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# ANALYSIS OF PLATOONING TRAIN OPERATIONS UNDER V2V COMMUNICATION-BASED SIGNALING: FUNDAMENTAL MODELLING AND CAPACITY IMPACTS OF VIRTUAL COUPLING.

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**ABSTRACT**

The ever-increasing need for railway capacity has led infrastructure managers to explore next generation signaling systems to drastically reduce train separation by overcoming traditional fixed-block railway operations. Technologies like ETCS Level 3 are under development to bring the railways to a configuration without track-side signaling where trains move at an absolute braking distance from each other. The railway industry is however looking into the alternative concept of Virtual Coupling which separates trains by a relative braking distance as for cars on the road. By means of a V2V communication architecture trains could move synchronously in platoons which could be treated as a single convoy at junctions, so to improve capacity. On the other hand, the concept might introduce additional safety risks, especially at diverging junctions where points need to be switched and locked in between trains of a platoon. There is the need to understand whether capacity benefits provided by Virtual Coupling are sufficient to motivate the railway industry to invest in it, despite the unclear safety implications. This paper addresses such a need by assessing impacts of Virtual Coupling on railway capacity and potential benefits with respect to ETCS Level 3. For the first time in literature, operational principles and capacity occupation models have been developed and simulated to describe train operations under Virtual Coupling. An application to a case study in the UK shows the advantages that such a concept provides in terms of capacity utilization, as well as space and time train headways.

## INTRODUCTION

Railway transport demand of passengers and goods will massively increase in the next decades because of population growth and the expansion of international markets. Also, an epochal shift to railways is expected to happen as an effect of strategic actions on sustainable mobility such as the EU "White Paper on Transport" [1]. In 2050 the amount of passengers and freight moving by railways are estimated ([2], [3]) to grow by more than 40% and 50%, respectively.

Such a scenario poses a big challenge to infrastructure managers who need to expand the capacity of existing networks which, already today, operate under saturated conditions. Constructing new railway tracks is very costly and not always an option, especially in densely built-up areas. Railway industry is therefore considering next-generation signaling systems which overcome traditional fixed-block separation by letting trains move as close as cars do on the road. To this end, research programs like Shift2Rail [4] and Digital Railway [5] have been initiated to deploy technologies allowing the migration of vital systems (e.g. signals, track-free detection elements) from track-side to on-board. Such a migration is achieved by the signaling technology ERTMS/ETCS Level 3 [6] which replaces vital track-side systems with on-board devices for braking curve supervision and train integrity monitoring. Information updates on train positions and Movement Authority MA (i.e. the max distance that is safe for the train to cross) are instead exchanged via radio to/from a track-side antenna called Radio Block Centre. ETCS Level 3 builds on the concept that trains are separated by a safety margin plus an absolute braking distance that is the distance needed by a train to reach a standstill from current speed. Should a train stop instantly, the following train is always able to safely halt before hitting the train ahead. Although ETCS Level 3 goes beyond fixed-block separation, distances between trains can still reach up to 4-5 Km on high-speed lines where speeds are around 300 Km/h. In this regard, the principle of full braking distance separation does not seem to be sufficient to face the need for an ever-increasing capacity. Railway industry is hence looking into an alternative approach, questioning the unrealistic assumption that a train ahead can stop instantly. Two trains can run much closer to each other if a vehicle-to-vehicle communication link is introduced to ensure that the train behind slows down together with the train ahead, so to keep a safety distance. Trains can be so separated by a relative braking distance, that is the distance needed by a train to slow down from its current speed to the one of the leading train. Such a concept has been proposed under the name of "Virtual Coupling" or "Train Convoy" since trains move synchronously with a leading train, as if they are virtually coupled in one convoy. Platoons of trains are so formed which can be treated as a single convoy at junctions thereby improving capacity at bottlenecks. The concept of Virtual Coupling has already been proved in the road sector for platoons of autonomous cars under cooperative adaptive cruise control [7]. However, the railway industry still doubts its applicability to railways, given that operational principles for trains have not been fully defined yet, making implications on safety and capacity unclear. Whilst Virtual Coupling is surely more effective than ETCS Level 3 on plain tracks, the same cannot be surely stated at diverging junctions, where an absolute braking distance separation should be imposed anyway for safety reasons. So far, little research has been done to identify the benefits of Virtual Coupling over ETCS Level 3. The railway industry is instead in need to understand whether it is worth investing in this concept, despite the unclear safety implications.

To such purpose, this paper contributes to address this need by defining basic operational principles and a model for assessing capacity occupation of trains running under Virtual Coupling.

Defined principles are implemented in the microscopic railway simulation model EGTRAIN to reproduce virtually coupled trains moving in a platoon under undisturbed free-flow conditions. The railway section between London Waterloo and Surbiton on the South West Main Line in the UK is used as a case study. Specified capacity occupation models are then applied to assess capacity impacts of Virtual Coupling and potential gains when compared to ETCS Level 3.

A review on ETCS Level 3 and Virtual Coupling is provided in Section 2. Operational principles and a capacity occupation model for Virtual Coupling are defined in Section 3. An application to a case study is described in Section 4 where results are provided together with a comparison versus ETCS Level 3. Conclusions are reported in Section 5.

## LITERATURE REVIEW ON ETCS LEVEL 3 AND VIRTUAL COUPLING TECHNOLOGIES

In ETCS Level 3, the track-side system is reduced to the only Radio Block Centre and transponders (called balises) working in a passive mode as a positioning reference. The concept of ETCS Level 3 sets the passage from fixed block train separation to moving block, where block sections exist no longer. Legacy line-side signals, track-free detection devices and block section marker-boards are therefore removed, being train positioning and integrity monitoring entirely transferred on-board. Verification of train integrity is performed by an on-board device called Train Integrity Monitoring (TIM) which is still an open challenge for trains with variable composition. The British and the Dutch railway infrastructure managers propose a hybrid version of ETCS Level 3 which leaves in place track-free detection devices to monitor train integrity [8]. Legrand et al. [9] propose instead an integrity monitoring technology which can meet required safety standards by combining Global Navigation Satellite Systems (GNSS) with Inertial Navigation Systems (INS). Biagi et al.[10], show how missed train integrity and/or position reporting due to communication break-up in ETCS Level 3 can drastically reduce network capacity.

A train separation based on a relative braking distance has been initially suggested by Ning [11] who also proposes the use of car-following models to study train dynamics under this kind of separation. Emery [12] suggests an alternative approach which separates trains by the absolute emergency braking distance to overcome safety risks that a relative braking distance separation would raise at diverging junctions. At the same time, relying on an absolute emergency braking distance separation could provide capacity gains over ETCS Level 3, although emergency braking causes discomfort to passengers while damaging tracks and rolling stock.

The railway industry is investigating the concept of “Virtual Coupling”, building on the assertion that it is unrealistic that a train in front stops in one instant. Trains communicate via a V2V communication architecture to move synchronously in a platoon that can be treated as a single convoy at junctions, thereby reducing train separation at bottlenecks. The Institution of Railway Signal Engineers [13] have considered this concept technologically viable, although it is the trade-off between safety and capacity to deserve a clearer understanding. One of the biggest challenges regards for instance the management of train platoons at diverging junctions, where points need to be moved and locked in between the trains, raising non-negligible safety risks.

## OPERATIONAL PRINCIPLES OF VIRTUAL COUPLING

The signaling architecture of Virtual Coupling builds on the basic modules of ETCS Level 3 and introduces a vehicle-to-vehicle communication layer (V2V comm) on top of it, as illustrated in

Figure 1(a). Track-side equipment is entirely removed given that on-board devices now support train positioning and integrity monitoring functionalities. The TIM checks that the train is integer and has not accidentally split, leaving one or more of its cars dangerously stranded on the tracks. On-board odometers measure train positions while balises, evenly spread along the track, are used as location references to offset position measurement errors. Reports on train integrity and train position are regularly broadcasted from trains to RBCs via a vehicle-to-infrastructure communication layer (V2I comm) based on GSM-R. The V2I communication layer is also used to send updated movement authorities from the RBC to trains. The on-board European Vital Computer (EVC) ensures trains do not overrun authorized limits (called End of Authority) by dynamically supervising train braking curves. In case the train does not comply with imposed movement and/or speed restrictions, several warnings are activated before triggering an emergency braking to safely stop the train.

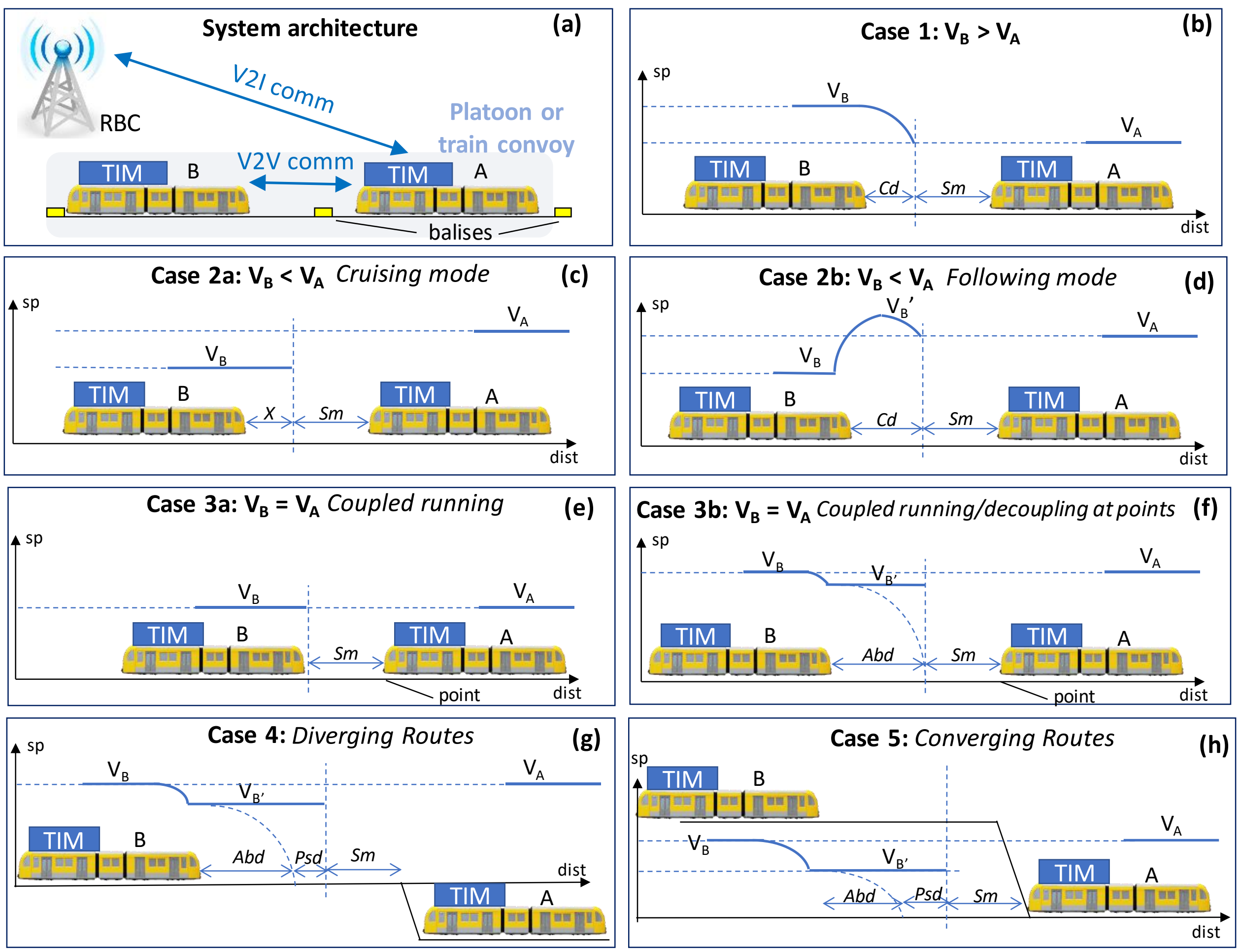


**Figure 1. Virtual Coupling signaling architecture (a) and cases defining the operational principles (b-h).**

All the functionalities described so far are common to ETCS Level 3 as well. In Virtual Coupling trains always move under the control of ETCS Level 3 until they come close to each other and conditions for train platooning are met. A platoon can be composed of two or more trains travelling on a shared section of their route. The leading train of a platoon moves under ETCS

Level 3, so the on-board EVC supervises its absolute braking distance until the End of Authority. A train getting closer to a train ahead will instead switch its control from ETCS Level 3 to Virtual Coupling. In such a case, the train connects to the train ahead by means of the V2V communication to gather information on speed, position, acceleration and MA of the leading train. This information is used by the on-board subsystem to compute the relative braking curve which let the train move at the same speed of the leader. The EVC shifts the supervision from the absolute to the relative braking distance to allow trains in a platoon moving together while keeping a safety margin in between.
Given the very short reaction times needed to coordinate the movement of trains in a platoon, Automatic Train Operation (ATO) becomes a necessity for Virtual Coupling.
The EVC shall also safely supervise decoupling operations when trains in a platoon need to split apart to take different routes. Particularly interesting is the situation of a platoon approaching a station where its composing trains need to stop at different platforms. In this circumstance the EVC shall swap back to supervise the absolute braking distance from the diverging/converging point to avoid accidents, should the point fail in its position.

Transitions from coupled to uncoupled train movements and vice versa represent safety-critical phases requiring additional supervision.

Crucial is to understand the operational principles which regulate those transitions and let trains moving in coordination when running under Virtual Coupling. Operational principles for Virtual Coupling are defined as follows for all possible cases which might occur during real-life operations. These cases are illustrated in Figure 1(b)-(h) where distance (*dist*) and speed (*sp*) are reported on the x-axis and y-axis, respectively. For the sake of clarity, the case description refers to only one leading train *A* and one following train *B*, but concepts are easily extendible to multiple trains.

*Case 1: Follower faster than leader ($V_B > V_A$)*

Figure 1(b) describes the case of train B moving at speed $V_B$, getting behind train A which runs at a lower speed $V_A$. In this situation the two trains can be virtually coupled if train B is slowed down until reaching the speed VA. Such a speed shall be achieved at a safety margin *Sm* from the tale of train A, so that a safe distance is in between the trains. The braking curve from $V_B$ to $V_A$ is computed and supervised by the EVC on board train B, after receiving kinematic information of train A. The distance covered by train B when braking to reach speed $V_A$ and move in coordination with train A is called *Coordination distance Cd*. After such a distance train A and B are considered as virtually coupled in a platoon, because moving at the same speed at a safe distance *Sm* from each other.

*Case 2: Follower slower than leader ($V_B < V_A$)*

When train B runs slower than train A, no safety issues arise. Differently from the previous case, it is not mandatory to control the train behind to avoid a collision with the train ahead. However, letting train B moving as slow as it desires is not efficient for capacity and better would be to have it moving in coordination with the train ahead. Making an analogy with cooperative control for platoons of autonomous cars [14], two operational modes can be identified: *cruising mode* and *following mode*. As shown in Figure 1(c), the cruising mode implies that train B can run at its desired speed $V_B$ without needing to catch up and coordinate with the train ahead. AV2V communication takes place and trains travel in a platoon although distances in between trains are

larger than the minimum safety margin *Sm*. If trains keep a speed differential ($V_A$-$V_B$) for a time interval $\Delta$t, their separation increases by a value
$X = (V_A-V_B) \cdot \Delta t$.
Figure 1(d) illustrates instead the following mode where train B is controlled by the on-board system to catch up with the train ahead. Train B will be first accelerated to reach speed $V_{B'}$ so to get closer to train A. Then it will be decelerated to reach speed $V_A$ at a distance *Sm* from the tail of train A. The coordination distance *Cd* covered by train B to coordinate with train A is hence the distance to accelerate from $V_B$ to $V_{B'}$ plus the distance to brake from $V_{B'}$ to $V_A$. Clearly, the following mode is way more efficient than the cruising mode in terms of capacity utilization.
Anyway, train B needs to get information about the route of the train ahead before deciding whether to run in following or cruising mode. If the train ahead is going to keep the same route of train B for some time, then the following mode shall be adopted. But if the train ahead diverges to a different route just a short time after, the cruising mode would make more sense. If the following mode would be used, there might be the risk that the trains need to be split by the time train B reaches train A. In this case there would not be sufficient time to practically form a platoon. In addition, train B will be forced to quickly slow down to allow an absolute braking distance separation before train A diverges at the junction.

*Case 3: Follower and leader moving at the same speed ($V_B = V_A$)*

If train B and train A move at the same speed, they can be virtually coupled in a platoon to travel at a minimum safe distance *Sm* from each other. Of course, trains can be coupled in a platoon only on those portions of the network where they all share the same route. For shared portions of route, virtual coupling has the advantage to minimize train separation even at junctions, where the platoon can be treated as a single convoy. Significant improvements in traffic throughput can be so achieved. This mode of operation is here called as *coupled running* or *train convoy* and illustrated in Figure 1(e). Trains are separated by a minimum safe distance even on points, as long as these latter are locked and do not move in between the trains. Trains at junctions separated by less than the absolute braking distance can be however a questionable condition from the safety perspective. Risks exist that a train can derail when crossing a point even if the point was set into position and locked. In such a situation, a following train might not be able to safely stop unless it had an absolute braking distance separation from the train ahead. A safer operational mode is *coupled running/decoupling at points* (Figure 1(f)) where trains in a platoon are spaced out by an absolute braking distance whenever approaching a junction. When approaching a point, a train B moving in *coupled running* with the train ahead (train A) will need to slow down to speed $V_{B'}$ to get an absolute braking distance separation (*Abd*). The platoon will be so decoupled at any junction even if trains do share the same exact route.

*Case 4: Follower and leader with diverging routes*

When trains moving in a coupled platoon need to take diverging routes at a junction, the platoon shall be spaced out for safety reasons. Points will indeed need to be moved and locked in different positions between two consecutive trains of the platoon. Tangible safety risks can arise if trains are not sufficiently separated, should a point fail in a position or have not enough time to be locked before being crossed by another train. A safe train separation shall allow the point being set and locked, and the train behind coming to a stop in case of point failure or derailment of the train ahead. Figure 1(g) depicts the case of a junction where trains A and B moving in a coupled platoon take diverging routes. At the junction, train B is slowed down to speed $V_{B'}$ to reach a safety distance from the train ahead. The safety distance includes the absolute braking distance *Abd*, the point set-up distance *Psd* (i.e. the distance to allow the point being set and locked) and the safety margin *Sm*.

*Case 5: Follower and leader with converging routes*

Trains running on different routes might meet at converging junctions where their routes merge. To allow trains converging to the same route, points need to be set and locked in different positions between a train and the other. As for the previous case, significant risks arise if trains are not sufficiently separated and a point fails, or it is not yet locked before a train crosses it. A safe train separation should enable the point to be set up and the train behind to stop, should the point fail or the train ahead derail. Such a condition is represented in Figure 1(h) where train B and train A run on different routes and meet at a converging junction. When approaching the junction train B brakes from $V_B$ to $V_{B'}$ so to be at a safety distance from the point. Such a safety distance is the sum of the absolute braking distance *Abd*, the point set-up distance *Psd* and the safety margin *Sm*. Given that trains A and B run on different routes they are supervised by ETCS Level 3 until the junction and only after they can be virtually coupled. This means that in the case of a converging junction an absolute braking distance separation is always provided because of the ETCS Level 3 supervision. Different would be the situation where train B just decoupled from a platoon to take a different route. In that event train B shall be able to: *i*) end the V2V comm with the trains of the platoon, *ii*) set a V2I comm with the RBC to be supervised by ETCS Level 3 at the junction, *iii*) start a new V2V comm with train A to couple with it after the junction. Communication breakups and/or long handovers from Virtual Coupling to ETCS Level 3 and vice versa could dangerously increase safety risks. Those risks can be mitigated if Virtual Coupling can supervise both the relative and the absolute braking curves. In this way, the safe distance from a converging junction would be supervised directly by Virtual Coupling without the need of many communication switches.

## A MODEL FOR COMPUTING CAPACITY OCCUPATION OF VIRTUAL COUPLING

Capacity occupation is the total time a portion of infrastructure is occupied by train movements within a reference time interval (usually an hour). The time a train occupies a given portion of infrastructure can be computed by means of the blocking time theory [15]. This theory draws on the railway principle that when a section of track is occupied by a train, the access to that section is blocked to other trains. The blocking time is defined as the total amount of time a section is allocated to a train. The blocking time starts from the instant a movement authority is issued and ends when the section has been completely released. Specifically, the blocking time is composed of:

- *Setup time* $t_s$ for the route, necessary to detect, set and lock switches in the required position.
- *Sight and reaction time* $t_{sr}$ needed by the driver to view the indication of the signaling system and react to it.
- *Approaching time* $t_{ap}$ for the train to approach the section after that a movement authority has been provided.
- *Running time* $t_{run}$ for the train to entirely cross the section
- *Clearing time* $t_c$ for the tale of the train to completely clear the section
- *Release time* $t_{rel}$ for the signaling system to reset the track to a “free” status after the train has left.

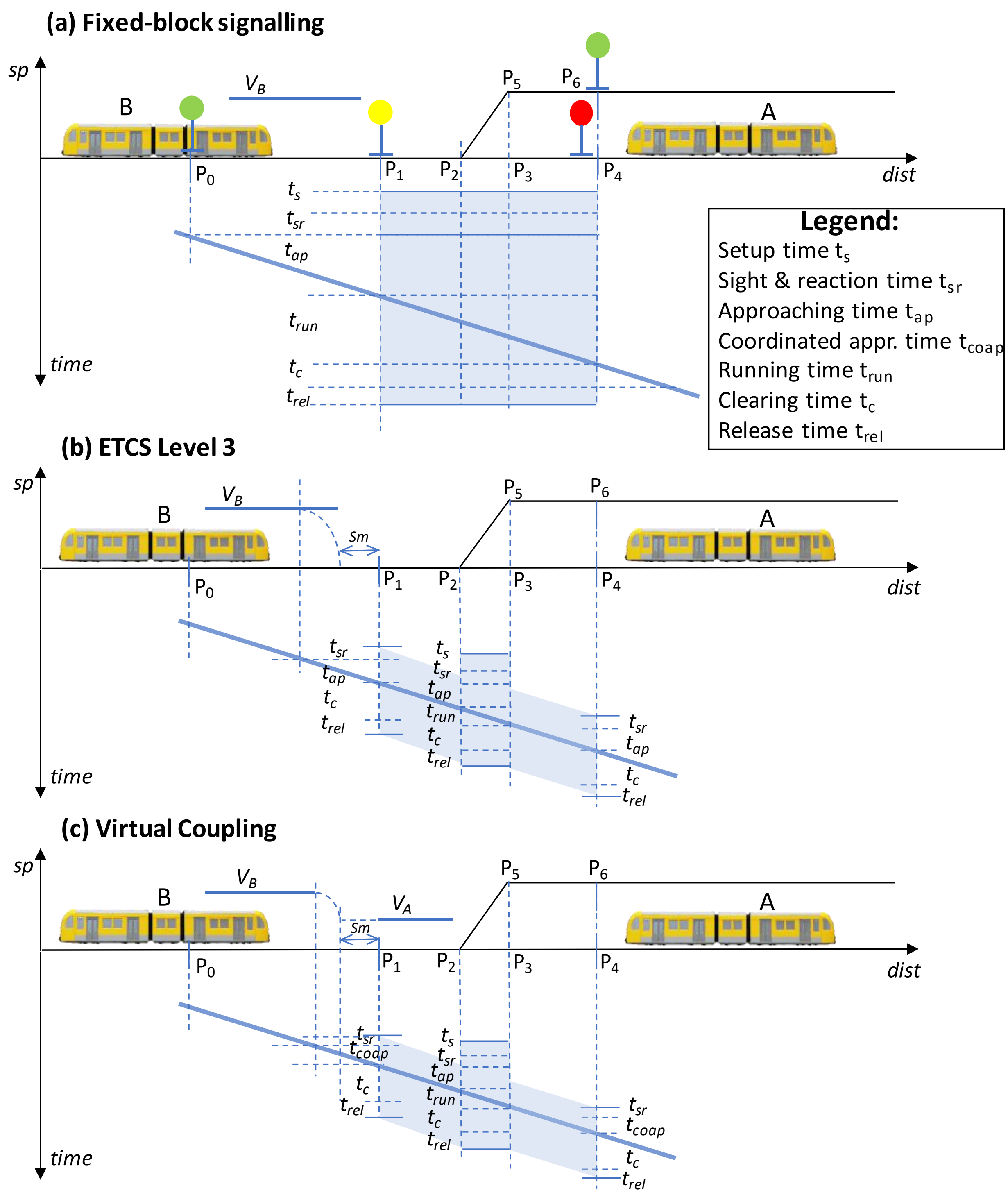


**Figure 2. Models for train capacity occupation for fixed-block signaling (a), ETCS Level 3(b) and Virtual Coupling (c).**

Figure 2 illustrates blocking times when computed for traditional fixed-block signaling, ETCS Level 3 and Virtual Coupling, respectively. Two trains running on diverging routes are represented. Train A goes across points $P_2$, $P_3$ and $P_4$, while train B moves towards points $P_2$, $P_5$ and $P_6$. Distance is reported on the x-axis while speeds and time on the y-axis.

In fixed-block signaling, the infrastructure is divided into block sections delimited by line-side signals, which can be occupied by one train at a time. In this case the blocking time for block section $P_1$-$P_6$ when being allocated to train B has the following components. The setup time is the time to detect, set and lock the point in position $P_2$-$P_5$. Time $t_{sr}$ is the time for the train driver to look at and react to the aspect of signal $P_0$, which gives the approach indication to signal $P_1$. Time $t_{ap}$ is the time for the train to move from signal $P_0$ to signal $P_1$ at the entrance of block section $P_1$-$P_6$. Time $t_{run}$ is the running time between the entrance signal $P_1$ and the exit signal $P_6$. Time $t_c$ is the time for the train to clear block section $P_1$-$P_6$ with its entire length.

Time $t_{rel}$ is the technical time needed by the track-side train detection equipment (e.g. track circuits) to report the status of block section $P_1$-$P_6$ as free after train B has cleared it.

In ETCS Level 3 block sections exist no longer. The concept of blocking time needs to be adapted from a section to a non-dimensional point of the infrastructure, here called as location. Consequently, the definition for some of the blocking time components needs to be adjusted accordingly. The variable $t_{sr}$ becomes the time for the train driver to view and react to the speed indication provided by the EVC on the Driver Machine Interface (DMI) in the driving-cab. The approaching time $t_{ap}$ becomes the time for the train to run over the absolute braking distance plus a safety margin from the location. The variable $t_{rel}$ is the communication delay for the RBC to acknowledge that the location has been cleared by the train.

The time train B occupies the portion of infrastructure between $P_1$ and $P_6$ changes depending on the location. For those infrastructure locations corresponding to switches and level crossings, blocking times are still computed as for fixed-block signalling. The two edges $P_2$ and $P_5$ of the switch blade are indeed considered as part of the same block section since a train reserves and releases them both together. For those locations, all blocking time components are non-null including the time $t_s$ to set and lock the points and the train running time $t_{run}$ between $P_2$ and $P_5$. For all the other plain track locations like $P_1$ and $P_6$, blocking times have a null setup time and a zero-running time. Setup time does not indeed apply to non-movable portions of track while the running time for a location that has an infinitesimal length is 0.

For ETCS Level 3 the blocking time diagram changes the shape from a typical rectangular block to a bandwidth, wrapped around the time-distance diagram of trains.

For Virtual Coupling, blocking times are computed in the same manner as for ETCS Level 3, however some of the blocking time components assume a slightly different definition. The sight and reaction time $t_{sr}$ becomes the time for the ATO system to react to the instructions provided by the on-board computer. Train operating under Virtual Coupling will indeed be controlled by an automated driving system attended by a human driver. The values for $t_{sr}$ are therefore lower than those for ETCS Level 3. The approaching time $t_{ap}$ becomes the coordinated approaching time $t_{coap}$. This latter is composed of two terms. The first term is called *coordination time* that is the time for a train to coordinate its speed with the train ahead, before reaching a minimum safe separation *Sm*. The second term is the time to cross the safety margin *Sm*. The coordinated approaching time depends on the operational conditions that a train and the train ahead satisfy. For each of the operational cases described in Figure 1 (b)-(h), the coordinated approaching time $t_{coap}$ has indeed a different mathematical expression. Such an expression is reported below for any of the operational cases defined for Virtual Coupling in the previous section. For the sake of clarity, expression numbering matches the numbering of the operational cases in Figure 1 (b)-(h).

(1) $$t_{coap} = \int_{VB}^{VA} \frac{m \cdot f_p}{m \cdot f_p \cdot b - R(v)} dv + \frac{S_m}{V_A}$$ for $V_B > V_A$

(2a) $$t_{coap} = \frac{X + S_m}{V_B} \qquad with\ X = (V_A - V_B) \cdot \Delta t$$ for $V_B < V_A$ in cruising mode

(2b) $$t_{coap} = \int_{VB}^{VB\prime} \frac{m \cdot f_p}{T(v) - R(v)} dv + \int_{VB\prime}^{VA} \frac{m \cdot f_p}{m \cdot f_p \cdot b - R(v)} dv + \frac{S_m}{V_A}$$ for $V_B < V_A$ in following mode

(3a) $$t_{coap} = \frac{S_m}{V_B}$$ for $V_B = V_A$ in coupled running

(3b) $$t_{coap} = \frac{Abd + S_m}{V_{B\prime}}, \qquad with\ Abd = \int_{VB\prime}^{0} \frac{m \cdot f_p}{m \cdot f_p \cdot b - R(v)} dv$$ for $V_B = V_A$ in coupled running/decoupling at points

(4) $$t_{coap} = \frac{Abd + S_m}{V_{B\prime}}, \qquad with\ Abd = \int_{VB\prime}^{0} \frac{m \cdot f_p}{m \cdot f_p \cdot b - R(v)} dv$$ for diverging junction

(5) $$t_{coap} = \frac{Abd + S_m}{V_{B\prime}}, \qquad with\ Abd = \int_{VB\prime}^{0} \frac{m \cdot f_p}{m \cdot f_p \cdot b - R(v)} dv$$ for converging junction

The variables $V_B$ and $V_{B\prime}$ are the speed of train B while $V_A$ is the speed of the leading train A. Variables $m$, $f_p$ and $b$, respectively represent the mass, the rotating mass factor and the service braking rate of train B. *T(v)* is the tractive effort-speed curve of train B. *R(v)* is the motion resistance curve of train B, which includes air resistances for wagons and traction unit, rolling resistances and line resistances due to track gradients and curvature. *Sm* represents a safety margin from a location which can be either an infrastructure element or the tale of the train ahead. Variable $\Delta t$ is the time interval over which a positive speed difference ($V_A$ - $V_B$) is kept by trains A and B.

Equation (1) provides the coordinated approaching time for operational *Case 1* when train B runs faster than the leader train A. The first term of the equation provides the coordination time for train B to brake from speed $V_B$ to the speed of the train ahead, $V_A$. The ratio $\frac{m \cdot f_p}{m \cdot f_p \cdot b - R(v)}$ is indeed the reciprocal of the train deceleration as provided by Newton's motion formula, where factor $m \cdot f_p \cdot b$ is the braking force applied. The second term of equation (1) is the time for train B to cross distance *Sm* after having coordinated with speed $V_A$.

Equation (2a) refers to *Case 2a* where train B moves at a desired speed $V_B$ which is lower than the speed $V_A$ of train A. If the two trains keep the speed difference ($V_A$ - $V_B$) over a time interval $\Delta t$, their separation will increase by a value $X = (V_A - V_B) \cdot \Delta t$. In this instance, $t_{coap}$ is the time for train B to travel over the distance X + *Sm* at speed $V_B$.

Equation (2b) provides the coordinated approaching time for *Case 2b* where the slower train B catches up with train A. Here, the coordination time needed by train B to reach the speed of the leading train A is given by the first two terms of the equation. The first term represents the time for train B to accelerate from speed $V_B$ to $V_{B'}$. The factor $\frac{m \cdot f_p}{T(v)-R(v)}$ is indeed the reciprocal of the acceleration as obtained from Newton's motion formula. The second term of the equation provides instead the time for train B to decelerate from speed $V_{B'}$ to $V_A$. The third term is again the time for train B to cross distance *Sm* after that it reached speed $V_A$.

Equation (3a) describes *Case 3a* where trains A and B move together at a minimum safety distance *Sm* from each other. The time $t_{coap}$ is simply computed as the time for train B to cross distance *Sm* at the coordinated running speed $V_B = V_A$.

Equation (3b) provides $t_{coap}$ at a junction for C*ase 3b* which considers trains to be separated by an absolute braking distance when approaching junctions. Being *Abd* the absolute braking distance from current speed $V_{B'}$, $t_{coap}$ is the time for train B to run over *Abd* plus distance *Sm*.

Equations (4) and (5) respectively referring to *Cases 4* and *5*, also impose an absolute braking distance separation at junctions. The expressions of $t_{coap}$ for these cases are similar to equation(3b). It is worth noticing that for *Cases 3b, 4* and *5*, $t_{coap}$ coincides with the approaching time of ETCS Level 3, since an absolute braking distance is imposed between trains.

## EGTRAIN: A MICROSCOPIC SIMULATION MODEL OF RAILWAY OPERATIONS

EGTRAIN (Environment for the desiGn and simulaTion of RAIlway Networks) is a time-driven microscopic simulation model of railway operations [16]. This is an object-oriented model developed in C++ representing in detail all elements of the railway network.

Input data are administered in four interacting modules. The infrastructure module builds on a directed-graph representation of the network where nodes are assets like switches, signals, balises and station platforms while links are tracks in between. Geographical coordinates of node assets are considered together with physical track characteristics such as gradients, speed limits and curvature radii. The rolling stock module collects physical and mechanical train features. Vehicle mass, braking rate, tractive effort-speed curve, motion resistance coefficients, train length and composition are all included here. The signaling system module stores data about operational principles and rules of the signaling and interlocking systems. Dependencies between signal aspects, speed codes of the Automatic Train Protection (ATP) system, are contained here including the communication of MA and train positioning between trains and the RBC. The timetabling module contains data about the train schedule such as planned departure/arrival times and minimum dwell times at stations. This module also takes as input stochastic distributions of entrance delays and station dwell times to assess impacts of disturbances on planned operations.

The core of EGTRAIN simulates train movements by an integration over time of the Newton's motion formula. At each time step, speed and position of trains are calculated and the status of the signaling system is updated accordingly so to respect safety constraints.

Outputs of the simulation are train diagrams (e.g. time-distance, speed-time), delay statistics, mechanical energy consumption and blocking time diagrams. An additional functionality for capacity analysis allows computing infrastructure occupation of railway traffic by means of the blocking time compression method [17] introduced by the UIC.

EGTRAIN features an API module for customizing functions, modifying model parameters and interface the simulation with external applications like optimization tools. Operational principles and capacity occupation models developed here for Virtual Coupling have been implemented in the API. Such implementation enables to assess the impacts of Virtual Coupling on capacity and potential benefits over ETCS Level 3.

## A COMPARATIVE ANALYSIS BETWEEN ETCS LEVEL 3 AND VIRTUAL COUPLING: THE CASE STUDY OF THE SOUTH WEST MAIN LINE IN THE UK

Operational principles and capacity occupation models developed for Virtual Coupling have been analyzed for a real case study. The railway corridor between London Waterloo (WTL) and Surbiton (SBT) on the South West Main Line (SWML) has been considered. The SWML is one of the busiest networks in the UK with more than 40 trains per hour which include intercity, regional, suburban and commuter trains. The stretch between WTL and SBT is about 20 Km long and develops over four tracks. Two tracks for the fast line and the other two for the slow line. A schematic layout of this corridor is provided in Figure 3.

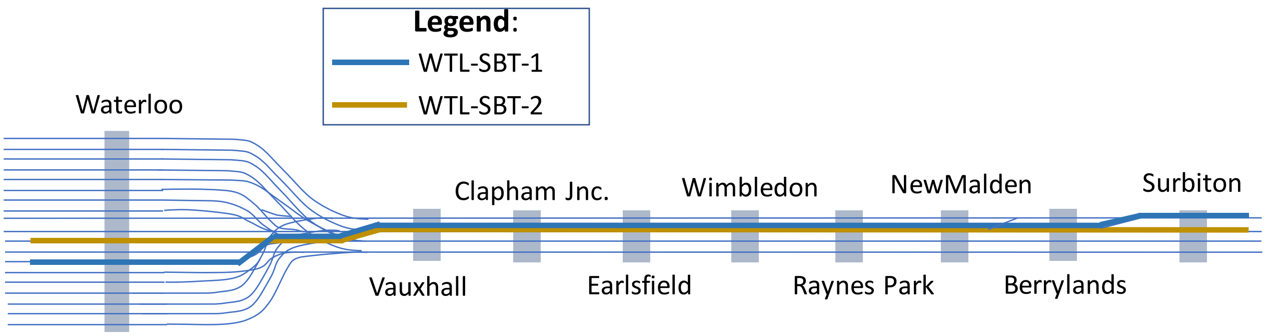


**Figure 3. Schematic layout of the London Waterloo – Surbiton railway corridor on the South West Main Line in the UK.**

A total of nine stations can be counted, including the main station of Waterloo with 19 platform tracks. The other stations have instead 4 tracks. The timetable currently operated on this network has a large number of services and complex train interactions which are not suitable to clearly understand train dynamics under Virtual Coupling. A timetable tailored to this purpose has been therefore considered which has two commuter lines operating between WTL and SBT. These lines are named WTL-SBT-1 and WTL-SBT-2, and their routes are illustrated in Figure 3 with a blue and a dark gold line, respectively. The two lines depart from different platform tracks at Waterloo, merge onto the same route just before Vauxhall until they split right after Berrylands. They depart from Waterloo with a scheduled frequency of 10 min which yields 6 trains per hour per line. A simulation period of 1 hour is considered. A total number of 12 trains (6 for WTL-SBT-1 and 6 for WTL-SBT-2) is therefore simulated. Both lines use the same rolling stock, a British Rail Class 455 with 8 cars. Thus, trains have the same free-flow speed-distance diagram on the shared portions of route, so reproducing the same effect of trains travelling under Virtual Coupling.

With the objective of assessing the impacts of Virtual Coupling on capacity, simulation experiments have been set up as follows. Free-flow train trajectories have been first simulated for all trains considering a 5% running time recovery. Blocking times have been computed for each train using the operational principles and the blocking time models defined in this paper for Virtual Coupling. Specifically, blocking times have been calculated for the configuration of Virtual Coupling that maximizes capacity performance. Operational case *3b* in Figure 1 has been hence disregarded from the analysis, since increasing separation at any junction (even if trains have the

same route) is capacity inefficient. This means that trains will travel in *coupled running*, unless diverging or converging junctions are approached.
Capacity occupation for the railway corridor has been then assessed by compressing computed blocking times using the UIC Code 406 method. The same procedure has been repeated for ETCS Level 3 to compare the two signaling systems and identify potential capacity benefits produced by Virtual Coupling.

Capacity performance of Virtual Coupling have been compared to ETCS Level 3 for a scenario where all trains have a scheduled stop of 75 s at 5 stations: Waterloo, Clapham Junction (CLPMJN), Wimbledon (WMBLD), Raynes Park (RNPK) and Surbiton.

The value for the sight and reaction time *tsr* used for ETCS Level 3 is 2 s while for Virtual Coupling is 0.5 s, since automated driving is assumed. A release time $t_{rel}$ of 7 s, a point setup time $t_s$ of 5 s and a safety margin *Sm* of 50 m are used for both signaling systems.

## Results

Results of the simulation experiments are shown in Figure 4. Compressed blocking time diagrams for the route of WTL-SBT-2 are reported in Figure 4 (a) and (b), for ETCS Level 3 and Virtual Coupling, respectively.

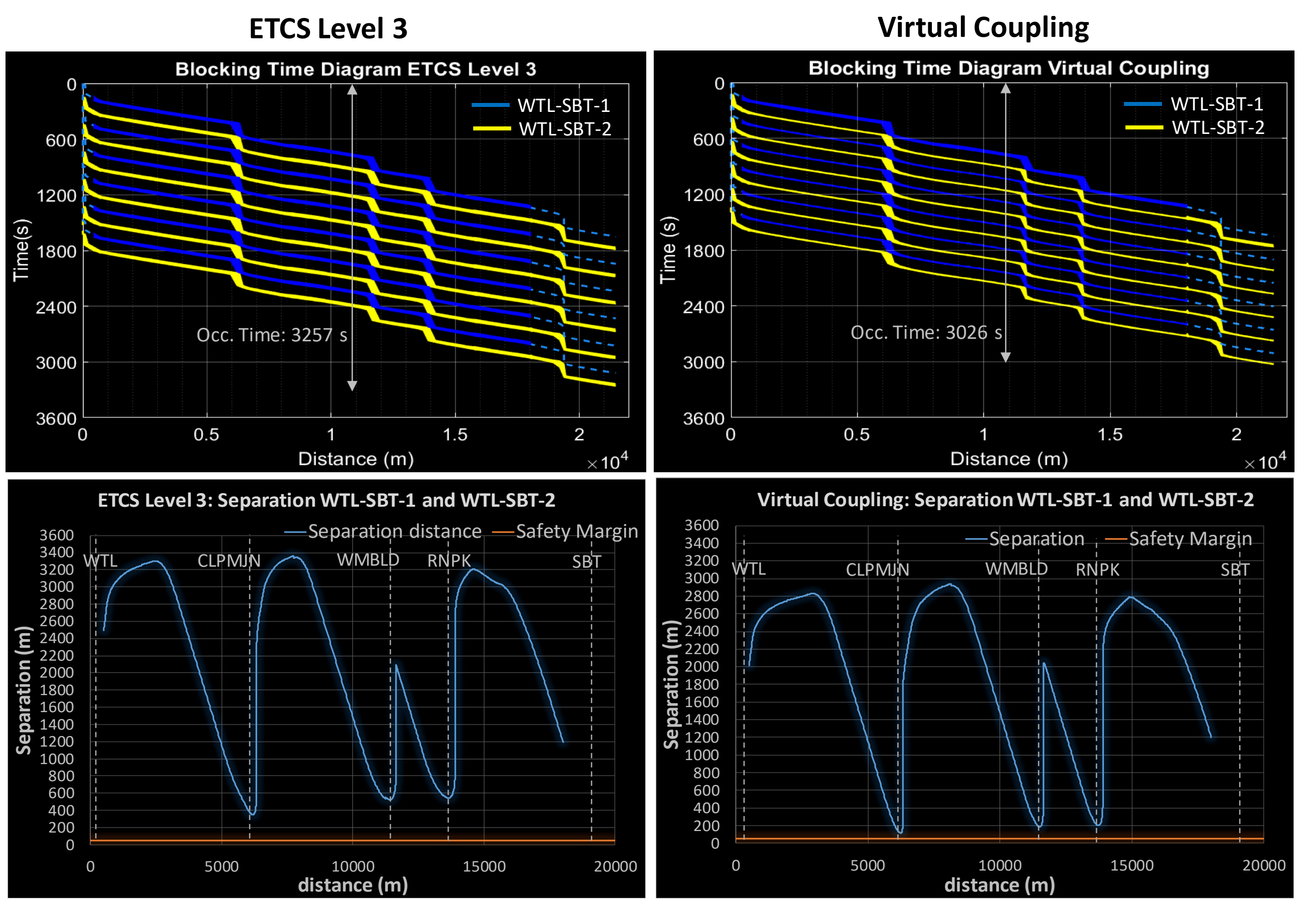


**Figure 4. Time-distance diagrams and train separation for conflict-free train movements under ETCS Level 3 and Virtual Coupling**

Trains of line WTL-SBT-1 are represented in light gold while those of line WTL-SBT-2 in blue. Blue dashed lines represent time-distance diagrams of WTL-SBT-1 trains, for those tracks that are not shared with line WTL-SBT-2. Compressed blocking time diagrams provide the infrastructure occupancy time of scheduled trains as defined by the UIC Code 406. The occupancy time is indeed the interval between the time the first train starts occupying the corridor and the last train ends occupying it. In other words, the occupancy time of a corridor is the minimum time all scheduled trains can operate along the corridor without any occupation conflict. As indicated by the light grey arrow, the occupancy time for ETCS Level 3 is 3257 s versus only 3026 s obtained for Virtual Coupling. Under Virtual Coupling the same set of trains can be operated in about 4 min less time than under ETCS Level 3, meaning a reduction of 7% in capacity utilization.

Separation distances (i.e. space headways) between two consecutive trains are instead illustrated in Figure 4 (c) and (d) for ETCS Level 3 and Virtual Coupling, respectively. These charts describe how separation between a WTL-SBT-1 train and a following WTL-SBT-2 varies along the shared part of route. Such a separation is compared with the minimum safety margin *Sm* (red horizontal line) which is reached when trains travel in a coupled platoon. The two trains depart at WTL 2 min after each other, which explains the large separation at the beginning of the corridor. This separation however decreases progressively reaching a minimum at any station with a scheduled stop. Every time the train ahead performs a service stop, the train behind has the chance of getting closer to it, so reducing the separation. For ETCS Level 3, train separation reaches its minimum at CLPJMN where trains travel at 348 m from each other, a distance dictated by the absolute braking curve. The minimum time headway between the two trains is instead 148 s. Under Virtual Coupling the minimum train separation is also reached at CLPJMN. However, in this case trains travel in a platoon at only 117 m from each other until the train behind breaks the platoon to perform a service stop. Virtual Coupling decreases train separation distance by 66% with respect to ETCS Level 3. Similar conclusions are drawn when it comes to time separation where Virtual Coupling allows a minimum time headway of 125 s, meaning a reduction of 23 s when compared to ETCS Level 3.

The separation distance increases again once the train behind performs a service stop at a station. The maximum train separation gets to a value of 3361 m for ETCS Level 3 and 2941 m for Virtual Coupling. Even the maximum train separation is decreased by 13% when trains move under Virtual Coupling.

## CONCLUSIONS

The ever-increasing need for capacity is leading the railway industry towards next-generation signaling systems going beyond traditional fixed-block operations to drastically reduce train separation. ETCS Level 3 introduces the concept of moving-block train operations where all track-side equipment is removed, and trains are separated by an absolute braking distance. On high-speed lines braking distances can however reach up to a 4-5 km, meaning large distances in between trains. The railway industry is hence investigating alternative concepts by which trains can be separated by a relative braking distance, as cars do on the road. Virtual Coupling relies on a V2V communication architecture that would allow trains to move synchronously in a platoon at a minimum safety separation distance. Travelling at a relative braking distance would of course introduce non-negligible safety risks, especially at diverging junctions where points should be moved and locked in between trains. On the other hand, substantial gains in capacity could be provided. It is still unclear whether capacity benefits expected from Virtual Coupling are sufficient to motivate the railway industry to invest in it, despite the questionable safety performance. So far, no research has been performed to address such a question, also because operational principles of Virtual Coupling have not been fully defined yet. This paper tries to give a concrete support to the railway industry by identifying impacts of Virtual Coupling on capacity and potential benefits over ETCS Level 3. Operational principles for Virtual Coupling have been here defined which set the basic conditions for a train to couple/uncouple to/from other trains travelling in a platoon. Several operational modes have also been introduced making analogies with platooning of autonomous road cars. A capacity occupation model has been developed for Virtual Coupling, by extending the blocking time theory with the operational principles here defined. These principles have been implemented together with the developed capacity occupation models in a microscopic railway simulator to assess capacity impacts of Virtual Coupling. The application to a railway corridor on the South West Main Line in the UK shows that Virtual Coupling reduces infrastructure occupation when compared to ETCS Level 3. Significant improvements are also observed in terms of train separation where Virtual Coupling decreases both minimum space and time headways by 66% and 16%, respectively.

These results provide a first insight on the benefits that Virtual Coupling could deliver and set the basis for future research in this direction. Operational principles and time occupation models defined in this paper pave the way for timetable design techniques for train operations under Virtual Coupling. Future research will investigate potential gains of Virtual Coupling on capacity and punctuality by referring to scenarios with perturbed operations. The development of train-following models will be considered to simulate and study dynamics of trains when moving in a coupled platoon. The possibility of using the developed capacity occupation models for timetable design and real-time rescheduling of train operations under Virtual Coupling will also be studied.

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