Institution of Railway Signal Engineers

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Exploring Virtual Coupling: operational principles and analysis

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Overview

- Background and criticalities
- The need for migrating to moving-block operations
- Objective: assessing impacts of Virtual Coupling signalling
- Literature gaps and paper contributions
- Case study and results
- Conclusions

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Background: Current situation in Europe

Railways are running out of space

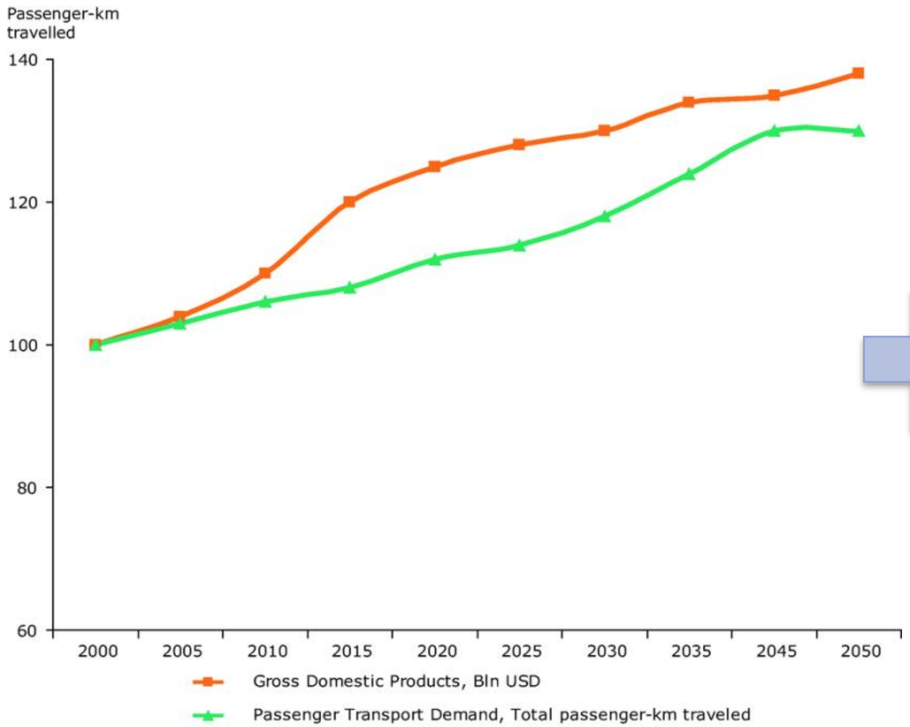
Delays

Overcrowding

Near-to-saturation operations

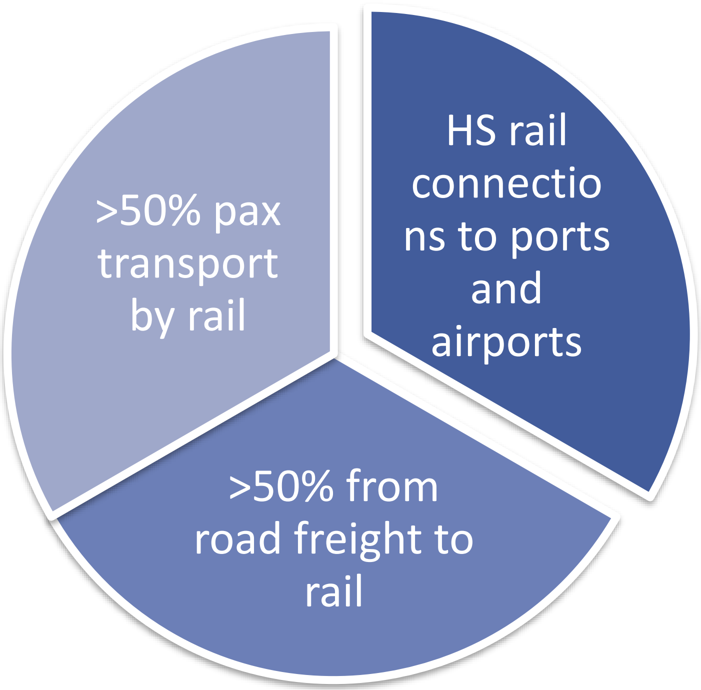
Background: Future prospects and plans to 2050

Rail demand increase for population growth



Source: European Environment Agency

Massive modal shift to rail planned by the EU



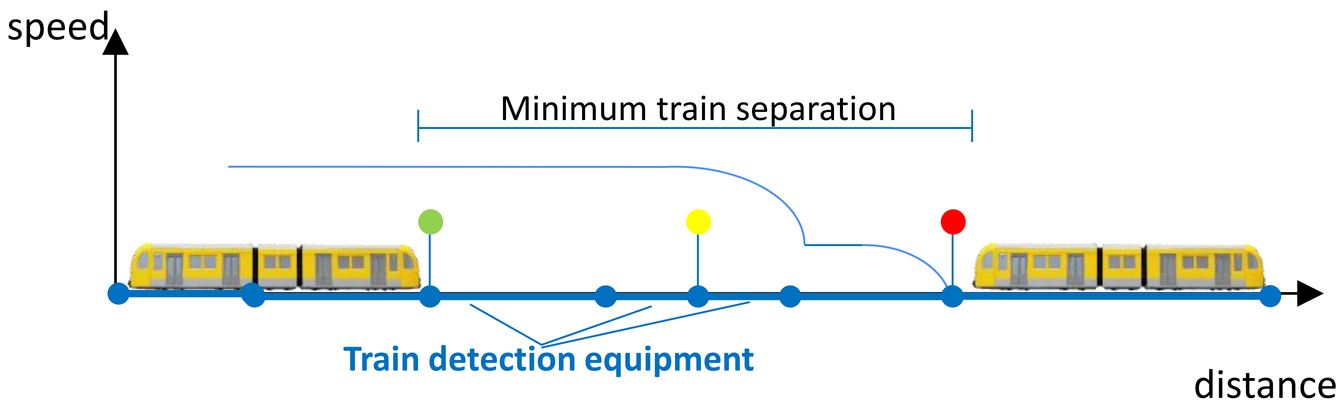
Criticality: How EU railways will look like in 2050?

Infra enhancements rarely possible at bottlenecks

Increasing delays and overcrowding

Objectives: Migration to Moving-block operations

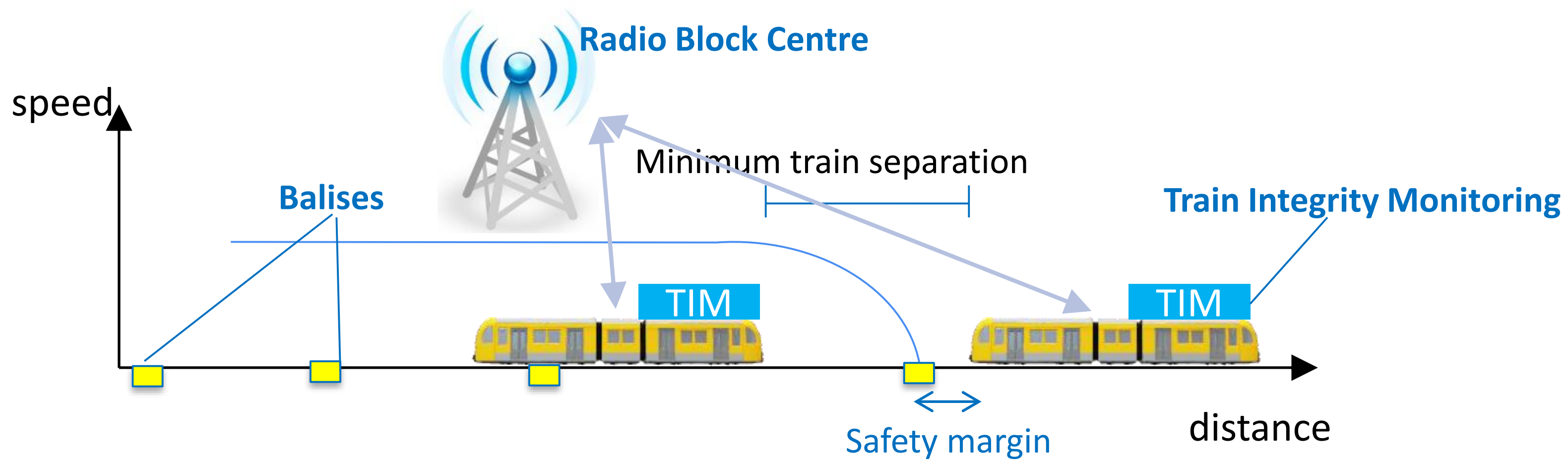
Traditional fixed-block signalling



- Track-side detection
- Line-side signals
- Human driving
- N-block separation

Objectives: Migration to Moving-block operations

ETCS Level 3



On-board Train Integrity Monitoring (TIM)

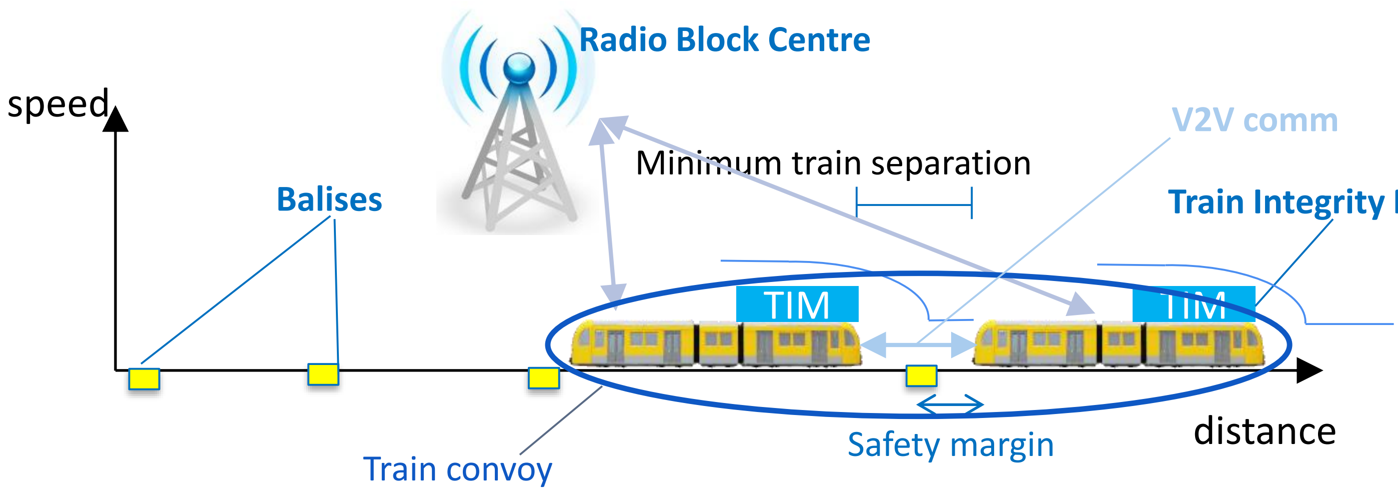
Train position and MA via RBC

Human or ATO driving

Absolute braking distance separation

Objectives: Migration to Moving-block operations

Virtual Coupling (VC)



On-board Train Integrity Monitoring (TIM)

Position and MA via RBC and V2V comm.

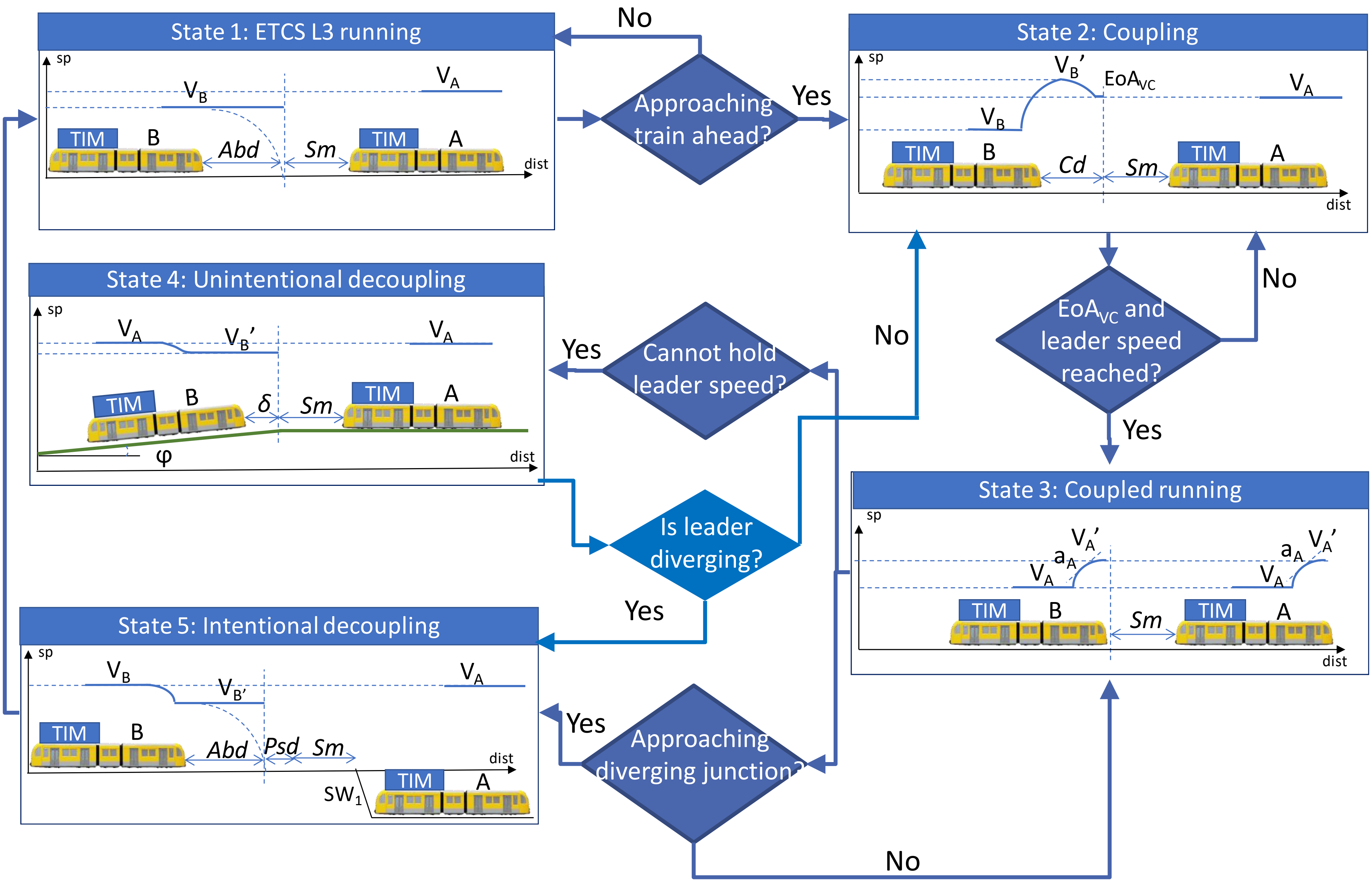
ATO driving

Relative braking distance separation

Literature gaps and paper contributions

Gaps		Contributions
Conceptual Undefined operational principles for VC	→	Definition of safe VC operational principles
Analytical No models to identify capacity benefits over plain moving-block	→	A novel train-following model to assess VC operations

Virtual Coupling operational principles



A multi-state train-following model for VC

State 1: ETCS Level 3 running

$$\begin{cases} v_t = v_{t-1} + \dfrac{F(v_{t-1}) - R(v_{t-1},\varphi,r)}{M \cdot f_p} \cdot \Delta t; \\ s_t = s_{t-1} + \dfrac{M \cdot f_p}{F(v_{t-1}) - R(v_{t-1},\varphi,r)} \cdot v_{t-1} \cdot (v_t - v_{t-1}) \end{cases}$$

$$\text{where} \quad F(v_{t-1}) = \begin{cases} T(v_{t-1}) & if\ accel. \\ M \cdot b \cdot f_p & if\ braking \\ R(v_{t-1},\varphi,r) & if\ cruising \end{cases}$$

State 2: Coupling

$$P_{coupling} = EoA_{VC} + t_{coord} \cdot v_{lead};$$

$$with\ \ EoA_{VC} = Tail_{lead} - sm$$

$$\begin{cases} t_{coord} = \displaystyle\int_{v_{t-1}}^{v_{targ}=v_{lead}} \frac{M \cdot f_p}{M \cdot f_p \cdot b - R(v,\varphi,r)} dv, & if\ \ v_{t-1} > v_{lead} \\ t_{coord} = \displaystyle\int_{v_{t-1}}^{V_{B'}} \frac{M \cdot f_p}{T(v) - R(v,\varphi,r)} dv + \int_{V_{B'}}^{v_{targ}=v_{lead}} \frac{M \cdot f_p}{M \cdot f_p \cdot b - R(v,\varphi,r)} dv, & \text{else} \end{cases}$$

State 3: Coupled running

$$if\ \ |v_{t-1} - v_{lead}| \le th_v \ \ and\ \ |s_{t-1} - P_{coupling}| \le th_s$$

$$\begin{cases} v_t = v_{t-1} + a_{t-1} \cdot \Delta t; \\ s_t = s_{t-1} + v_{t-1} \cdot \Delta t; \end{cases}$$

where

$$\begin{cases} a_{t-1} = a_{lead} \\ a_{t-1} = a_{t-1}^{max} \quad if\ \ a_{lead} > a_{t-1}^{max} = \dfrac{T(v_{t-1}) - R(v_{t-1},\varphi,r)}{M \cdot f_p} \\ a_{t-1} = a_{t-1}^{min} \quad if\ \ a_{lead} < a_{t-1}^{min} = \dfrac{M \cdot f_p \cdot b_{max} - R(v_{t-1},\varphi,r)}{M \cdot f_p} \end{cases}$$

State 4: Unintentional decoupling

$$if\ \ |s_{t-1} - EoA_{VC}| > th_s$$

then switch to State2: Coupling

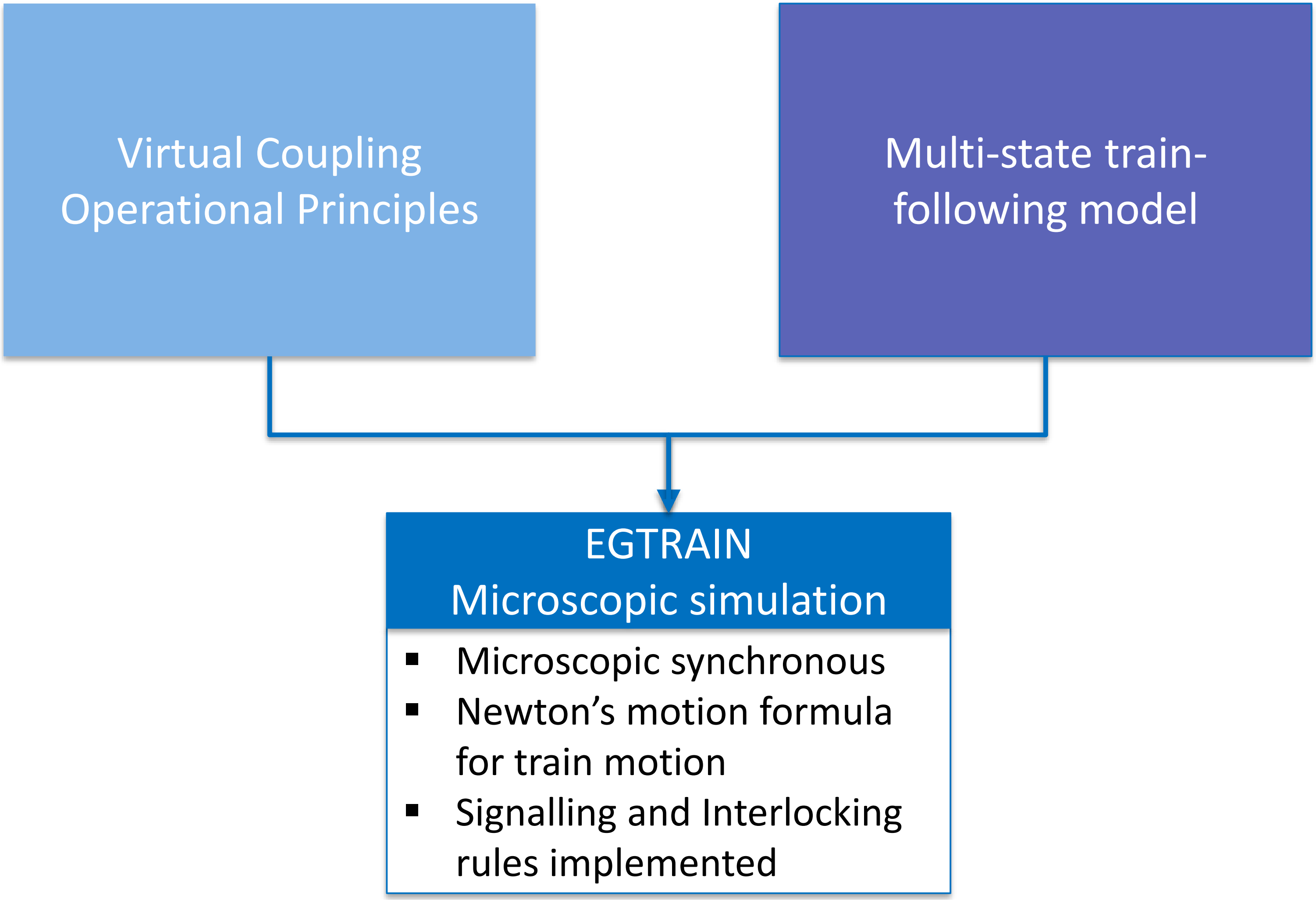
State 5: Intentional decoupling

$$BIP_{decoupling} = P_{decoupling} - \int_{V_{t-1}}^{0} \frac{M \cdot f_p}{M \cdot f_p \cdot b - R(v,\varphi,r)} \cdot v \cdot dv$$

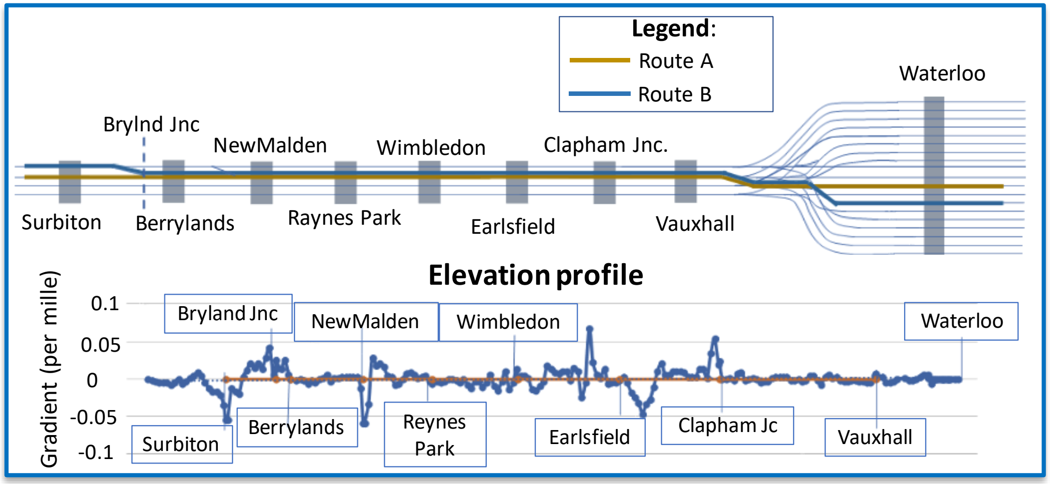
$$if\ (s_{t-1} \ge BIP_{decoupling})\ and\ (v_{t-1} > v_{target} = 0)$$

then switch to State 1: ETCS Level 3 running;

Capacity evaluation framework



Case Study: Waterloo-Surbiton on the SWML (UK)



VC versus ETCS L3, L2 & TPWS

Operational data:

- 20 km long,
- 9 stations
- 2 trains BR Class 455 with 8 cars

Simulation scenarios:

1: Non-stopping trains

- **Case a**: same route
- **Case b**: different route (split at Berryland)

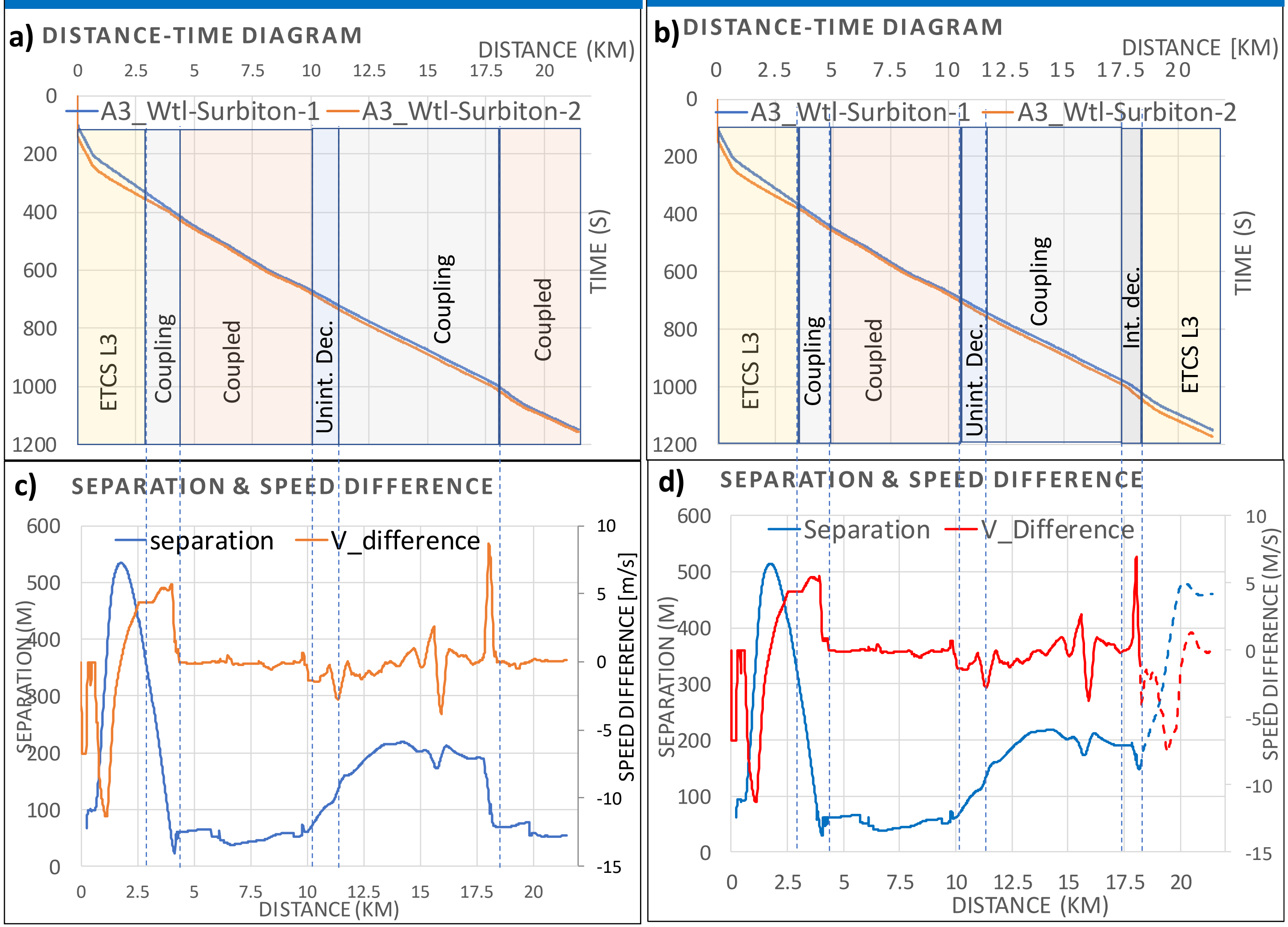
2: Stopping trains (Clpm, Wmb, RPk, Sbn)

- **Case a**: same route
- **Case b**: different route (split at Berryland)

Results 1: State transition and train separation

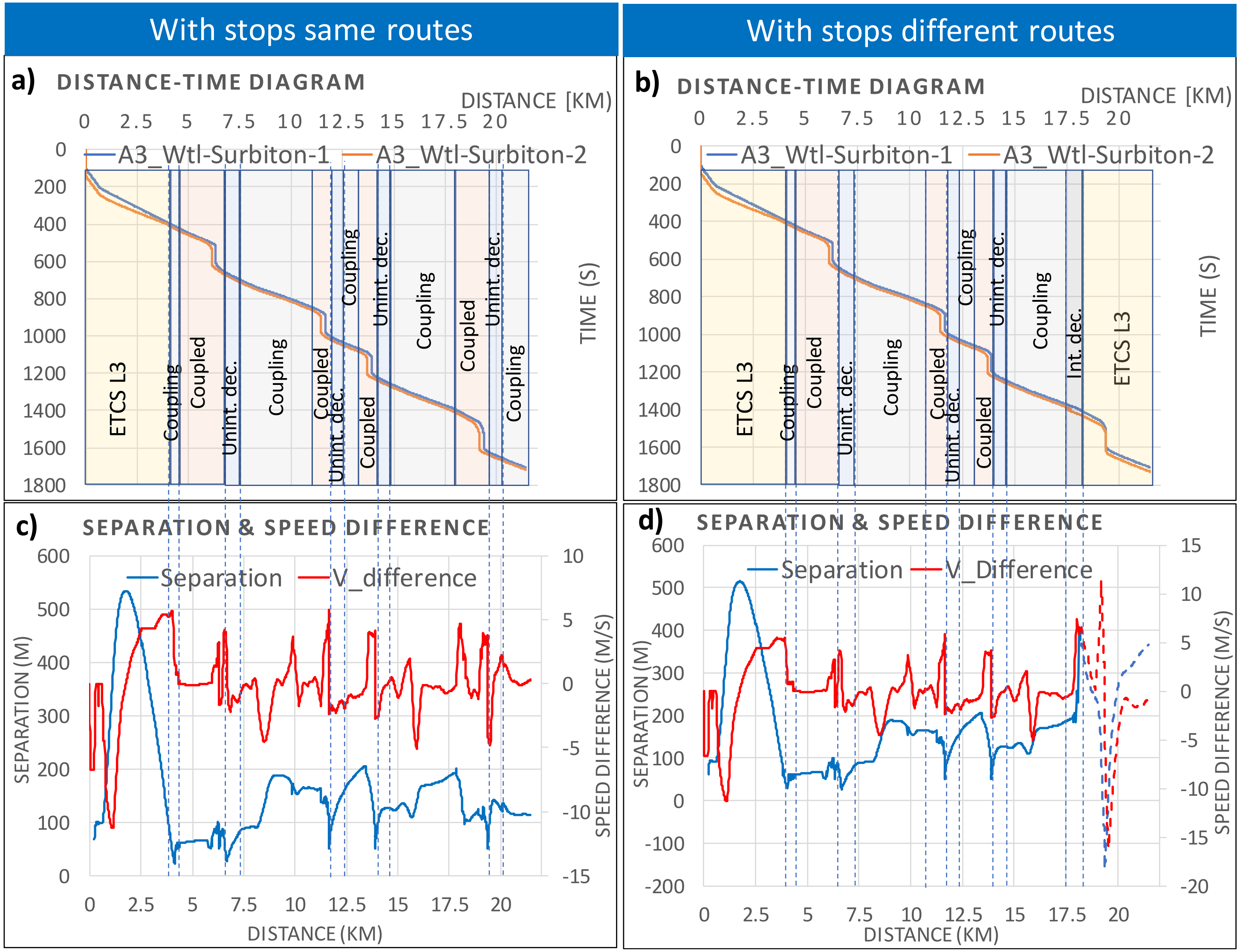
Scenario 1: Non-stopping trains

No stops same routes	No stops different routes



Results 1: State transition and train separation

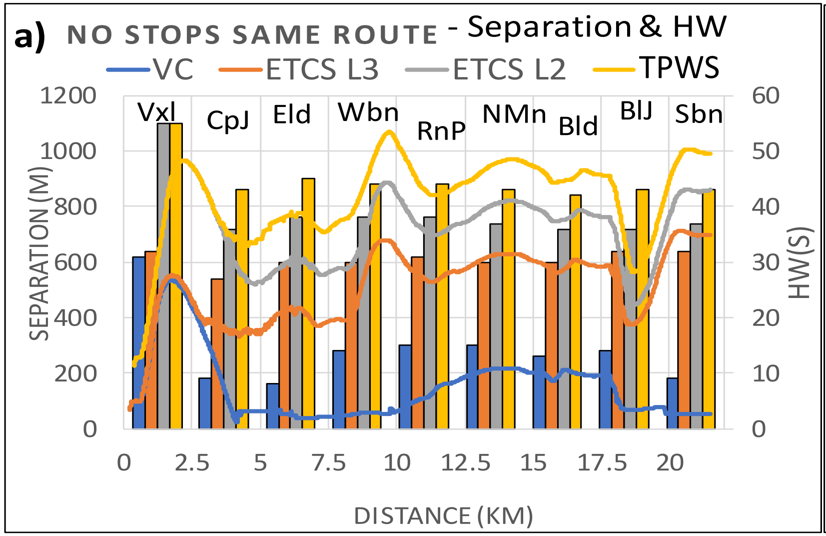
Scenario 2: Stopping trains

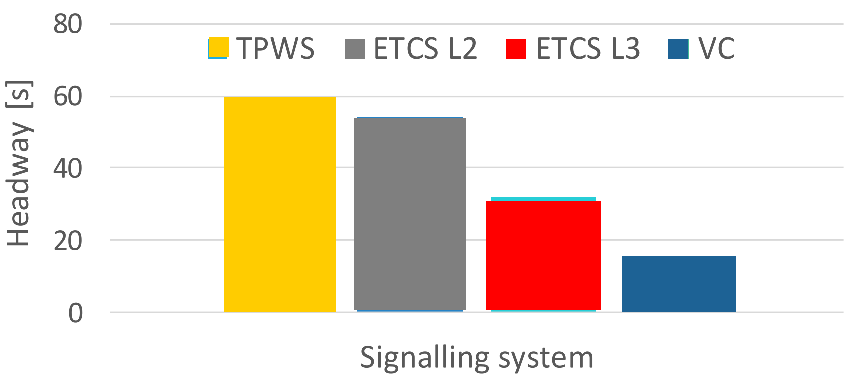


Results 2: Train separation and line headway

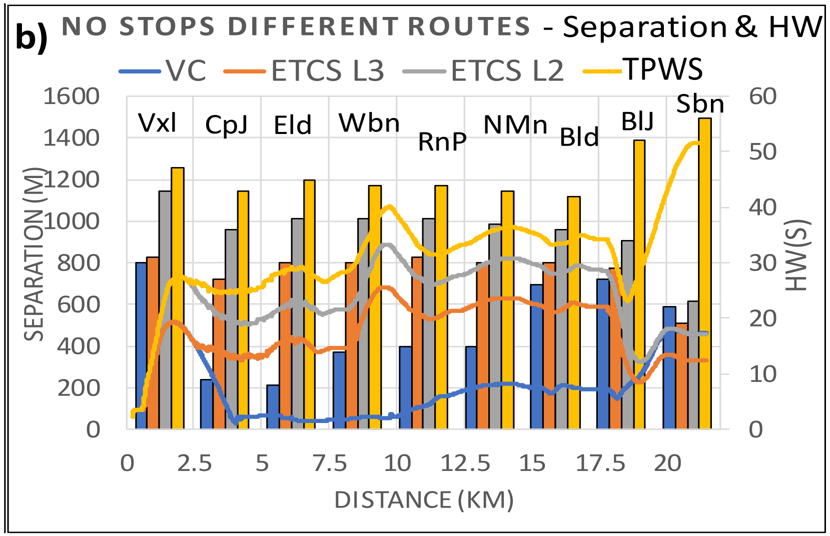
Scenario 1: Non-stopping trains

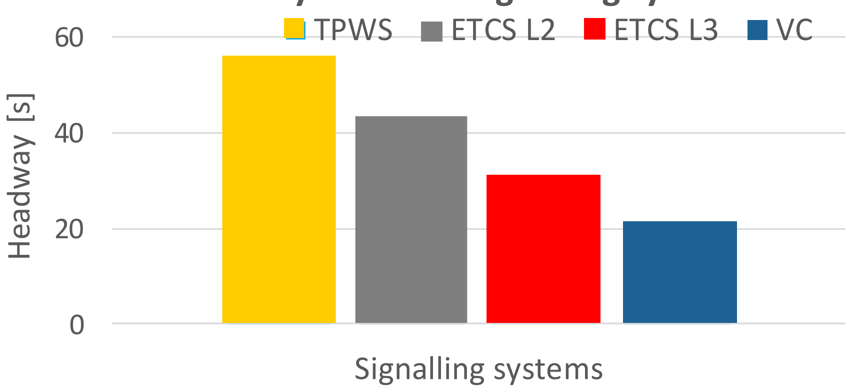
Trains with same route





Trains with different route

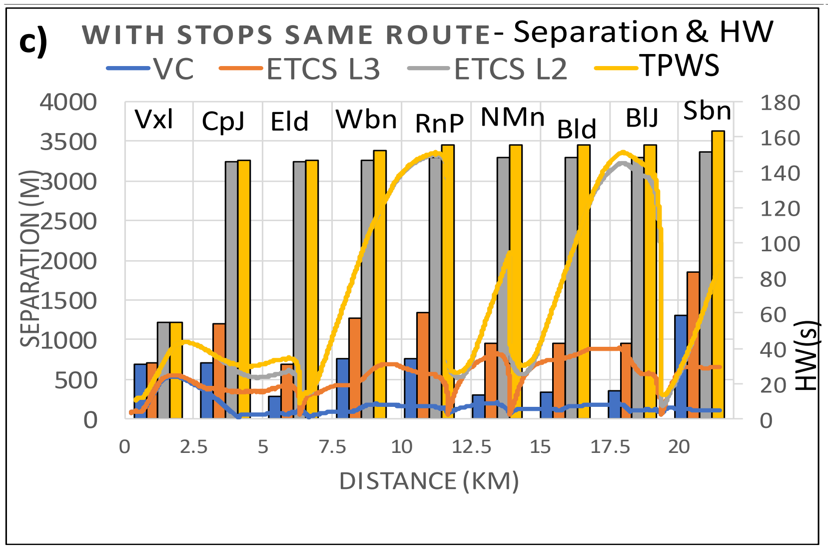


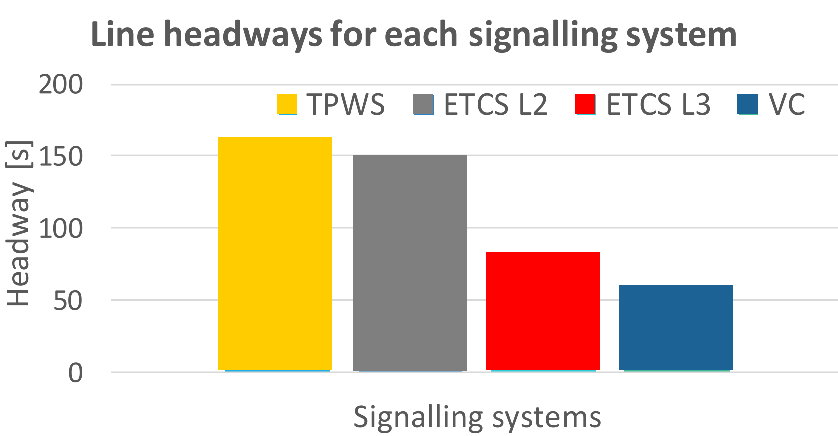


Results 2: Train separation and line headway

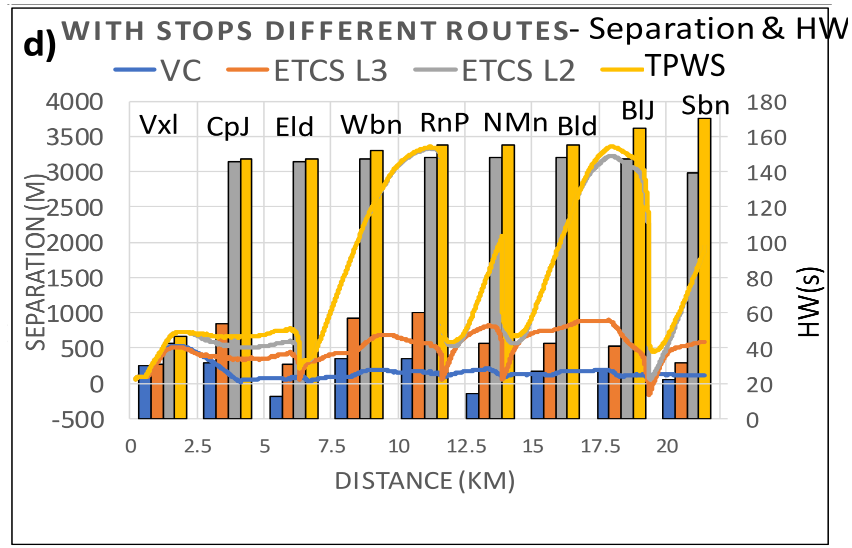
Scenario 2: Stopping trains

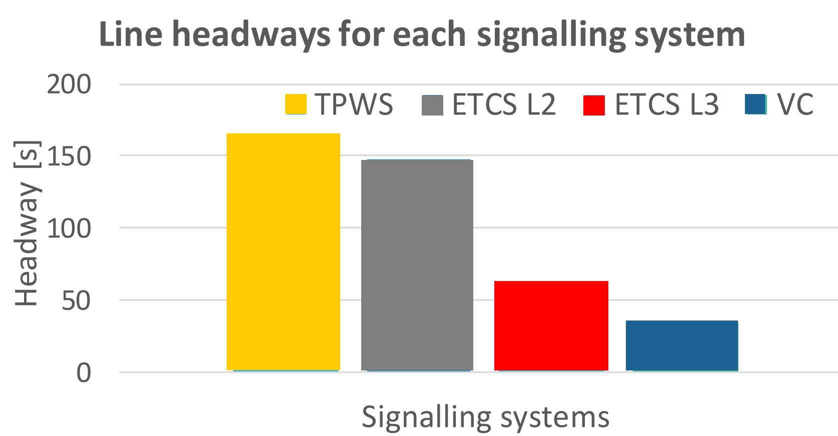
Trains with same route





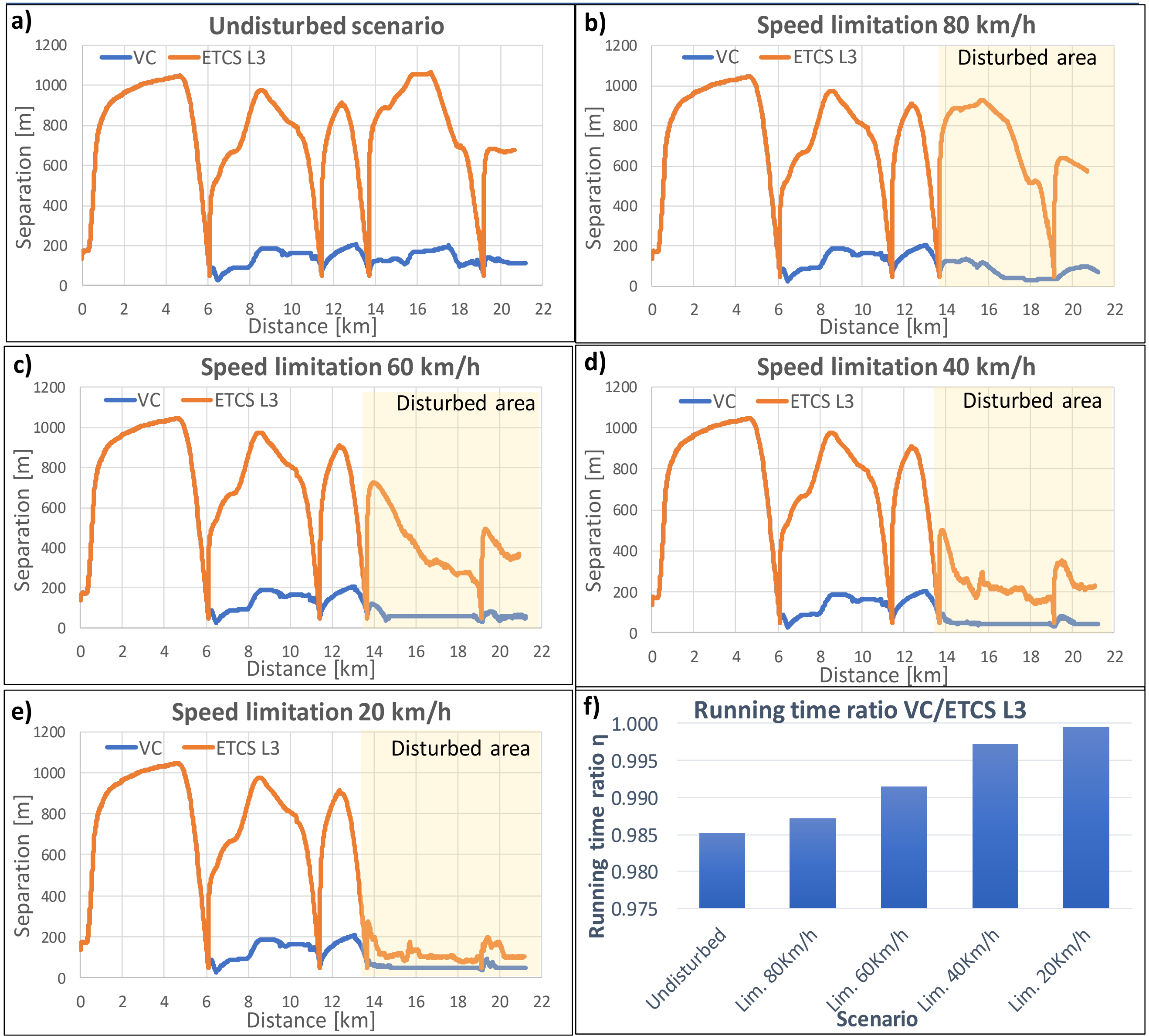
Trains with different route





Results 3: Sensitivity on running speed

Train separation and VC/ETCS L3 running time ratio



Several speed restrictions imposed to the first train in a disturbed area

Below 40 km/h train separation in ETCS L3 and VC is very similar

At low speeds ETCS L3 and VC tend to perform the same

Conclusions

- Virtual Coupling is a promising solution to face demand growth but deeper safety and operational investigations are needed
- Operational principles and a train-following model to analyse VC are provided for the first time in literature
- For a stretch of the SWML, VC is shown to outperform moving-block and fixed-block signalling in terms of capacity
- VC reduces headways the most for the case of stopping trains with different routes (-79% wrt TPWS, -77% wrt ETCS L2 and -43% wrt ETCS L3)
- At low speeds VC and ETCS L3 have similar performances given that absolute and relative braking distances differ only marginally

Thank you for your kind attention

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