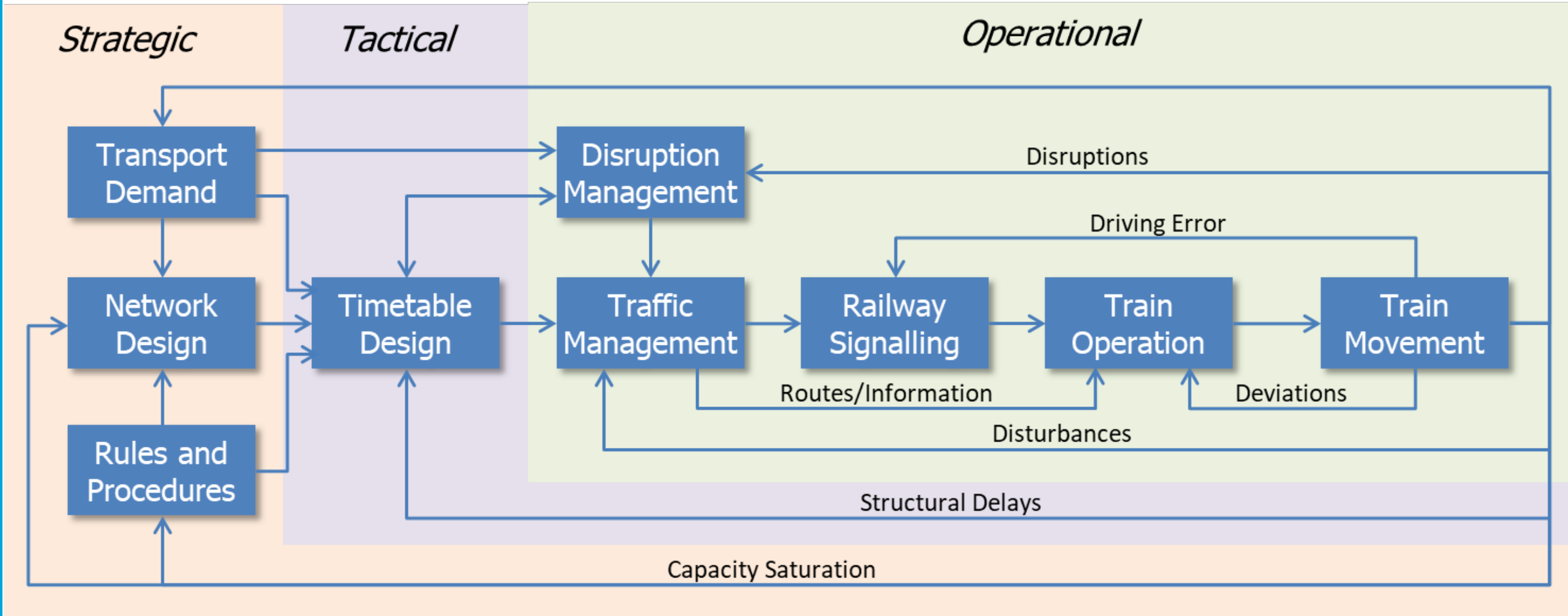
Digital Rail Traffic Lab

The **Digital Rail Traffic Lab** develops innovative concepts, models and methods to realize resilient railway traffic systems that optimize capacity, performance, energy consumption and safety.

Focus is on optimization and automation for improved railway timetabling, railway traffic management, disruption management, energy-efficient train operation, and railway signalling.

Methods: domain knowledge, mathematical modelling, operations research, optimal control, data analytics, artificial intelligence, simulation.

Directors: Prof. Dr. Rob Goverde and Dr. Egidio Quaglietta



TU Delft

Outline

- Introduction
- TMS
- ATO
- TMS versus ATO
- Optimal TMS – ATO interaction
- TMS – ATO feedback control loops
- Conclusions

EU-Rail FP1-MOTIONAL (2022-2026)

WP15/16 - Linking TMS to ATO/C-DAS for optimized operations (WP leader Rob Goverde)

Europe`s Rail

FP1 MOTIONAL
European Rail Network and Mobility Management

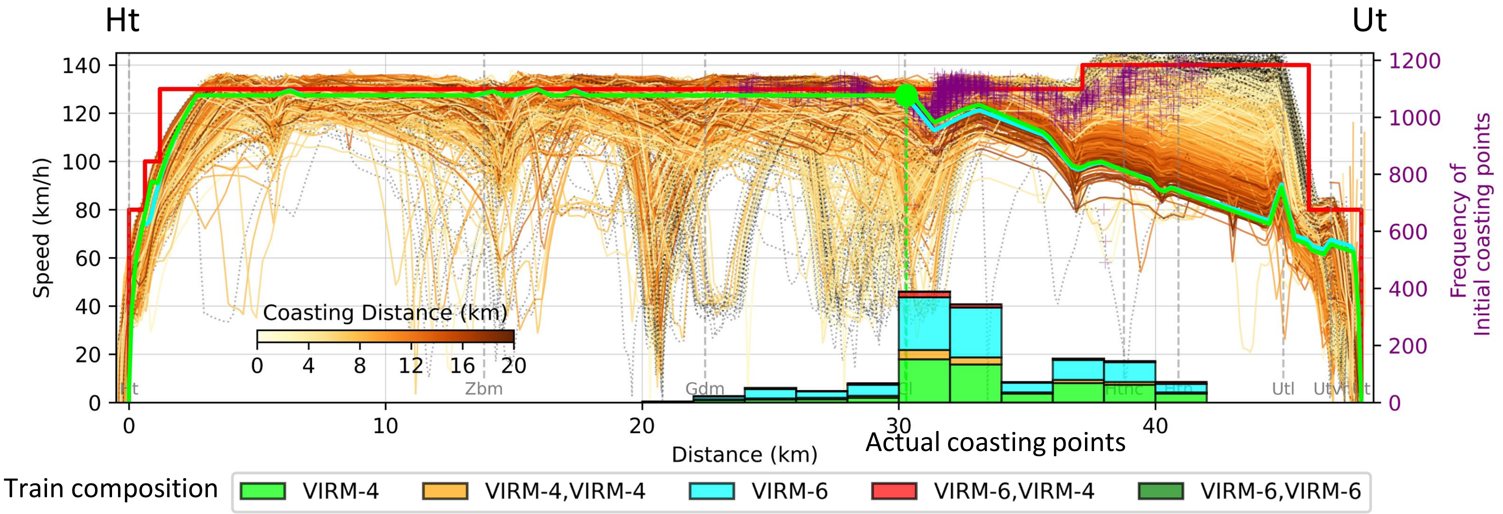
This project has received funding from the Europe's Rail Joint Undertaking under the European Union's Horizon Europe research and innovation programme under grant agreement number 101101973 (FP1 – MOTIONAL)

TUDelft

Introduction

Aim

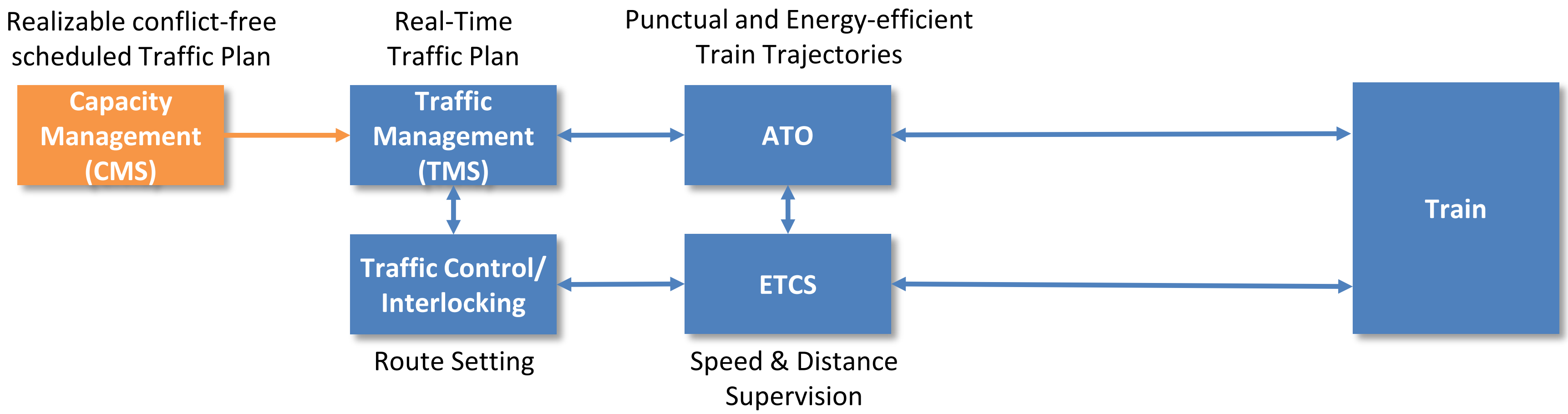
- Improve railway operations performance (capacity, robustness, punctuality, energy consumption) both in normal and disturbed conditions by optimal interaction of traffic management and ATO



- GPS data of 1.618 IC trips from ’s Hertogenbosch to Utrecht from 16-12-2024 to 31-01-2025 with at most 1 min delay at both departure and arrival
- NS trains equipped with DAS (TimTim) without TMS interaction

Introduction

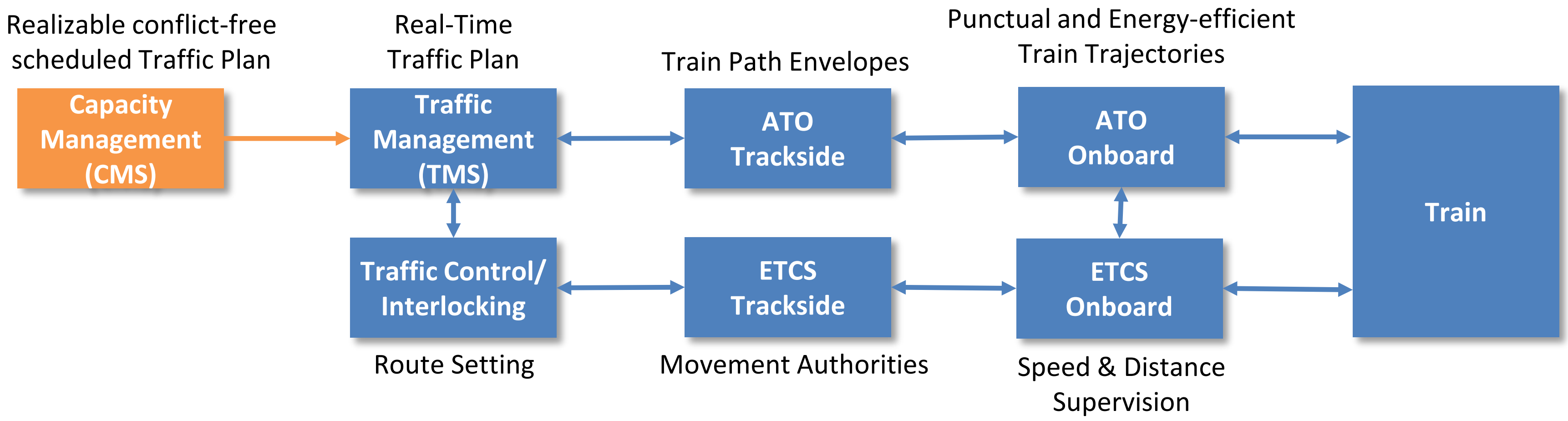
- **Digital Automated Train Operation**



- Goal: synchronize route setting and train trajectories for conflict-free and efficient operations

Introduction

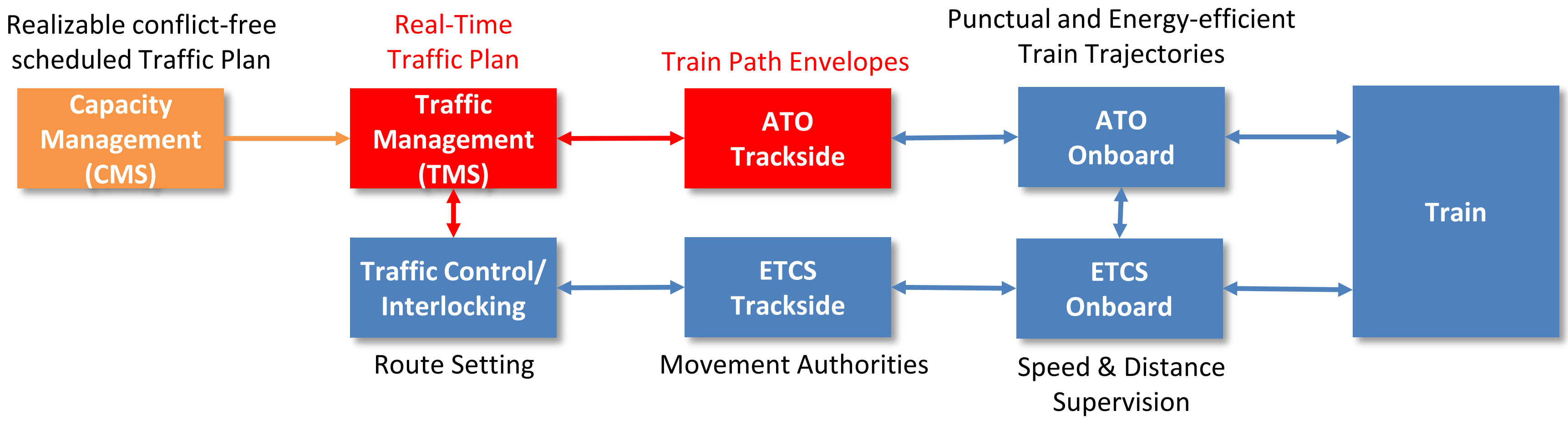
- **Digital Automated Train Operation**



- Goal: synchronize route setting and train trajectories for conflict-free and efficient operations
- Optimal interaction of Trackside and Onboard systems

Introduction

- **Digital Automated Train Operation**

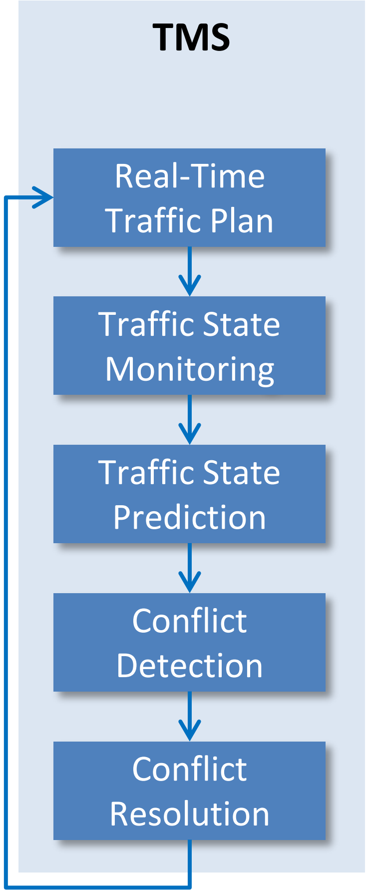


- Goal: synchronize route setting and train trajectories for conflict-free and efficient operations
- Optimal interaction of Trackside and Onboard systems

What does the TMS do?

The Real-Time Traffic Plan

- Proactive traffic management using a Real-Time Traffic Plan
- Real-Time Traffic Plan specifies for all trains
  - Exact route between stops
  - Time targets or time windows at (stopping and passing) timetable points
  - Orders at switches and crossings
- TMS continuously updates the Real-Time Traffic Plan by monitoring and forecasting train traffic, and proactively detecting and resolving conflicts due to disturbances and disruptions, to allow conflict-free traffic
- Conflict detection and resolution includes retiming, reordering, rerouting
- The Real-Time Traffic Plan coordinates all actors (signallers, train drivers, passenger information) and systems (Automatic Route Setting, Automatic Train Operation)



References: FP1 MOTIONAL D15.2, Tschirner et al. (JRTPM 2014), Quaglietta et al. (TRC 2016)

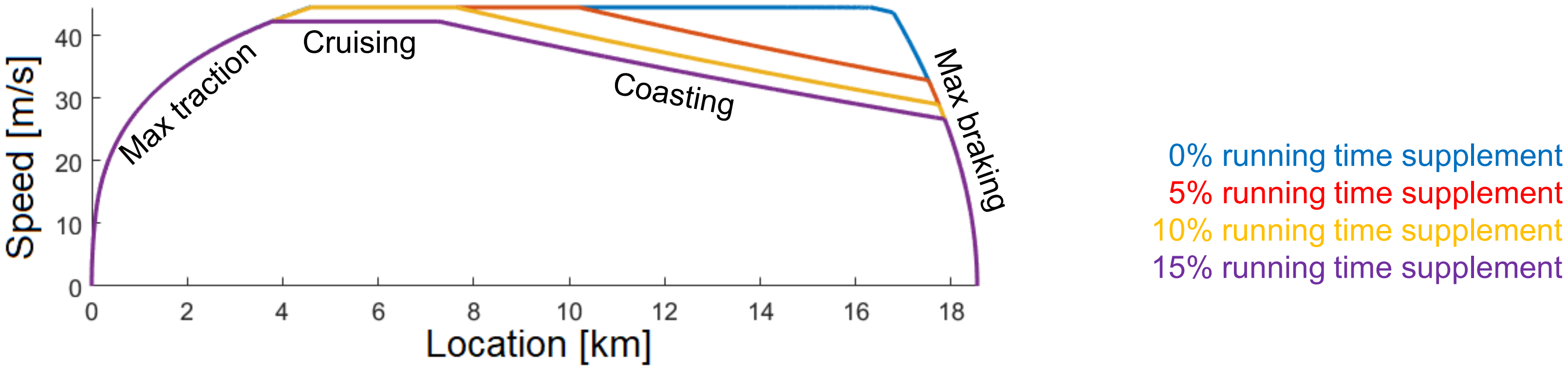
Digital Rail Traffic Lab

What does ATO do?

TU Delft

Train trajectories

- ATO generates and tracks the train trajectory (speed and time profile) over the route between stops
- A train trajectory generation algorithm computes a feasible speed profile considering train and track characteristics, traction and braking control bounds, and timing point constraints (time targets or windows)
- An energy-optimal train trajectory consists of a sequence of four driving regimes
  - maximum traction, cruising by partial traction/braking, coasting, maximum service braking
- Optimal control problem determines optimal cruising speed and optimal switching time between regimes
- The train trajectory is the reference for a speed tracking algorithm (GoA2+) or for driver advice (C-DAS)



TMS versus ATO

What can go wrong?

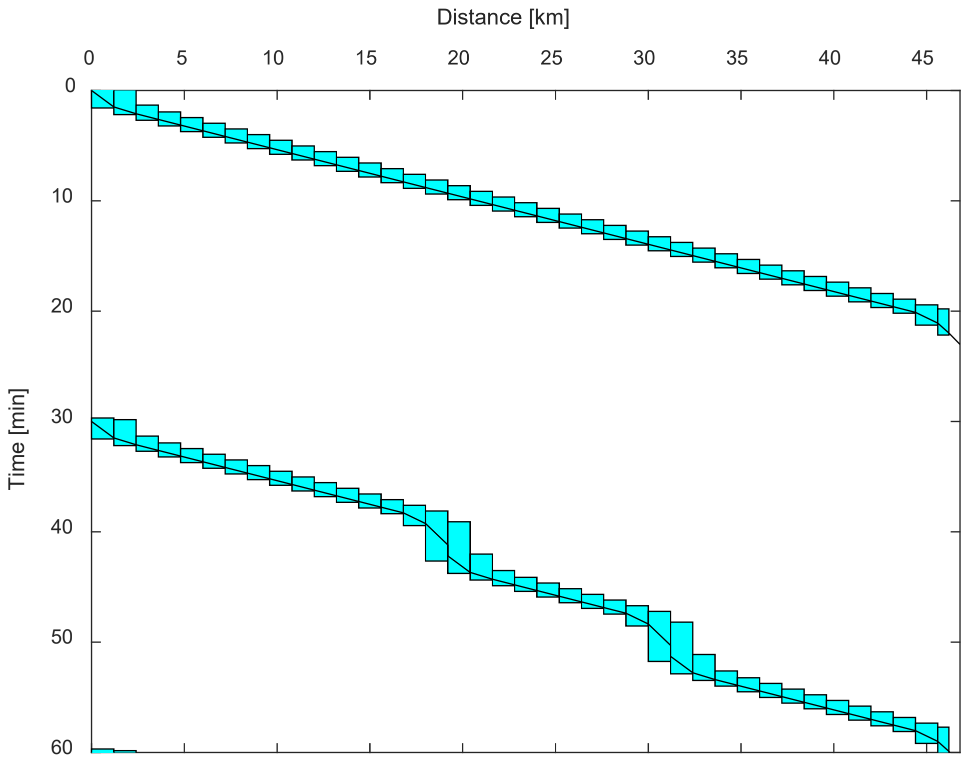
- TMS maintains a Real-Time Traffic Plan with ‘conflict-free’ train paths based on
  - The planned timetable (Capacity Management System)
  - Conflict Detection and Resolution algorithms/rules within the TMS due to disturbances

- The actual train paths may deviate from the real ones (even with the same departure and arrival time)
  - Different train trajectories exist over a line with the same scheduled departure and arrival time
  - The CMS/TMS may not fully know the actual train characteristics
  - The actual train characteristics vary depending on actual train compositions
  - The actual driving behaviour may be unknown or vary depending on driver or ATO algorithm
  - Planning and CDR algorithms are usually based on a fixed train driving strategy
  - Planning and CDR algorithms may not consider detailed speed profiles (fixed-speed CDR models)

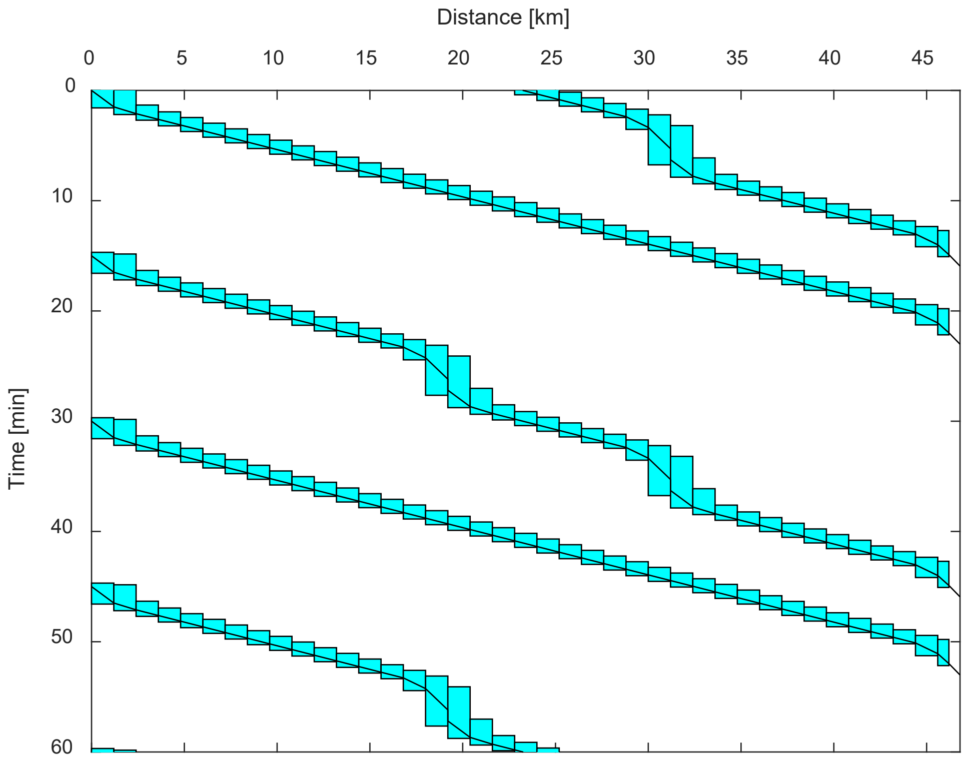
- Dense traffic can still have train path conflicts between stops due to uncertainty in actual train paths

- An RTTP guarantees that realizable and conflict-free train trajectories exist but not for all train trajectories

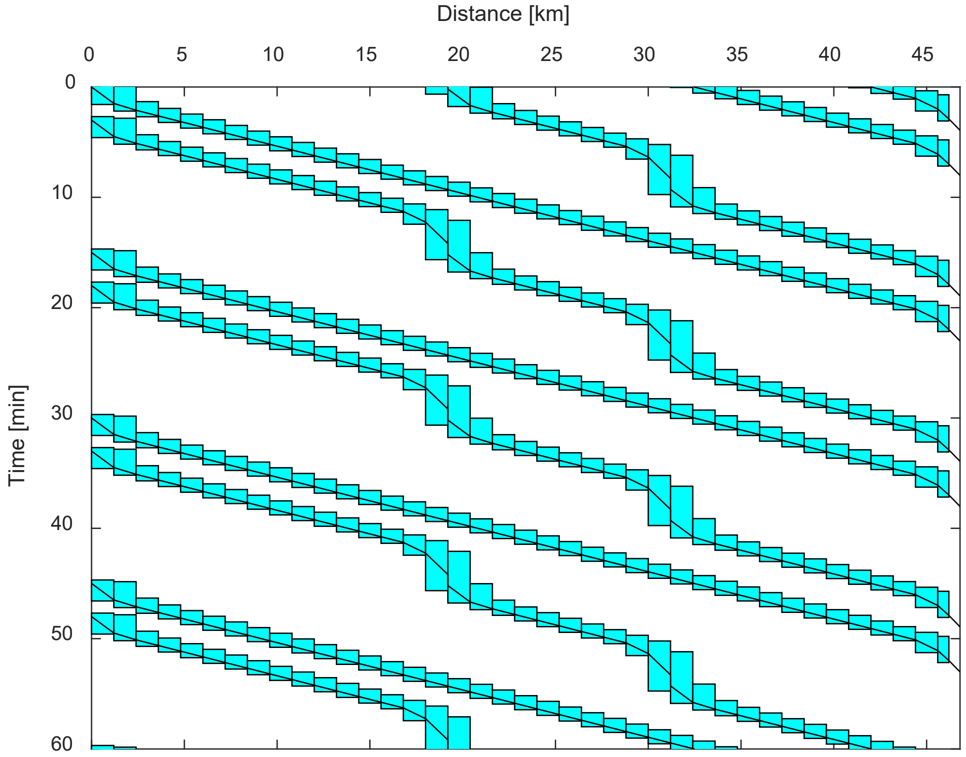
No problem here



No problem here



No problem here?



Optimal TMS – ATO interaction

Train path envelope (TPE)

- A TPE consists of a list of Timing Points with time windows or targets over the train route for each train
- TPEs include scheduled departure and arrival from the RTTP but may include additional Timing Points
- TPEs are sent to the ATO Onboard as constraints to the train trajectory generation algorithm
- A train trajectory computed within the TPE must be conflict-free

- TPEs are the link between the RTTP from the TMS and the Train Trajectory of the ATO Onboard

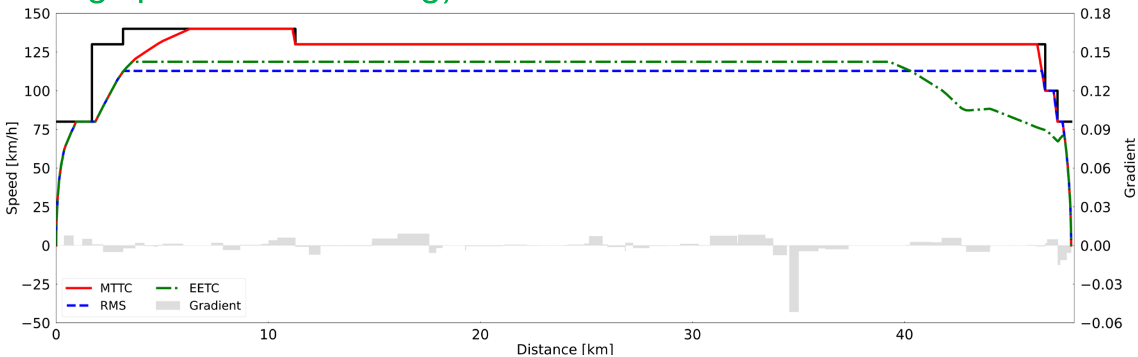
- TPEs should maximize flexibility while guaranteeing conflict-free train operation
  - Providing Timing Points at each block will not work
  - Providing Timing Points only at departure and arrival may work or not depending on the situation

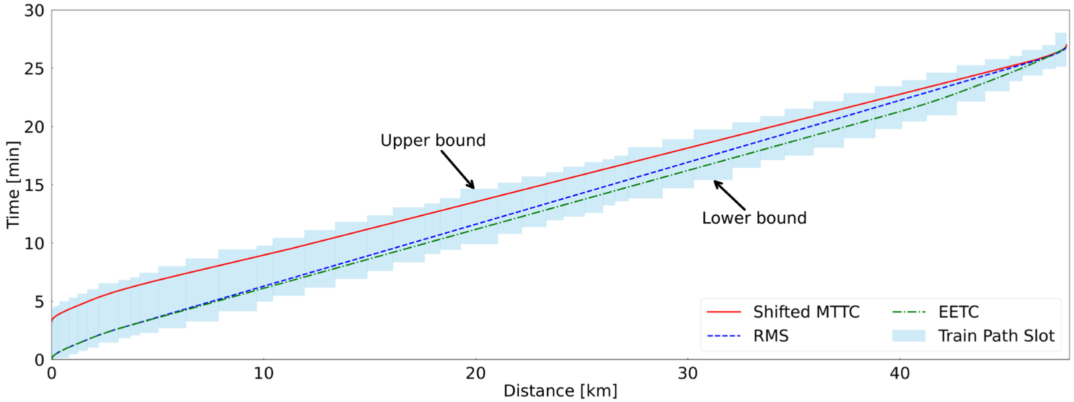
Train path envelope (TPE)

- TPE should allow for multiple train driving strategies to provide flexibility to the ATO Onboard algorithms
  - Shifted minimum-time train control (absorbs full running time supplement)
  - Reduced cruising speed (no coasting)
  - Energy-efficient driving (optimal cruising speed and coasting)

Conflict-free TPEs

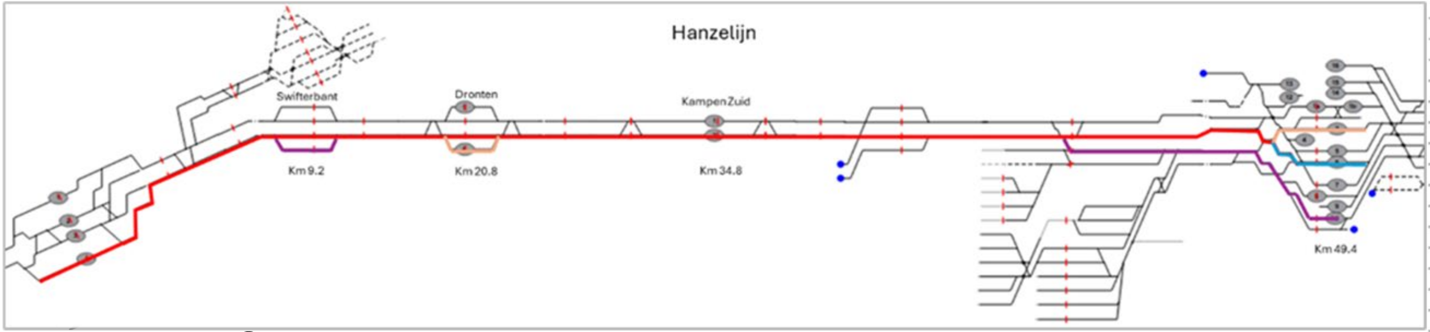
- Latest and earliest trajectory of successive trains must be conflict-free (no blocking time overlaps)
- Latest trajectory can be adjusted by reducing departure tolerance and reducing maximum train speed
- Earliest trajectory can be adjusted by adding extra timing point before conflicting block (critical block)

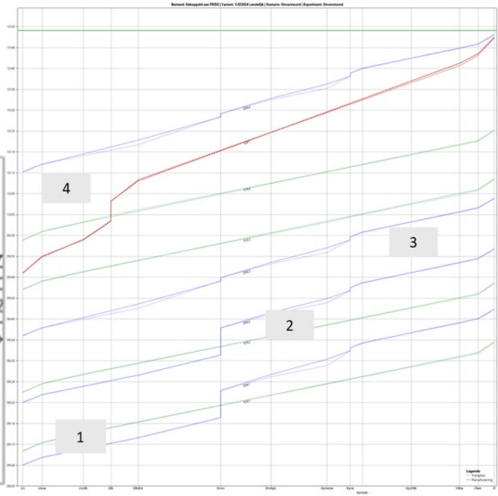




TPE generation example

- 50 km Dutch railway corridor with ETCS L2 TTD between Lelystad and Zwolle (Hanzelijn)
  - Three train types: Intercity (IC), Sprinter (SP, local), Freight (G)
  - Two intermediate Sprinter stops Dronten and Kampen Zuid
  - One intermediate Freight stop Swifterbant
- 4 scenarios (included in one timetable)
  1. IC overtakes SP in Dronten
  2. IC overtakes SP in Dronten, shorter headway IC after SP
  3. IC approaches SP at arrival to Zwolle (no overtaking)
  4. IC overtakes G at Swifterbant, SP approaches G at arrival to Zwolle

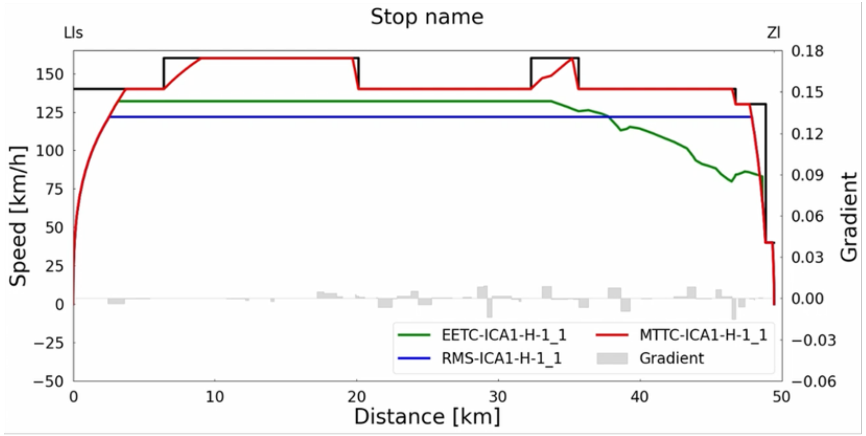




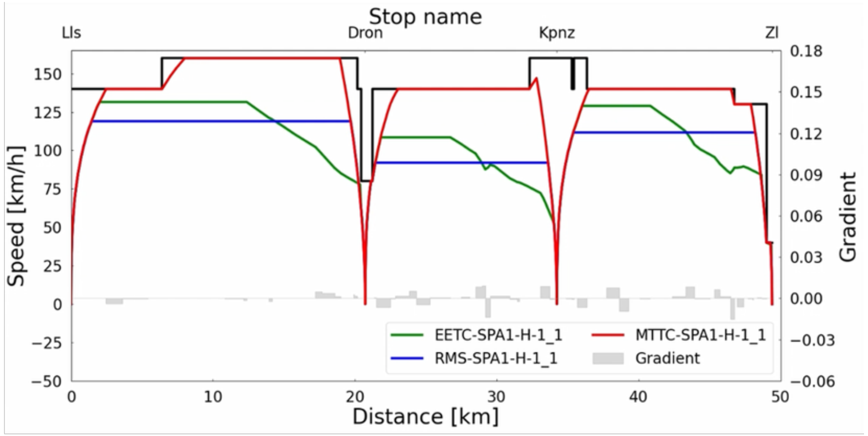
TPE generation example

- Step 1: Compute train trajectories for multiple driving strategies, including
  - Minimum-time train control (absorbs full running time supplement)
  - Energy-efficient driving (optimal cruising speed and coasting)
  - Reduced cruising speed (no coasting)

Intercity

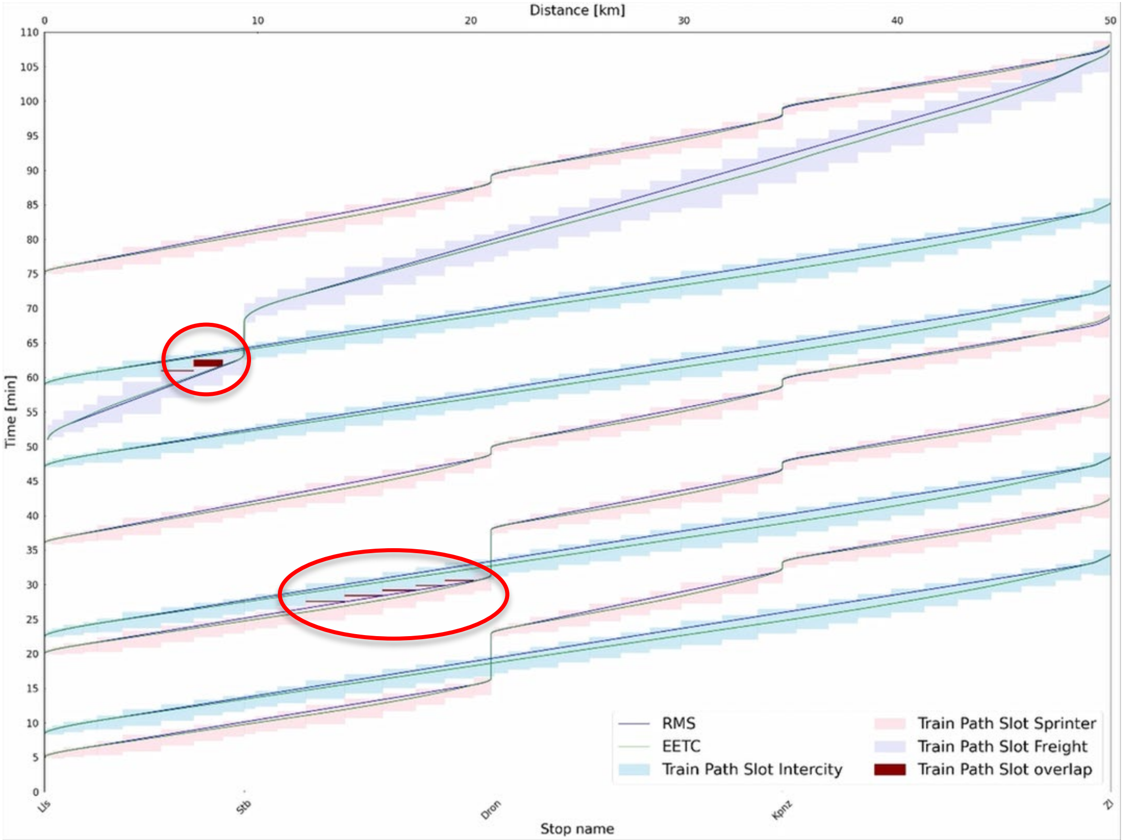


Sprinter



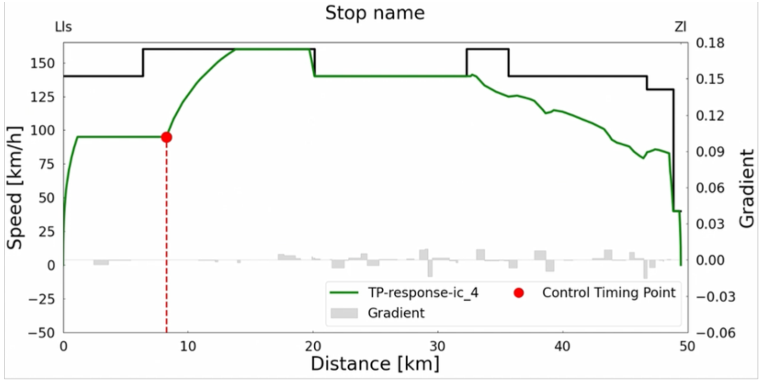
TPE generation example

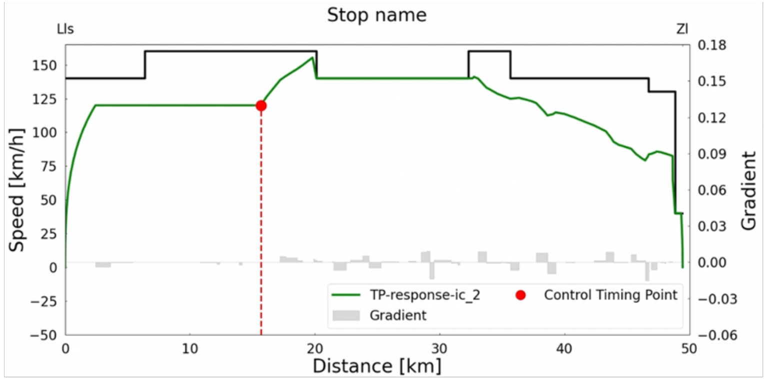
- Step 2: Compute blocking times for multiple driving strategies and detect conflicts (blocking time overlaps)



TPE generation example

- Step 3: Resolve blocking time overlaps by computing extra Timing Points at critical blocks, and compute adjusted train trajectories satisfying earliest passing time at extra Timing Points





Extra Timing Point Intercity train at last block before Swifterbant to avoid conflict with braking freight train stopping at Swifterbant

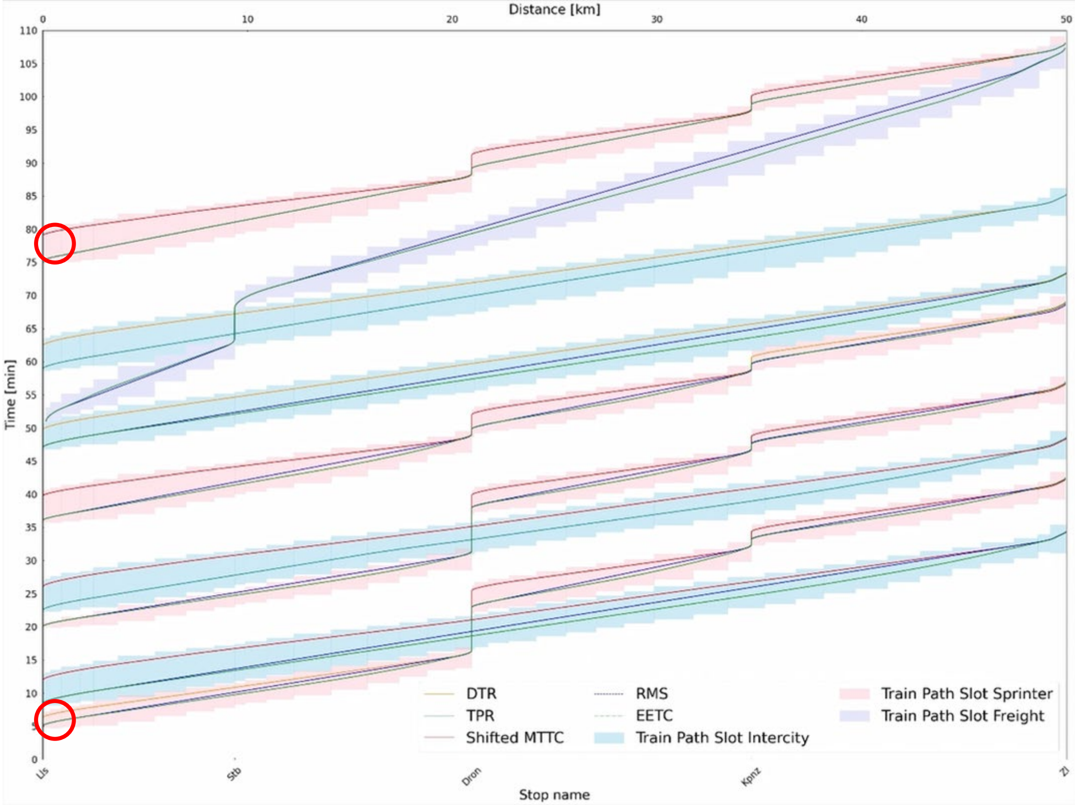
Extra Timing Point Intercity train at last block before Dronten to avoid conflict with braking Sprinter train stopping at Dronten

TPE generation example

- Step 4: Compute maximal tolerances and the final time windows/targets at all Timing Points (including stops)

- Step 5: Collect sequence of Timing Points with time windows in TPE (all stops and two extra timing points) and send to ATO-Onboards

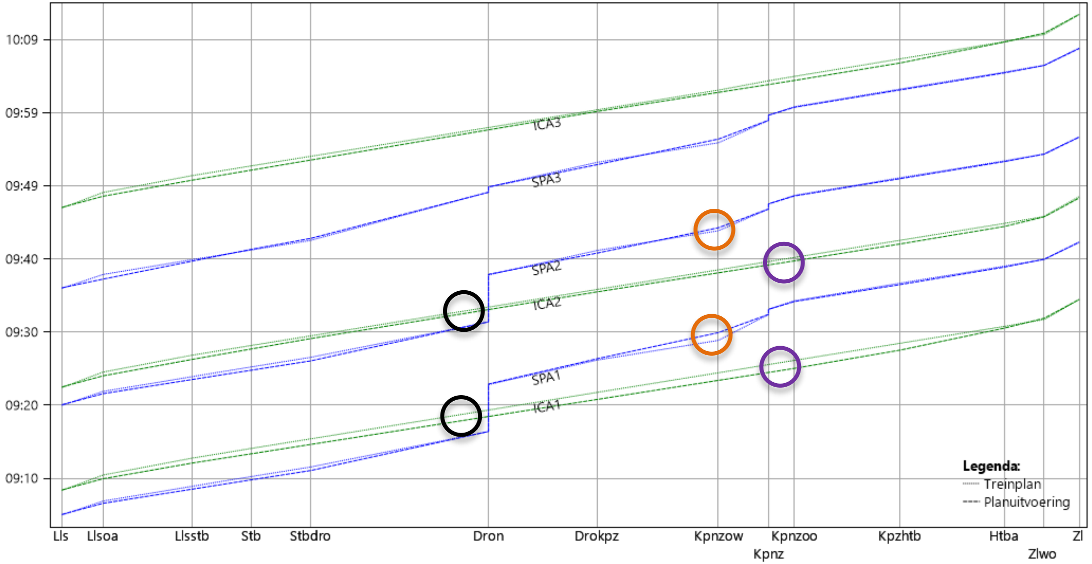
- Note: no change in routes, orders, or scheduled departure and arrival times (which is the task of the TMS/RTTP)



TPE generation example

Validation in ProRail FRISO simulation environment with ATO

- No conflicts
- Arrivals in Zl all between -12 s and +1 s
- Arrivals SP trains at intermediate stops between -2 s and +5 s
- The maximal deviations between plan and execution are in Scenario 1
  - 64 s late passage of the SPA1 through Kpnzow
  - 65 s early passages of the ICA1 through Kpnz and Kpnzoo



The main three objects

	Real-time traffic plan (RTTP)	Train path envelope (TPE)	Train trajectory (TT)
Scope	• Train traffic on rail network	• Train traffic on corridor	• Train on corridor
System	• Traffic Management System (TMS)	• ATO-Trackside or TMS	• ATO-Onboard
Content	• Routes • Train orders • Event times at timetabling points	• Timing points • Time targets • Time windows	• Arrival and departure times • Speed profile • Traction/brake control
Decisions	• Retiming • Reordering • Rerouting • Cancellation	• Departure tolerances • Timing points (locations) • Time windows • Feasibility	• Acceleration • Cruising • Coasting • Braking

The main three objects

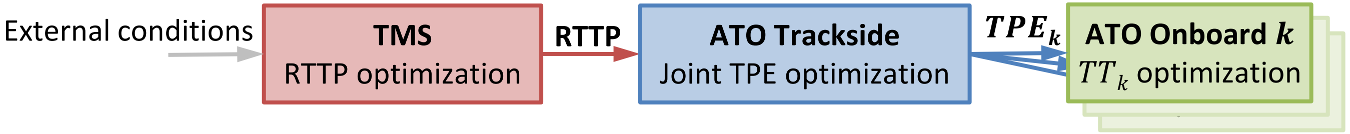
	Real-time traffic plan (RTTP)	Train path envelope (TPE)	Train trajectory (TT)
Scope	• Train traffic on rail network	• Train traffic on corridor	• Train on corridor
System	• Traffic Management System (TMS)	• ATO-Trackside or TMS	• ATO-Onboard
Content	• Routes • Train orders • Event times at timetabling points	• Timing points • Time targets • Time windows	• Arrival and departure times • Speed profile • Traction/brake control
Decisions	• Retiming • Reordering • Rerouting • Cancellation	• Departure tolerances • Timing points (locations) • Time windows • Feasibility	• Acceleration • Cruising • Coasting • Braking
Objectives	• Minimize travel times • Minimize schedule deviations • Effective capacity utilization • Maximize robustness	• Punctual departures and arrivals • Feasible train trajectories • Flexibility • Mutual conflict-free TPEs	• Energy efficiency • Punctuality • Drivability • Comfort
Constraints	• Minimum activity times • Maximum activity times • Minimum headway times • Track capacity	• Driving strategies • Train parameter variations • Speed tracking thresholds • Real-time traffic plan (RTTP)	• Train dynamics • Train characteristics • Track characteristics • Operational constraints (TPE)

TMS – ATO feedback control loops

TMS – ATO feedback control loops

Interaction TMS – ATO Trackside – ATO Onboard

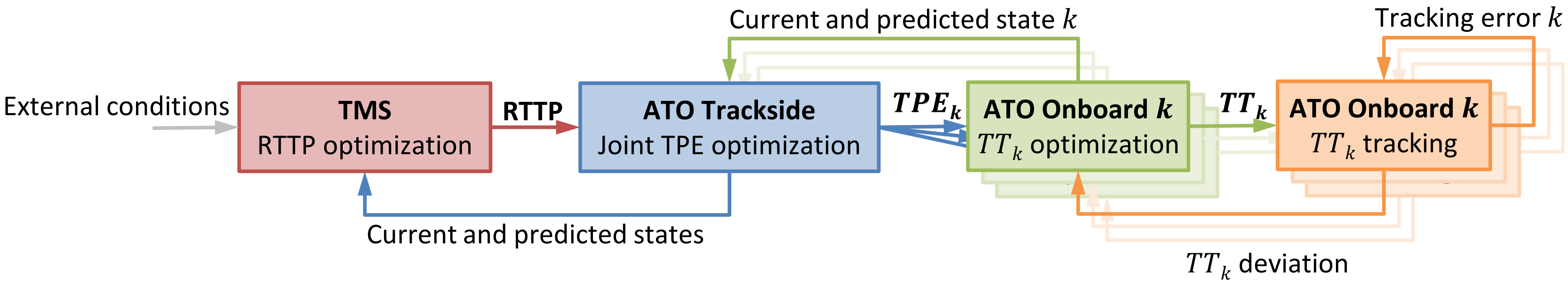
- **TMS** monitors and updates a conflict-free **Real-Time Traffic Plan** (RTTP)
- **ATO-Trackside** monitors and updates feasible **Train Path Envelopes** for each train k
- **ATO-Onboard** generates and tracks energy-efficient **train trajectory** for a train k



TMS – ATO feedback control loops

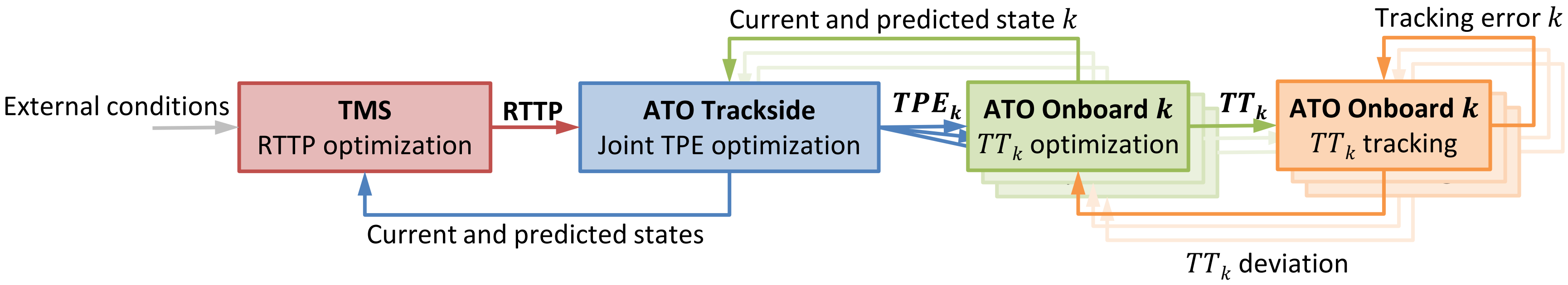
Interaction TMS – ATO Trackside – ATO Onboard

- **TMS** monitors and updates a conflict-free **Real-Time Traffic Plan** (RTTP)
- **ATO-Trackside** monitors and updates feasible **Train Path Envelopes** for each train k
- **ATO-Onboard** generates and tracks energy-efficient **train trajectory** for a train k



TMS – ATO variants

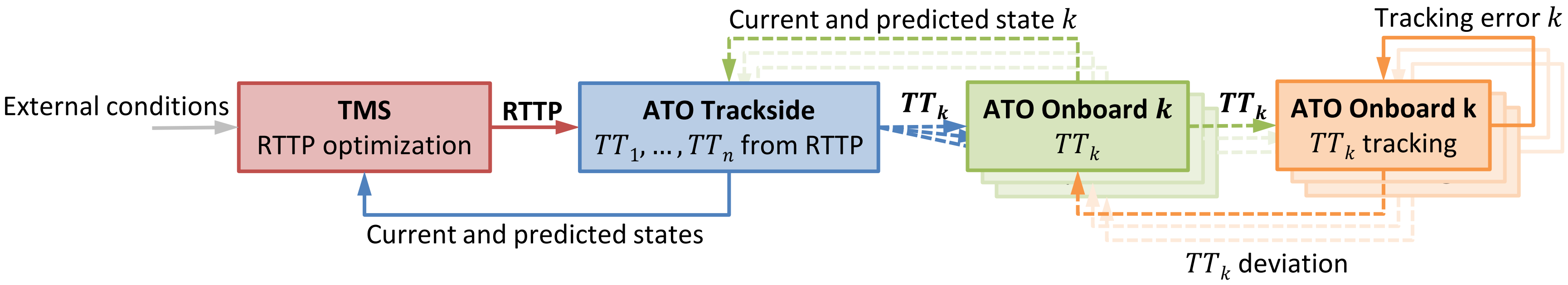
	Passive Onboard	Active Onboard
Passive Trackside	**Remote Control** TS: Train trajectory from RTTP OB: Train trajectory from TS	**Onboard Intelligence** TS: TPE from RTTP OB: Train trajectory optimization
Active Trackside	**Centralized Intelligence** TS: Train trajectory optimization OB: Train trajectory from TS	**Distributed Intelligence** TS: TPE optimization OB: Train trajectory optimization



Active ATO Trackside – Active ATO Onboard

TMS – ATO variants

	Passive Onboard	Active Onboard
Passive Trackside	**Remote Control** TS: Train trajectory from RTTP OB: Train trajectory from TS	**Onboard Intelligence** TS: TPE from RTTP OB: Train trajectory optimization
Active Trackside	**Centralized Intelligence** TS: Train trajectory optimization OB: Train trajectory from TS	**Distributed Intelligence** TS: TPE optimization OB: Train trajectory optimization

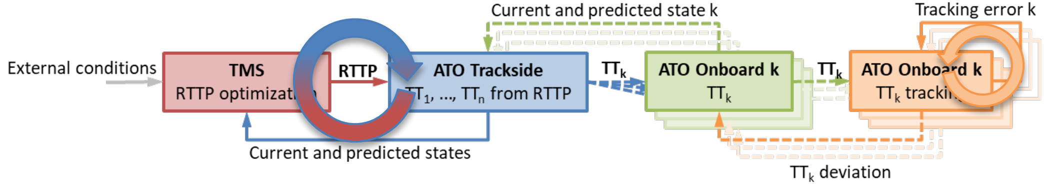


Solid lines: feedback control loops
Dashed lines: information flow

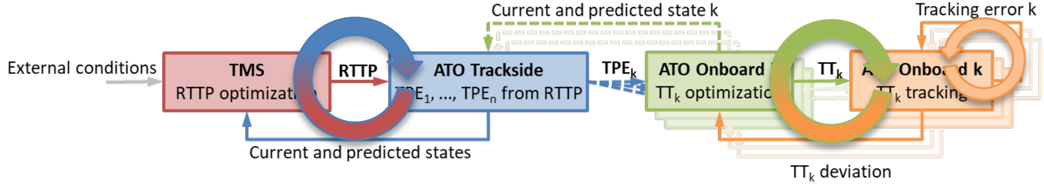
Passive ATO Trackside – Passive ATO Onboard

TMS – ATO variants

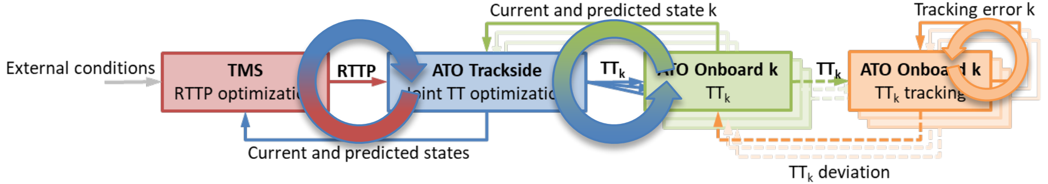
Passive Trackside – Passive Onboard



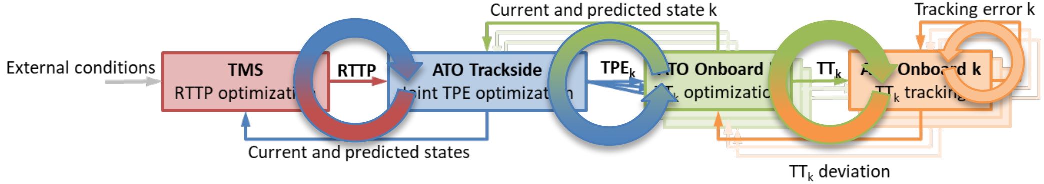
Passive Trackside – Active Onboard



Active Trackside – Passive Onboard



Active Trackside – Active Onboard



Conclusions

Conclusions

- The Real-Time Traffic Plan is the basis for proactive traffic management to allow conflict-free operations
- The Train Path Envelope enriches the RTTP into a list of timing points for each train with timing constraints to the ATO Onboard train trajectory algorithms (communicated in the Journey Profile from ERTMS/ATO Subset 126)
- The ATO Onboard can generate and track Train Trajectories within the TPEs to optimize punctuality and energy efficiency
- The TPE can be integrated in the TMS or in the ATO Trackside with different consequences to the feedback control loops and TMS-ATO interface specification
- Digital Automated Train Operation is obtained by automating TMS + CCS (CSS = ATO + ETCS + other vital and non-vital traffic control functions)

Take away messages

- The RTTP is the main train traffic coordination mechanism from the TMS
- The TPEs are the main coordination mechanism for successive train trajectories
- ATO should follow the RTTP and not dictate it
- ATO can support the TMS to improve smooth traffic (conflict-free, punctual, energy-efficient)

References (see www.tudelft.nl/drtlab or email r.m.p.goverde@tudelft.nl)

- FP1-MOTIONAL (2025). *D15.2: TMS and ATO/C-DAS Timetable Test & Simulation Environment*. EU-Rail.
- Z. Wang, E. Quaglietta, M.G.P. Bartholomeus, A. Cunillera, R.M.P. Goverde (2025). Optimising timing points for effective automatic train operation. *Computers & Industrial Engineering*, 206, 111237.

TU Delft

References

- FP1-MOTIONAL (2025). *D15.2: TMS and ATO/C-DAS Timetable Test & Simulation Environment*. EU-Rail
- E. Quaglietta, P. Pellegrini, R.M.P. Goverde, T. Albrecht, B. Jaekel, G. Marlière, J. Rodriguez, T. Dollevoet, B. Ambrogio, D. Carcasole, M. Giaroli, G. Nicholson (2016). The ON-TIME real-time railway traffic management framework: A proof-of-concept using a scalable standardised data communication architecture. *Transportation Research Part C: Emerging Technologies*, 63, 23–50.
- S. Su, Z. Tian, R.M.P. Goverde (2023). *Energy-Efficient Train Operation: A System Approach for Railway Networks*. Springer.
- S. Tschirner, B. Sandblad, A.W. Andersson (2014). Solutions to the problem of inconsistent plans in railway traffic operation. *Journal of Rail Transport Planning & Management*, 4(4), 87–97
- Z. Wang, E. Quaglietta, M.G.P. Bartholomeus, A. Cunillera, R.M.P. Goverde (2025). Optimising timing points for effective automatic train operation. *Computers & Industrial Engineering*, 206, 111237.