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Towards Railway Virtual Coupling

Francesco Flammini, Ph.D.

Department of Computer Science and Media Technology

francesco.flammini@lnu.se

Linnæus University

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- Cooperation
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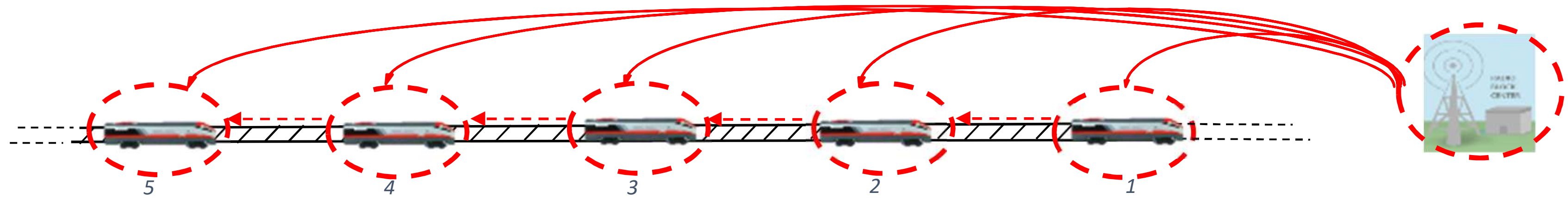
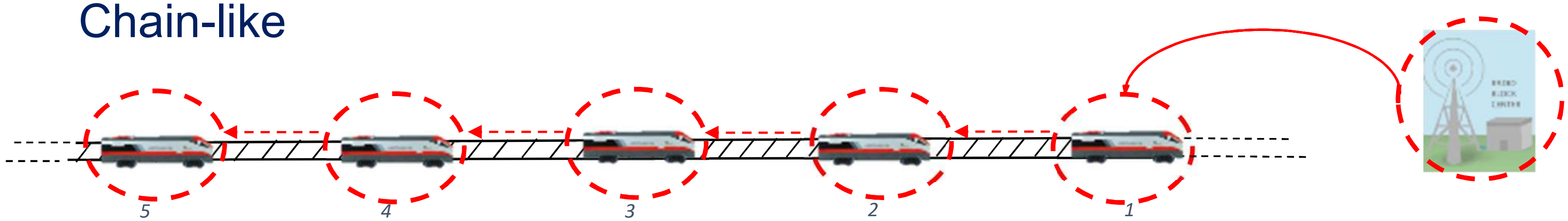
- Reference papers
  - Di Meo C, Di Vaio M, Flammini F, Nardone R, Santini S, Vittorini V (2019). **ERTMS/ETCS Virtual Coupling: Proof of Concept and Numerical Analysis.** IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS, DOI: 10.1109/TITS.2019.2920290. To appear.
  - Flammini F, Marrone S, Nardone R, Petrillo A, Santini S, Vittorini V (2018). **Towards Railway Virtual Coupling.** In: Proc. ESARS-ITEC Europe 2018, IEEE, November 7th-9th, 2018, Nottingham, UK. DOI: 10.1109/ESARS-ITEC.2018.8607523

Cooperative driving concept

Fully connected



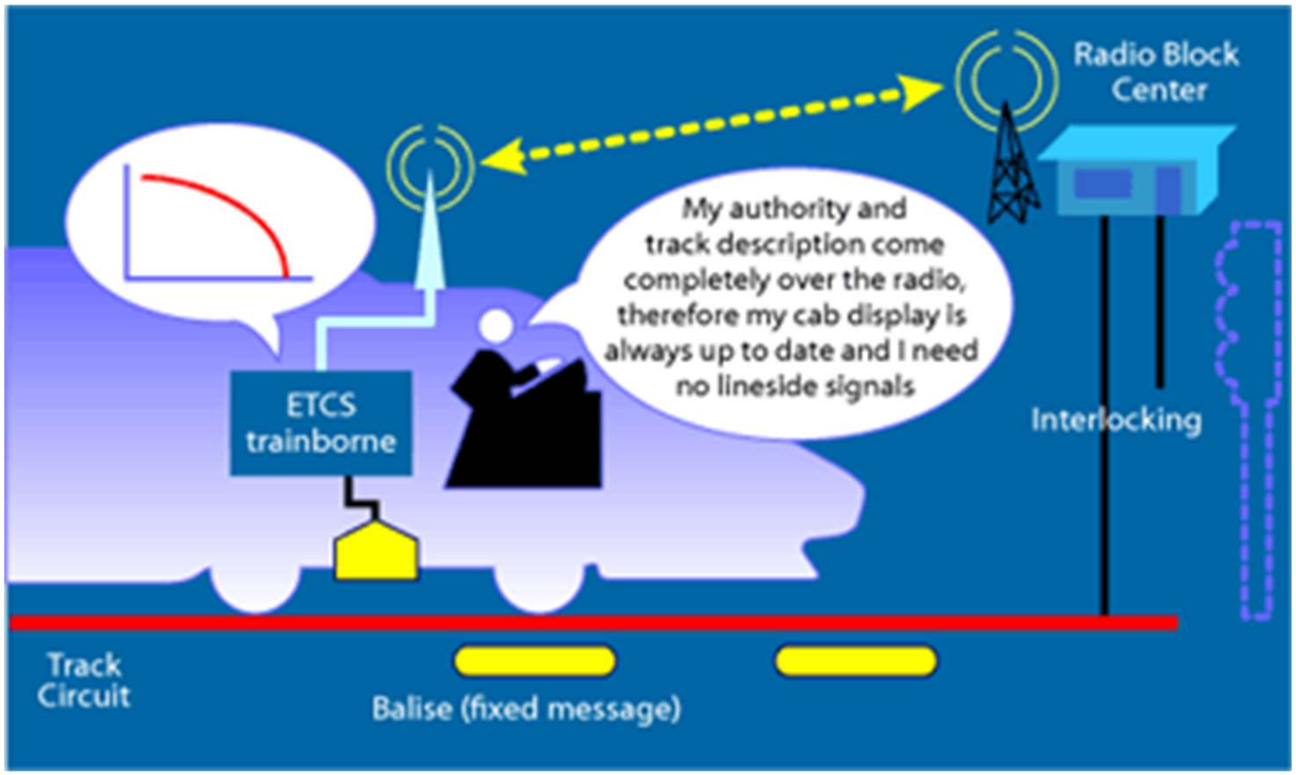
Chain-like



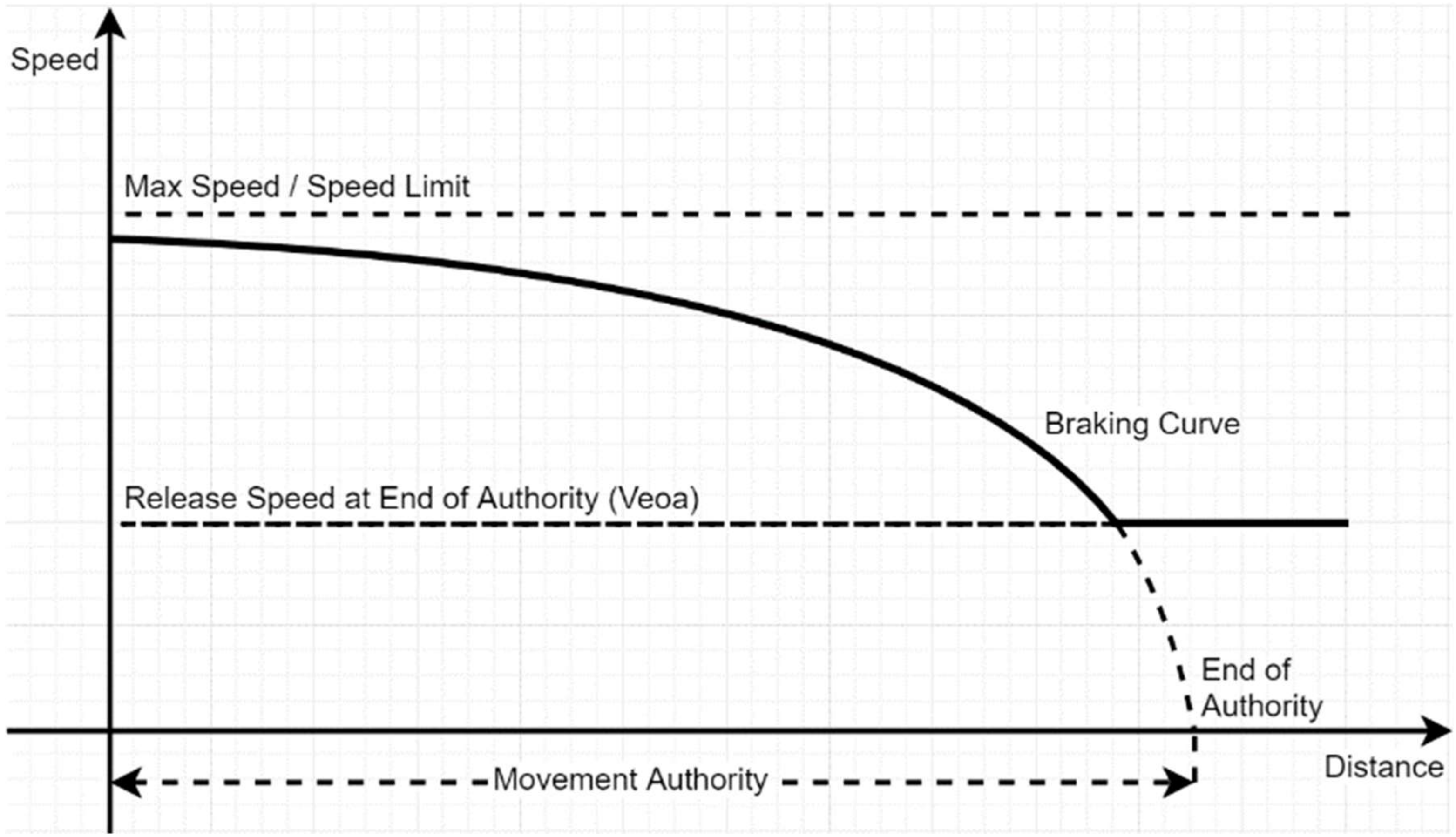
SHIFT2RAIL IP2:

Virtual Coupling (TD 2.8) aims to enable ‘virtually coupled trains’ to operate much closer to one another (within their absolute braking distance) and dynamically modify their own composition on the move (virtual coupling/uncoupling of train convoys), while ensuring at least the same level of safety as is currently provided.

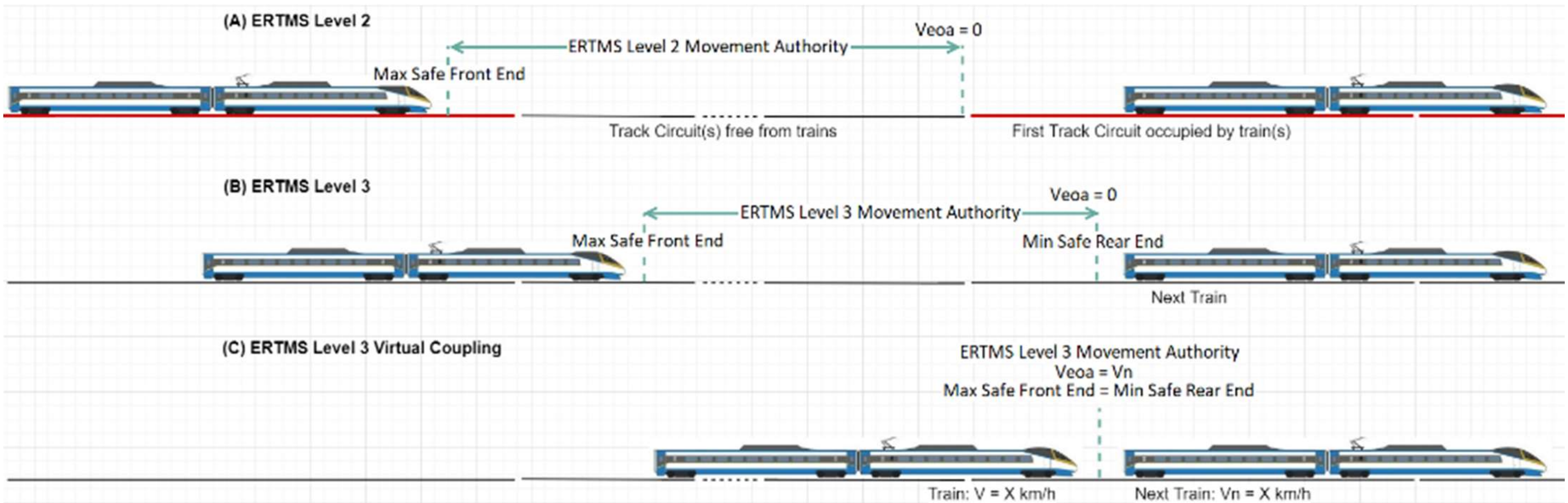
European Railway Traffic Management System (European Train Control System + GSM-R)



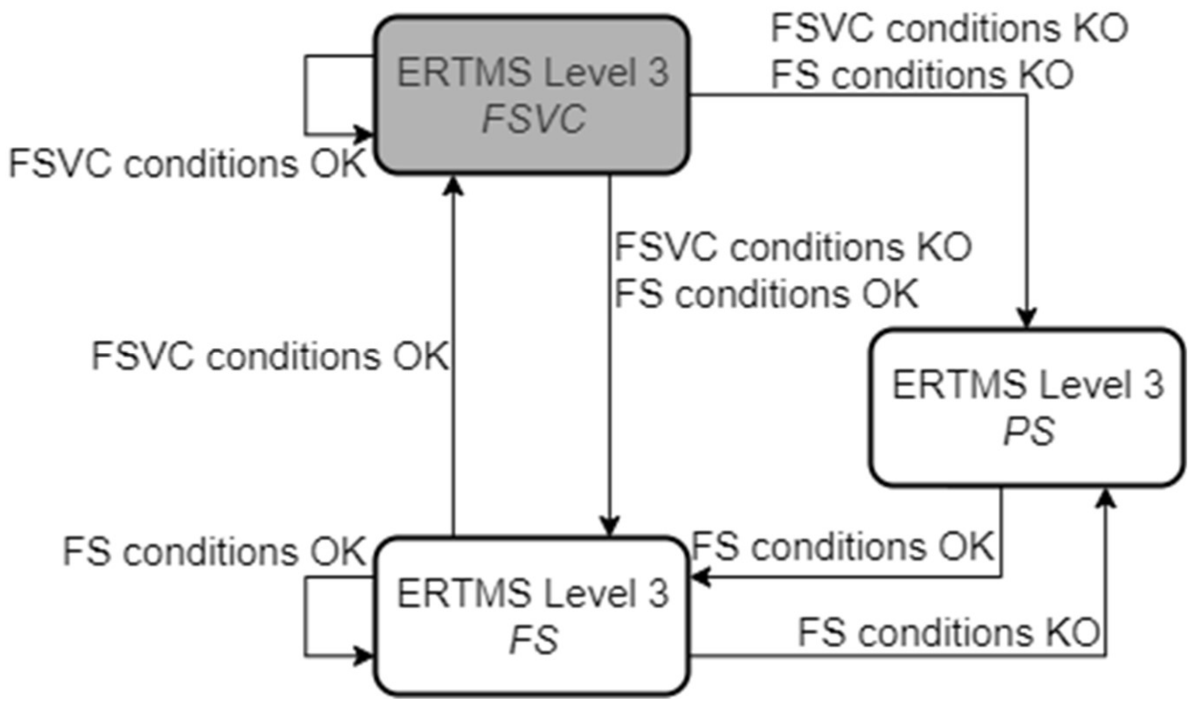
Braking Curve



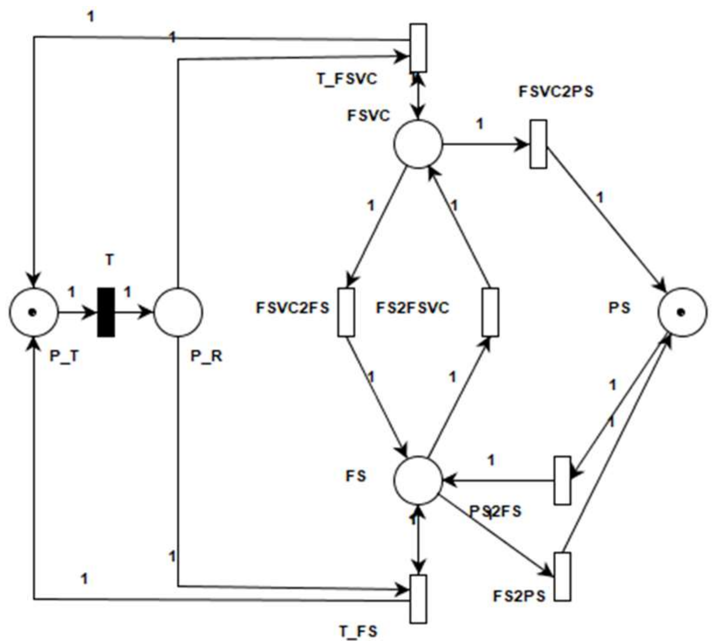
ERTMS Levels: Moving Block & Virtual Coupling

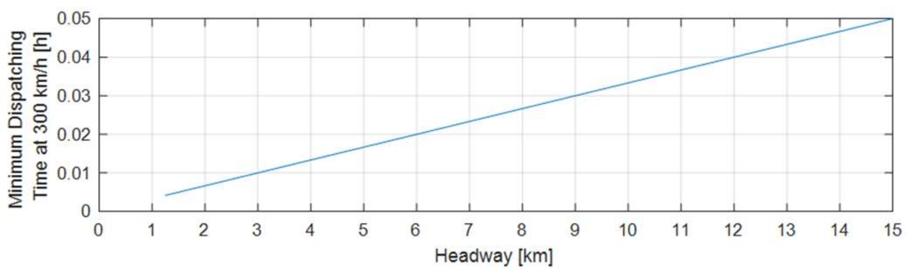


Extended ERTMS Level 3 Operating Modes



GSPN Performability model

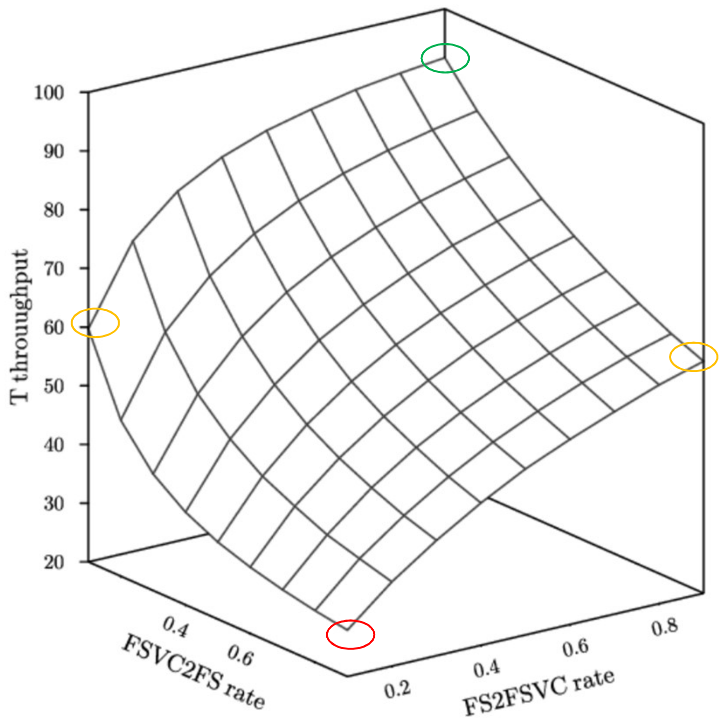




F. Flammini, S. Marrone, M. Iacono, N. Mazzocca, and V. Vittorini, "A multiformalism modular approach to ERTMS/ETCS failure modelling," International Journal of Reliability, Quality and Safety Engineering, vol. 21, no. 1, pp. 1 450 001–1, 02 2014.

- Transitions T_FSVC and T_FS: deterministic firing rate, i.e. frequency of trains at FSVC and FS respectively.
- Places P_T and P_R and transition T added to evaluate the train frequency on the track as a function of the sojourn times in FSVC, FS and PS.
- Transition T provides an upper bound to evaluate of system capacity.
- Firing rate of transitions FS2PS and FSVC2PS have been set according to ERTMS/ETCS RAMS specifications and results of previous studies.
- FS2FSVC and FSVC2FS feature parametric firing rates that are used for the analysis.

Preliminary Performability Evaluation Results



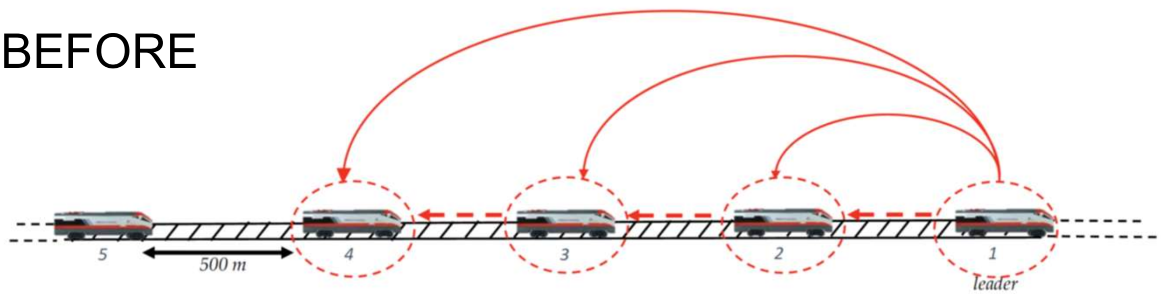
- No FSVC, Tmax = 20 trains/hour, i.e. 1 train each 3 min
- Ideal FSVC, Tmax = 100 trains/hour, i.e. 1 train each 36”
- Very reliable VC with very low FSVC2FS but very slow to reach FSVC, then around 60 trains/hour (left)
- Same with very efficient but unstable VC mechanism, with trains easily getting from FS to FSVC but also leaving FSVC often due to e.g. communication faults (right)
- For lower rates of FS2FSVC and higher rates of FSVC2FS (i.e. closer to the bottom point of the graph), it is more convenient to invest on improving the efficiency of the mechanism to get to FSVC (right)
- For lower rates of FSVC2FS and higher rates of FS2FSVC (i.e. close to the upper point of the graph), it would be more convenient to improve the reliability of keeping FSVC (e.g. by reducing communication errors).

Simulation Parameters

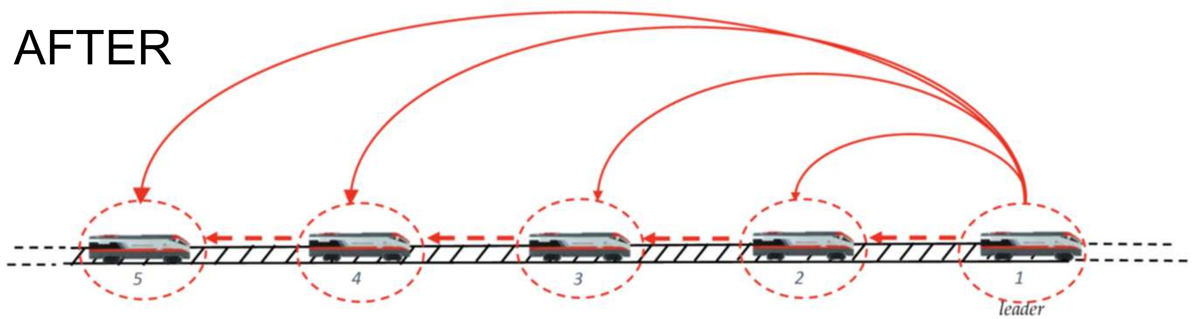
Scenario Parameters	
Maximum trains speed	300 [km/h]
Coupling reference speed	210 [km/h]
Virtual Coupling size	3 trains
Trains max acceleration	0.1 [m/s^2]
Trains max deceleration	-0.6 [m/s^2]
Trains length l_i	190 [m]
Trains mass m_i	380 [tonn]
$F_{i_{\max}}$	208 [N]
Davis parameter A	4.42 10^3 [N]
Davis parameter B	42 [Kg/s]
Davis parameter C	7 [Kg/m]
Control Parameters in Convergence Analysis	
Headway time h_{ij}	0.8 [s] $\forall i, j$
Headway time h_{i0}	0.8 [s] $\forall i$
Distance at standstill d^{st}	50 [m]
Control gains k_{ij}	$k_{10} = 0.01$, $k_{i0} = 0.001$ $(i \neq 0, i \neq 1)$ $k_{i,i-1} = 0.025$, $k_{ij} = 0$ otherwise
Control gains b_i	$b_i = 2$
Control gains γ_i	$\gamma_i = 0.0001$
α_1	0.016
α_2	533.5
Convergence rate	$2\delta = 0.025$

Join maneuver for the proof-of-concept

BEFORE

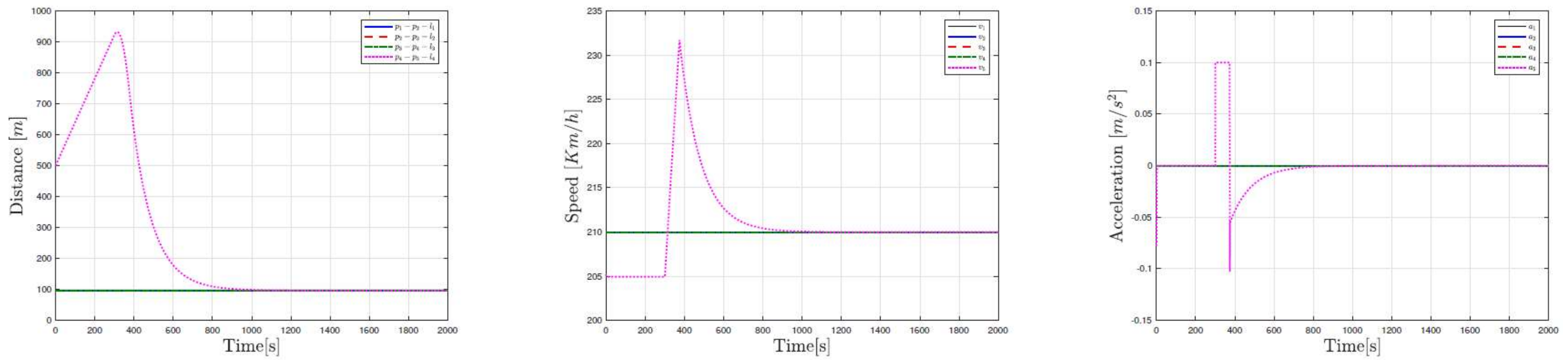


AFTER



- 4 trains in FSVC mode moving as a fleet and sharing their state information via chain-like communication
- Train fleet travels at the constant speed of 210km/ with a relative inter-train distance of 100m
- A 5th train in FS mode initially located at 500m from the 4th vehicle of the fleet performs a join maneuver
- 5th train moves at a constant speed of 205km/h sends a request to join the fleet at t = 300s
- After the RBC sends the coupling command, the EVC of train 5 switches from FS to FSVC
- Train 5 is hence able to communicate with the first and fourth trains within the fleet

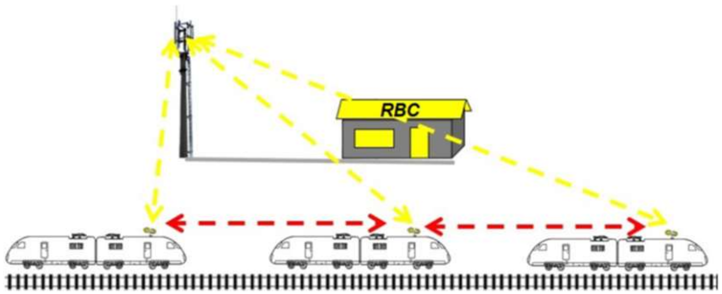
Preliminary results of the numerical analysis

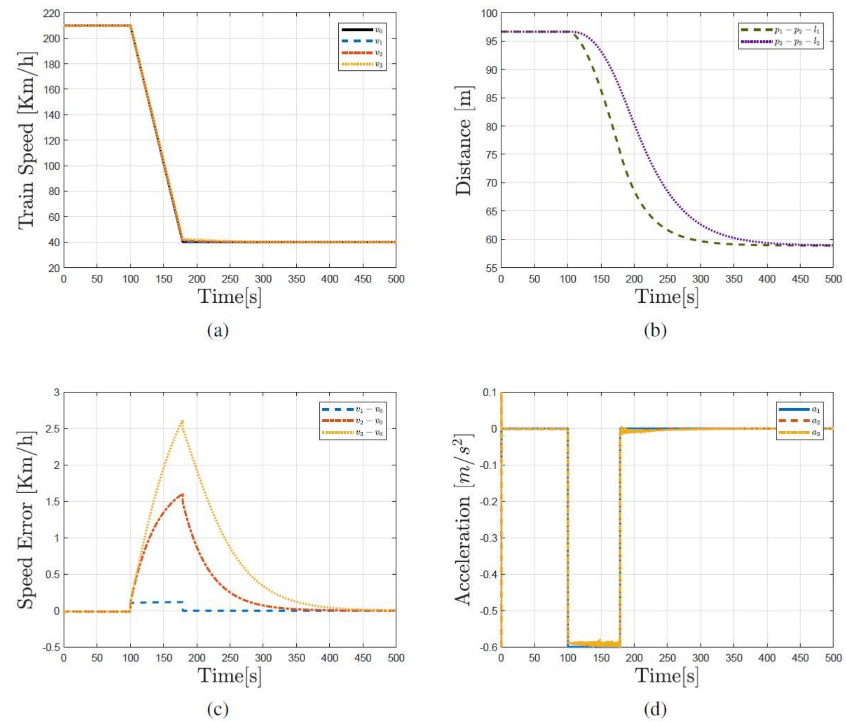


(a) (b) (c)

- Using shared information, local control algorithm computes the desired acceleration profile to be set on train 5 join the existing fleet.
- Simulation results show that under the action of the local control strategy, the train 5 accelerates to achieve the required spacing policy of 100m from train 4, and then it decelerates until it reaches the constant speed of 210km/h as set by the first vehicle of the fleet.

Coordinated emergency braking





- RBC sends TSR at time instant t = 100s
- Lead train starts decelerating from steady-state reference speed of 210 km/h towards 40 km/h
- Results show that the emergency maneuver is safely executed and all trains correctly follow the trapezoidal breaking profile set by the RBC (a) while preserving the bumper-to-bumper spacing as confirmed by time histories of distances (b) and relative speed error (c).
- During braking inter-train distance dynamically changes according to the spacing policy that safely shapes the gaps as the velocity changes.

Conclusions

- First model-based simulation study about Virtual Coupling in railways to provide a proof-of-concept
- Hints about practical implementation keeping compatibility with ERTMS/ETCS standard

- Next steps:
  - Extend the performability model possibly using CPN to get communication network requirements (bandwidth, latency, etc.)
  - Safety analysis of hazard conditions using GSPN/CPN
  - Further simulations in Matlab-Simulink accounting for communication faults and delays
  - Test Virtual Coupling using an industrial ERTMS simulator
  - Build hybrid co-simulation environments for VC

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Thank you for your kind attention!