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A COMPARATIVE CAPACITY ANALYSIS OF VIRTUAL COUPLING RAILWAY OPERATIONS

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ABSTRACT

Virtual Coupling is a next-generation signalling concept conceived to increase railway capacity by bringing moving-block operations one step further to separating trains by a relative braking distance, like cars on the road. Thanks to a Vehicle-to-Vehicle (V2V) communication layer, trains can move in virtually coupled platoons which can be treated as single convoys at junctions to improve capacity. This concept however introduces the need for additional operational constraints, especially at diverging junctions, which could make capacity gains insufficient to justify investments. The railway industry is hence investigating the benefits that Virtual Coupling can offer with respect to moving-block and fixed-block signalling systems. This paper introduces operational principles and an innovative train-following model capturing operational states and corresponding transitions of Virtual Coupling train operations. A comparative capacity analysis is conducted for a portion of the South West Main Line in the UK. Promising results are obtained, showing that the biggest capacity gains of Virtual Coupling refer to operational scenarios normally found in practice with trains having service stops and using different routes. The analysis of multiple disturbed scenarios reveals that performance improvements of Virtual Coupling over moving-block are instead only marginal on low-speed networks.

1 INTRODUCTION

To address the ever-increasing need for capacity, the railway industry is investigating moving-block operations. In a moving-block setting, track-side equipment like signals and track detection sections are removed and all vital functions for Train Integrity Monitoring (TIM) and braking curve supervision are entirely transferred onboard. Signalling systems such as ETCS Level 3 allow moving-block operations by separating trains by an absolute braking distance, that is the distance needed by a train to fully stop from its current speed. Such a kind of separation does not provide substantial capacity benefits on high-speed lines where braking distances can reach up to 4-5 km at speeds of 300 km/h. For this reason, the concept of Virtual Coupling (VC) is being considered which entails trains being separated by a relative braking distance taking into account the braking rate of the train ahead. In such a setting trains can move synchronously with each other in a platoon (here called convoy) while keeping a safe separation that is independent from the speed they run at. Trains in a virtually coupled convoy can be therefore considered as a single trainset at junctions so to improve capacity at network bottlenecks. To deploy Virtual Coupling, a Vehicle-to-Vehicle (V2V) communication layer is necessary to allow trains exchanging dynamic information about position, speed and acceleration. Also, the very short separations between trains, make sight and reaction times of human train drivers too long to safely control a train moving in virtually coupled convoy. Automated driving by means of Automatic Train Operation (ATO) is hence necessary in this case.

Feasibility and capacity benefits of VC need accurate analysis, especially due to non-negligible safety risks arising at diverging junctions where points would need to be moved and locked in between consecutive trains. Safety requirements would indeed impose that trains in a virtually coupled convoy shall be outdistanced by an absolute braking distance at diverging junctions. Such a condition would potentially make VC capacity gains at bottlenecks not worth the investment when compared with plain moving block. A deeper investigation on operational and capacity impacts of Virtual Coupling is hence essential to understand the actual benefits that this concept can bring to the railway industry. So far, critical knowledge gaps still exist in literature. From a conceptual perspective, there are no definitive operational principles to safely run trains under Virtual Coupling. From the theoretical point of view instead, there are no models able to reliably describe VC operations so to estimate capacity benefits with respect to moving- and fixed-block signaling. This paper contributes to bridge both gaps by introducing operational principles for safe VC operations as well as a novel train-following model to assess capacity impacts of VC. Defined operational principles and the train-following model are embedded in a microscopic simulation environment of railway traffic and applied to a real railway corridor on the South West Main Line in the UK. A comparative capacity analysis has been then performed to quantify capacity benefits that VC provides over moving and fixed-block signaling systems. Section 2 provides a literature review on research performed on moving block train operations as well as a description of VC signaling architecture. Section 3 introduces novel operational principles and a train-following model to represent safe Virtual Coupling operations. Section 4 reports an application of the defined principles and models to a real case study, while illustrating results of a comparative capacity analysis. Conclusions are provided in Section 5.

2 VIRTUAL COUPLING SIGNALLING ARCHITECTURE

2.1 Literature review on Virtual Coupling operations

The main concept behind Virtual Coupling is that trains are linked in a convoy by means of a V2V communication layer and move synchronously together so to be treated as a single train at junctions with the aim of increasing capacity at bottlenecks. The whole idea of Virtual

Coupling mainly builds on the assumption that it is unrealistic that a train stops instantly, hence allowing for trains behind to safely arrest before a collision. The Institution of Railway Signal Engineers (IRSE 2016) state that the principal hurdle to such a concept does not derive from technology but from a missing definition of clear principles for safe and effective Virtual Coupling train operations. Emery (2010) proposes operational principles for a hybrid version of ETCS L2 and Level 3 aiming to separate trains by an absolute emergency braking distance in order to overcome safety risks that a relative braking distance separation would raise at diverging junctions. Although such a proposition could provide some capacity gains over ETCS Level 3, relying on an emergency braking can cause substantial discomfort to passengers while damaging the tracks and the rolling stock. Quaglietta (2018) provides an initial definition for safe Virtual Coupling operational principles and an infrastructure occupation model, showing that significant capacity gains can be achieved over ETCS Level 3 when separating trains by a relative braking distance. The model formulated in Quaglietta (2018) refers to nominal conflict-free train diagrams which do not consider dynamic interaction among trains. Major safety-related risks are however likely to be observed when trains interact within perturbed traffic conditions. Dynamic speed models adjusting train speeds as function of nearby trains' kinematics can hence provide more insight in the safety risks and the actual capacity benefits of Virtual Coupling. Ning (1998) proposes the adoption of Car-Following (CF) models to study train operations under relative-braking distance separation. Di Meo et al. (2019) are among the first to formulate operating modes of Virtual Coupling that are compatible with the ERTMS/ETCS standard specification while defining a train-coupling algorithm that is tested numerically versus different V2V communication latencies.

2.2 System architecture of Moving-Block and Virtual Coupling signalling

In moving-block railway operations trains are no longer separated by fixed block sections but by a braking distance plus a safety margin (S_m). As shown in **Figure 1a**, the European signalling system ETCS Level 3 (Theeg and Vlasenko, 2009) consents a moving-block implementation where vital track-side train detection and line-side signals are replaced by on-board devices.

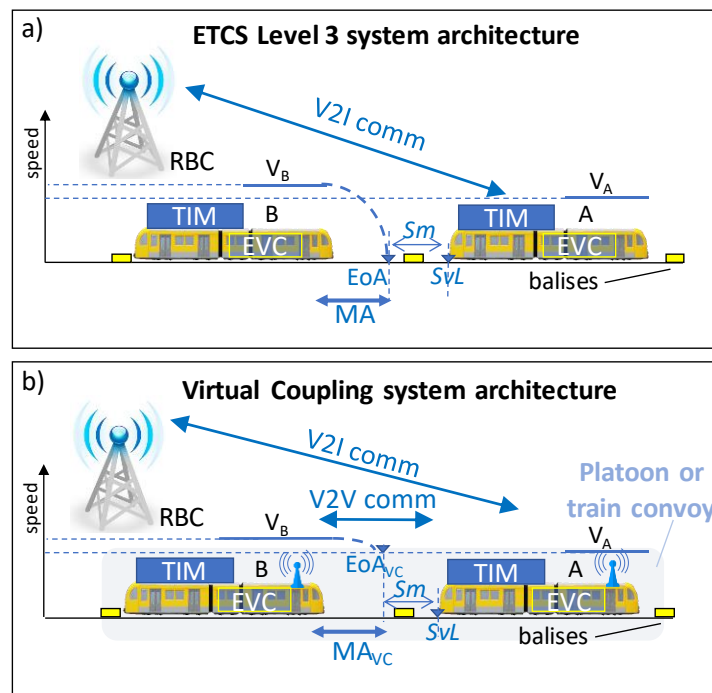


Figure 1. Schematic system architecture for ETCS Level 3 and Virtual Coupling.

Train position is monitored by means of odometers which are re-calibrated at each passage over a balise transponder. Train positions are regularly reported to the Radio-Block Centre (RBC) via a Vehicle-to-Infrastructure (V2I) communication. In return, the RBC sends a Movement Authority (MA), that is, the maximum distance that trains can safely run before encountering a danger point (e.g. a nearby train, a speed restriction and/or an unset switch). The MA is an encrypted message indicating the position of the danger point (called Supervised Location SvL) and the End of Authority (EoA) located at a safety margin (Sm) in rear of the SvL . This information is then used by the onboard European Vital Computer (EVC) to compute and safely supervise a braking curve not exceeding the EoA .

Integrity of the trainset is continuously checked by the Train Integrity Monitoring (TIM). The system architecture of Virtual Coupling is assumed in this paper to rely on the same technologies and functionalities of ETCS Level 3 plus an additional Vehicle-to-Vehicle (V2V) communication layer (see Figure 1b). The V2V layer enables a direct communication between neighbouring trains to exchange dynamic information about kinematic parameters (i.e. speed and acceleration), as well as their routes. Additional on-board antennas are considered to allow such a communication. Trains still report their positions to the RBC but in return they receive a MA which is later upgraded on board by combining it with the information deriving from the V2V communication layer. Such an upgraded MA is here called a Virtual Coupling Movement Authority (MA_{VC}) and contains the max safe running distance reported by the RBC as well as speeds, accelerations and routes exchanged by neighbouring trains, to enable virtual coupling “on-the-fly”. The end of MA_{VC} is here called the Virtual Coupling End of Authority (EoA_{VC}). Differently from the standard ETCS EoA (where the train is enforced to stop) or the Limit of Authority LoA , (where the target speed is instead not zero), the EoA_{VC} imposes that the train reaches the same speed of the train ahead (V_B needs to reach V_A) to allow virtual coupling. Clearly, the main purpose of the EoA_{VC} is to improve capacity utilisation by letting trains move together in a virtually-coupled *convoy*, while the standard EoA has a safety-critical role by guarding trains from any danger point on the route. In Virtual Coupling the EVC shall supervise both the EoA_{VC} (hence the relative braking curve) when two trains are trying to couple up, as well as the ETCS EoA (therefore the absolute braking curve) in case a train is running under ETCS Level 3 and/or two coupled trains need to split when approaching a potential danger point. Because of the very short driving reaction times required in Virtual Coupling an onboard Automatic Train Operation (ATO) system is essential. More details about the different operational modes identified for Virtual Coupling are provided in the next section.

3 VIRTUAL COUPLING OPERATIONS: PRINCIPLES AND MODELLING

3.1 Operational states and transitions

A model has been here developed that identifies five different operational states and corresponding transitions when running under Virtual Coupling. These are illustrated in the flow diagram in Figure 2. By default, a train is assumed to start operating under moving-block ETCS Level 3 (*State 1*). In such a state the EVC computes and supervises the absolute braking distance (Abd) to ensure that trains are always able to stop before the EoA at a safety margin Sm from the danger point SvL . When a train is approaching another one ahead, they can be virtually coupled only if they share the next portion of route. In such a case a transition from “ETCS Level 3 running” to a “Coupling” operational state (*State 2*) occurs. During the coupling state a train needs to catch up and coordinate its speed with the train ahead. The distance covered by a train to coordinate with the train ahead is called the *Coordination distance* (Cd). If for instance a train B has a speed V_B lower than the speed V_A of the train A ahead, then Cd includes the distance to catch the train ahead by accelerating to a higher speed V'_B plus the

distance to brake to the leader’s speed V_A (see State 2 in Figure 2). If train B is instead running faster than train A then Cd is merely the distance to slow down to the speed of train A. In the coupling state the EVC supervises a braking curve which is computed based on a predicted MA_{VC} . The MA_{VC} provided during coupling refers to the predicted *safe rear end* and speed of the leading train at the time the follower train has crossed the entire coordination distance Cd . In this state, the MA_{VC} hence contains not only the EoA_{VC} (referring to the tail of the leader at current time) but also a predicted threshold around the location where the trains will start being coupled (named $P_{coupling}$ in the remainder of the paper) and the coupling speed.

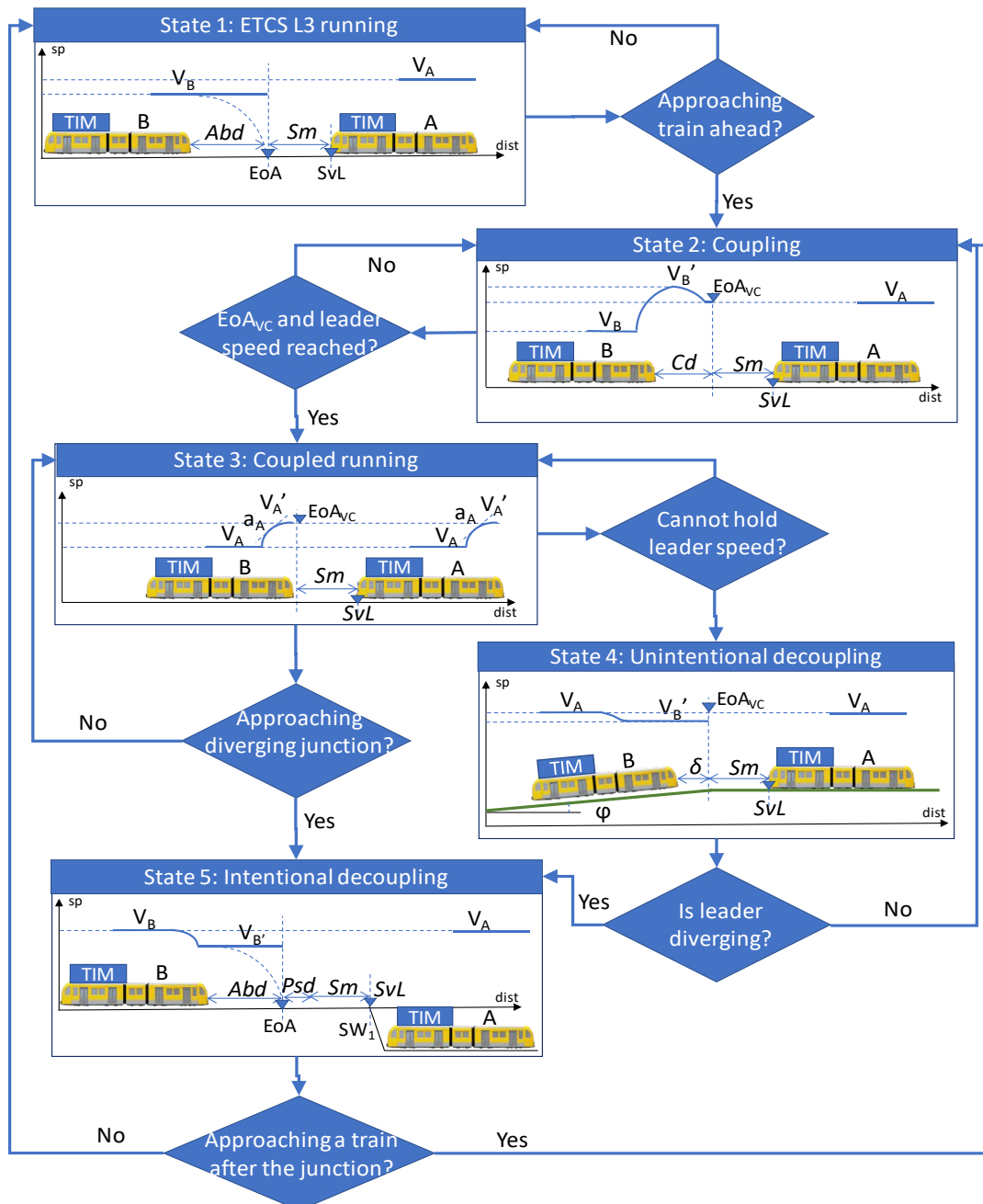


Figure 2. State flow-diagram of the Virtual Coupling train-following model.

Once a train achieves the leader’s speed within a given threshold from the predicted EoA_{VC} , then it transitions to a “Coupled running” state (State 3). In coupled running a train moves

synchronously with the leading train adopting a synchronized speed and acceleration, so to keep their separation within a certain threshold. Differently from the “Coupling” operational state, the EoA_{VC} transmitted to the follower does not refer to a prediction but to the last received information on speed, position and acceleration of the leading train. While in a “coupled running” state, two state transitions are possible, namely an “Unintentional decoupling” (State 4) or an “Intentional decoupling” (State 5). An unintentional decoupling is obtained when a train in coupled running cannot longer keep a close headway to the train ahead within the defined coupled threshold because for instance motion resistances (due to e.g. a steep uphill gradient ϕ) and/or traction power limitations. In this case the separation between the two trains increases by a distance δ (larger than the coupled threshold) (see State 4 in Figure 2).

When in unintentional decoupling a train aims to transition back to a “Coupling” state by driving at maximum power so to catch and couple back to the train ahead, whenever dynamic conditions of traction power and motion resistances allow to do so. A transition to an “Intentional decoupling” state happens instead when two coupled trains approach a diverging junction where the leading train switches to a different route. Such a situation leads to a safety-critical issue if the switch might not have enough time to be safely moved and locked in between the two trains, potentially causing derailments. Within a state of “intentional decoupling” the train behind needs to be decoupled from the leading train by being outdistanced by an absolute braking distance (Abd) plus the Point switching distance (Psd) necessary to move and lock the point in the correct position. In such a state, the EVC supervises the standard EoA since safety-critical track conditions apply. After the train has been intentionally decoupled from the train ahead, it keeps on running under ETCS Level 3 until potential conditions for coupling to a train occur.

The operational model for Virtual Coupling proposed in this paper aims at keeping a minimum separation between two consecutive trains, by driving a train at maximum power whenever there is a chance to couple with a train ahead. On tracks with a hilly elevation profile, such a model might hence show a sort of spring-mass behaviour where train separation alternatively increases and decreases depending on whether the gradient faced by a train allows it to keep the same speed and acceleration of the train ahead. Future research will be devoted to developing an cooperative control model that based on track and train characteristics adapts speeds and accelerations of all trains in a convoy to track a target train separation.

3.2 A multi-state train-following model for Virtual Coupling

The proposed operational model has been translated into a multi-state train-following model with the objective of simulating Virtual Coupling operations and assessing capacity impacts. This train-following model relies on a microscopic representation of the railway infrastructure, the rolling stock as well as the V2I (to/from the RBC) and the V2V (to/from other trains) communication layers. The railway network is modelled as a directed graph where nodes represent elements like balises, switches, stopping boards at platforms or line-side signals in case of fixed-block signalling systems. The links of the graph describe the railway tracks including physical attributes such as length, gradient, speed limit and curvature radius. The rolling stock data includes details relative to the tractive effort-speed curve of the traction unit, mass and length of the train, braking rates, and motion resistance coefficients. The train timetable is modelled in terms of detailed routes, stopping pattern and scheduled arrival/departure times at stations. Train movements are simulated by a time-driven integration of Newton’s motion formula (Hansen and Pachl, 2014). The RBC and the V2V communication layers are depicted considering all messages received/broadcasted from/to trains as well as the communication delay. The RBC receives position updates from trains and broadcasts the ETCS

MA. The V2V communication layer exchanges MA_{VC} messages among trains when they are in one of the defined Virtual Coupling operational states.

The following subsections present the motion equations and mathematical conditions describing train operations under Virtual Coupling for each of the defined five operational states.

3.2.1 State 1: ETCS Level 3 running

By default, trains start operating under ETCS Level 3 moving-block. The EVC hence supervises the EoA computing the braking Indication Point IP , i.e., the location where the train needs to start braking to reach the target speed at the End of Movement Authority. The IP at current speed v_0 is mathematically expressed as:

$$(1) \quad IP(v_0) = s_{target} - \int_{v_0}^{v_{target}} \frac{\rho M v}{\rho M b - R(v, \varphi)} dv$$

where s_{target} is the EoA if the target speed is zero or the LoA if the target speed is positive; v_{target} is the speed to be reached at the EoA/LoA, v_0 is the current train speed, M is the train mass, ρ the rotating mass factor, $b < 0$ the braking rate, $R(v, \varphi)$ denotes the motion resistance depending on the speed v , and the track gradient φ that may be piecewise constant. The integral in equation (1) merely represents the absolute braking distance to the EoA/LoA for a given current speed v_0 .

We implemented a finite-difference integration of Newton's motion formula with time step $\Delta t = t_k - t_{k-1}$, where we denote the current time as t_k . A train will be accelerating if at the previous time instant t_{k-1} its speed v_{k-1} is lower than the indicated max ceiling speed v_{lim} and its front position s_{k-1} has not yet reached point IP . Hence, for $s_{k-1} < IP$ and $v_{k-1} < v_{lim}$ the current speed v_k and front position s_k of the accelerating train are then computed from the previous time instant as (acceleration phase):

$$(2) \quad \begin{cases} v_k = v_{k-1} + \frac{T(v_{k-1}) - R(v_{k-1}, \varphi)}{\rho M} \cdot \Delta t \\ s_k = s_{k-1} + \frac{\rho M}{T(v_{k-1}) - R(v_{k-1}, \varphi)} \cdot v_{k-1} (v_k - v_{k-1}) \end{cases}$$

where $T(v_{k-1})$ represents the tractive effort of the train corresponding to the speed v_{k-1} at the previous time step. If at the previous time step the train is instead running faster than v_{lim} or its front position s_{k-1} is beyond point IP , the train enters a *braking phase* until it reaches the target speed before the *EoA/LoA*. The train motion for $s_{k-1} \geq IP$ or $v_{k-1} > v_{lim}$ is then computed as (braking phase):

$$(3) \quad \begin{cases} v_k = v_{k-1} + \frac{\rho M b - R(v_{k-1}, \varphi)}{\rho M} \cdot \Delta t \\ s_k = s_{k-1} + \frac{\rho M}{\rho M b - R(v_{k-1}, \varphi)} \cdot v_{k-1} \cdot (v_k - v_{k-1}) \end{cases}$$

with $b < 0$ the service braking rate. If at the previous time step the train has already reached the target speed (that can also represent the max ceiling speed indication v_{lim}) before reaching point IP , then the train will cruise at a constant speed v_{target} by selecting the tractive effort equal to the resistance. Hence, for $s_{k-1} < IP$ and $v_{k-1} = v_{target}$ the train motion is computed as (cruising phase):

$$(4) \quad \begin{cases} v_k = v_{k-1} \\ s_k = s_{k-1} + v_{k-1} \cdot \Delta t. \end{cases}$$

3.2.2 State 2: Coupling

When a train is approaching a train ahead sharing the next stretch of route then it transitions to a Coupling state receiving a MA_{VC} which contains not only the EoA_{VC} , referring to the current position of the leader's tail $Tail_{lead}$, but also the predicted location $P_{coupling}$ and the leader's speed v_{lead} at the time t_{coord} that the two trains are coordinated and can start being coupled (corresponding to the time lag needed by the follower to cross the coordination distance Cd). The predicted coupling point $P_{coupling}$ is therefore expressed as

$$(5) \quad P_{coupling} = EoA_{VC} + t_{coord} \cdot v_{lead},$$

with $EoA_{VC} = Tail_{lead} - Sm$ and Sm a safety margin, while t_{coord} can be computed as

$$(6) \quad t_{coord} = \begin{cases} \int_{v_{k-1}}^{V_{B'}} \frac{\rho M}{T(v) - R(v, \varphi)} dv + \int_{V_{B'}}^{v_{lead}} \frac{\rho M}{\rho M b - R(v, \varphi)} dv & \text{if } v_{k-1} \leq v_{lead} \\ \int_{v_{k-1}}^{v_{lead}} \frac{\rho M}{\rho M b - R(v, \varphi)} dv & \text{if } v_{k-1} > v_{lead} \end{cases}$$

If the train is running slower than the leader ($v_{k-1} \leq v_{lead}$) then t_{coord} includes the time to accelerate to a higher speed $V_{B'}$, to catch the leader and then brake to the leader's speed. Otherwise, it is merely the time to brake to the leader's speed.

3.2.3 State 3: Coupled running

A train transitions to a "Coupled running" state when at the previous time step it reached the predicted coupling location $P_{coupling}$ and the leader's speed v_{lead} within a certain thresholds for distance (th_s) and speed (th_v), respectively. Hence, if $|v_{k-1} - v_{lead}| \leq th_v$ and $|s_{k-1} - P_{coupling}| \leq th_s$ the train is coupled to the train ahead and from then the current speed v_k and front position s_k are computed according to the train-following equations

$$(7) \quad \begin{cases} v_k = v_{k-1} + a_{k-1} \Delta t \\ s_k = s_{k-1} + v_{k-1} \Delta t. \end{cases}$$

In coupled running, we assume that a train will accelerate at the same rate of the leader as long as such an acceleration or deceleration is between maximum (a_{k-1}^{max}) and minimum (a_{k-1}^{min}) acceleration boundaries which closely depend upon traction characteristics and motion resistances. However, in case the follower cannot brake as much as the leader, it is assumed that both trains brake at the maximum braking rate of the follower to keep a safe distance. Hence, the acceleration is computed as

$$(8) \quad a_{k-1} = \begin{cases} a_{k-1}^{max}, & \text{if } a_{lead} > a_{k-1}^{max} = \frac{T(v_{k-1}) - R(v_{k-1}, \varphi)}{\rho M} \\ a_{k-1}^{min}, & \text{if } a_{lead} < a_{k-1}^{min} = \frac{\rho M b_{max} - R(v_{k-1}, \varphi)}{\rho M} \\ a_{lead}, & \text{otherwise.} \end{cases}$$

3.2.4 State 4: Unintentional decoupling

If the acceleration of the leader exceeds the max acceleration of the follower (a_{k-1}^{max}) then the two trains will inevitably increase their separation. If at the previous time instant the front position s_{k-1} of a train goes beyond a certain threshold th_s from the tail of the leader $Tail_{lead}$, then it will unintentionally decouple and switch back to a Coupling state to reduce again the separation. So, if $|s_{k-1} - EoA_{VC}| > th_s$ with $EoA_{VC} = Tail_{lead} - Sm$ then switch to state 2 (Coupling).

3.2.5 State 5: Intentional decoupling

If two trains virtually coupled in a convoy are approaching a diverging junction, they need to be decoupled for safety reasons by allowing an absolute braking distance separation from the diverging switch, which represents the supervised location SvL . In this case the follower transitions to an ‘‘Intentional decoupling’’ state where the EVC computes a braking Indication Point $IP_{decoupling}$ where the train needs to start braking to decouple from the leader. The point $IP_{decoupling}$ is located at least at an absolute braking distance plus a safety margin plus the distance needed to move and lock the point (Psd) from the position of the diverging switch SvL ,

$$(9) \quad IP_{decoupling} = SvL - sm - Psd - \int_{v_{k-1}}^0 \frac{\rho M v}{\rho M b - R(v, \varphi)} dv,$$

with $b < 0$. Thus, intentional decoupling occurs if ($s_{k-1} \geq IP_{decoupling}$) and ($v_{k-1} > 0$) after which the train switches to State 1 (ETCS Level 3 running), which asserts that if at the previous time step t_{k-1} a train is moving ($v_{k-1} > 0$) and its front position s_{k-1} goes beyond location $IP_{decoupling}$, an intentional decoupling occurs which brings the train back to an ETCS Level 3 supervision.

4 CASE STUDY: A COMPARATIVE CAPACITY ANALYSIS

The described multi-state train-following model has been implemented in C++ and embedded in the microscopic railway simulation platform EGTRAIN (Quaglietta, 2014) to assess capacity impacts of Virtual Coupling. Several signalling systems can already be simulated in EGTRAIN among which fixed-block systems like the British three and four-aspect with Train Protection and Warning System (TPWS), ETCS Level 2 as well as the moving-block ETCS Level 3. A comparative analysis of these signalling systems has been performed versus Virtual Coupling to identify capacity benefits that this latter system can provide over state-of-the-practice signalling technologies. The analysis has been conducted for the 20 km long corridor between London Waterloo (WTL) and Surbiton (SBT) on the South West Main Line (SWML) in the UK (Figure 3). This corridor develops over four tracks with a very hilly elevation profile, especially after Clapham Junction. The maximum track speed limit on the corridor is 145 km/h.

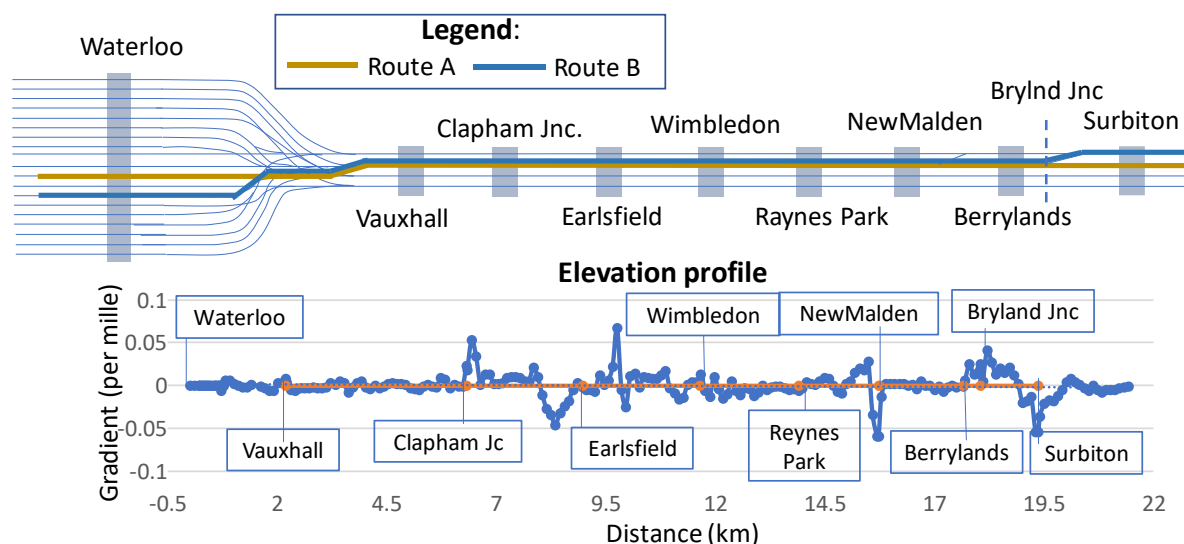


Figure 3. Layout and elevation profile of the Waterloo – Surbiton corridor on the South West Main Line in the UK.

The objective of our analysis is to understand operational implications of Virtual Coupling and the sensitivity of capacity gains to relevant service characteristics such as the choice of train routes, the presence/absence of service stops as well as service disturbances reducing running speeds. The choice of train routes might heavily affect capacity improvements, since if two virtually coupled trains have different routes, they will need to be outdistanced by an absolute braking curve at the diverging junction, potentially resulting in negligible capacity improvements of Virtual Coupling over ETCS Level 3. The same can happen when trains have service stops along their route, given that when approaching station areas their speeds need to be reduced at the point that the difference between relative and absolute braking distance separation might become too little to justify investments in Virtual Coupling. The same situation can verify when there are service disturbances such as temporary speed restrictions or rolling stock failures which can heavily reduce running speeds to such an extent that Virtual Coupling and ETCS Level 3 would result in a similar capacity performance. To this end, our investigation refers to two main scenarios. The first scenario considers only non-stop train services while the second scenario assumes that trains perform four service stops at Clapham Junction (CpJ), Wimbledon (Wbn), Raynes Park (RnP), and Surbiton (Sbn), respectively. All trains depart from Waterloo (Wtl) passing by timetabling locations such as Vauxhall (Vxl), Earlsfield (Eld), New Malden (NMn) and Berryland (Bld). For each scenario we then compare the case in which trains have the same route (*Route A* in Figure 3), versus the case in which trains operate on different routes (*Route A and B*) that are only partially shared and diverge at Berrylands Junction (BIJ). Then, for the case of stopping trains having the same route, several disturbed scenarios are analysed where different speed limitations are imposed to the first train due to a rolling stock malfunctioning from Raynes Park onwards. Such an analysis is addressed to determine the operational speed below which capacity performances of ETCS Level 3 and Virtual Coupling become comparable in disturbed service. Simulation experiments consider two consecutive trains, since this is sufficient to achieve our investigation objectives. Also, limiting the number of simulated trains allows a better understanding of how train dynamics under Virtual Coupling can affect capacity measures. The two train services (respectively named *A3-Wtl-Surbiton-1* and *A3-Wtl-Surbiton-2*) use the same rolling stock, namely a 161.8m long eight-car British Rail Class 455. In the experiments we assume that the second departing train enters the network as soon as the signalling system allows it. The MA and the MA_{VC} are broadcasted with an update interval of 1s and a communication delay of 1s. A safety margin

S_m of 50 m is used for both the EoA and the EoA_{VC}. A space tolerance (th_s) of 30 m and a speed tolerance (th_v) of 0.278 m/s (i.e. 1 km/h) have been adopted in the train-following model to identify whether a follower train is coupled/unintentionally decoupled to/from the train ahead. In ETCS Level 3 and Virtual Coupling, trains are automatically driven by ATO with a reaction time of 0.5 s. In addition, for these signalling systems we allow the two trains to enter a station area together and line up at the same platform to perform their stop. Such an assumption has been made to estimate capacity gains when using the entire potential of moving-block operations. For ETCS Level 2 and TPWS a human driver is instead considered with a sight and reaction time of 2.5 s. For these fixed-block signalling systems state-of-practice rules have been used for modelling stopping operations where a train cannot enter a platform if it is already occupied by another train.

4.1 Analysis of Virtual Coupling operational states

Simulation results produced by the Virtual Coupling multi-state train following model are reported for the first (non-stopping trains) and second scenario (stopping trains) in Figure 4.

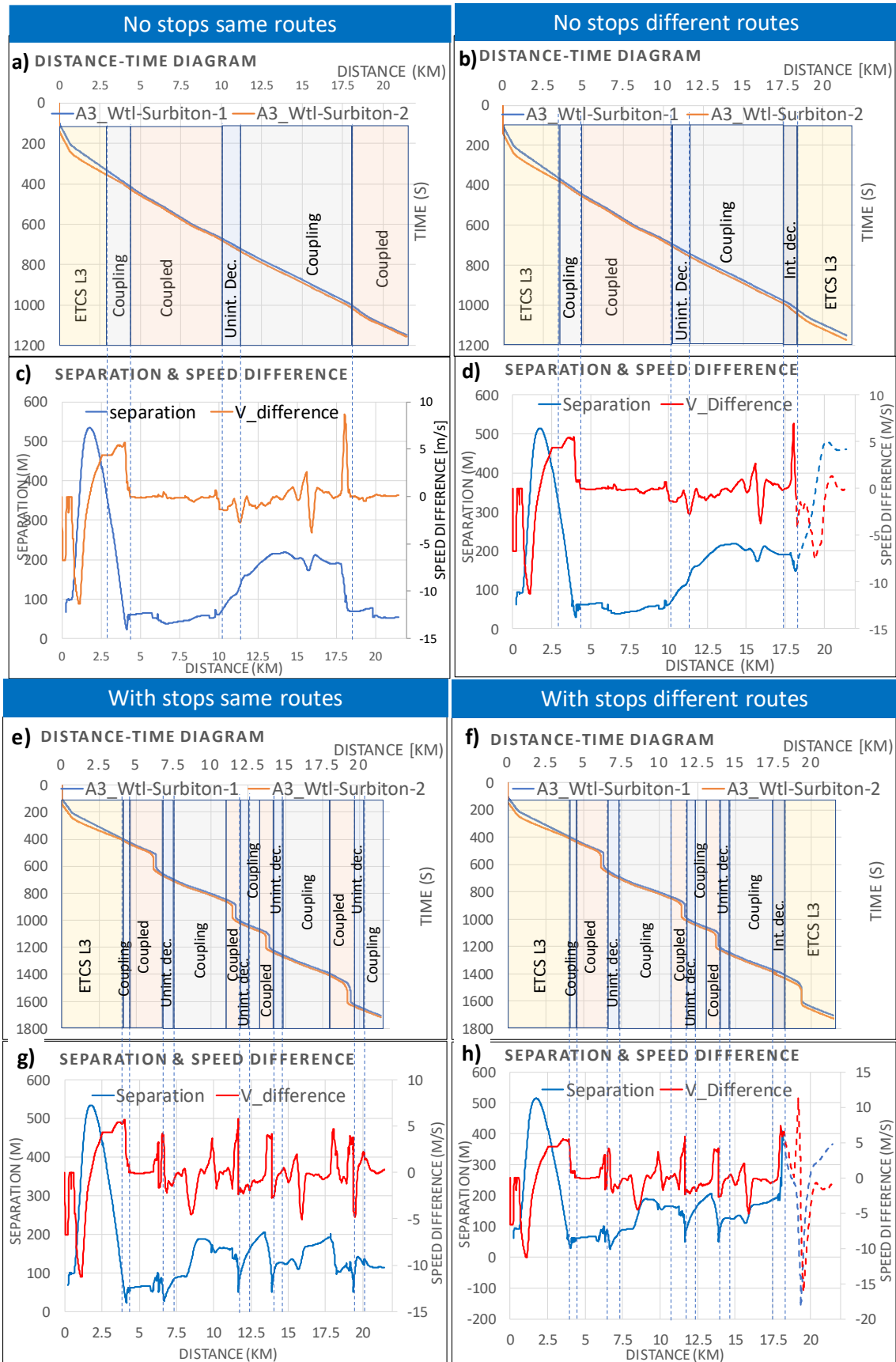


Figure 4. Distance-time diagram, separation and speed differentials between leader and follower for non-stopping and stopping trains with the same (left) or a different route (right).

Simulated time-distance diagrams of the two trains and the sequence of operational states of the follower (letters (a)-(b) for non stopping trains and (e)-(f) for stopping trains) are illustrated, together with the speed difference and the separation between the trains over their route (letters (c)-(d) for non stopping trains and (g)-(h) for stopping trains). The diagrams on the left-side refer to the case in which trains have the same route (*route A*), while those on the right-side relate to the case of different train routes where the leader runs over *route A* and the follower on *route B*. By default, the follower starts running under ETCS Level 3 and switches to a “coupling” state as soon as it approaches the train ahead. When the conditions for coupling are satisfied the train starts being “coupled” to the leader and moves with the same accelerations and speeds.

For the scenario of non stopping trains, speed differentials between leader and follower (red line in letters *c* and *d*) oscillate around zero when they are coupled. After Clapham Junction the follower enters a state of “unintentional decoupling”. This is mainly due to the very hilly track elevation profile which makes it hard for the follower on a steep uphill to keep up with the leader running instead on a flatter ground or even a downhill. As shown by the separation diagrams (blue lines in letters *c* and *d*), the unintentional separation between the two trains keeps however below 215 m at an average train speed of 22 m/s (≈ 80 km/h) that is anyway a much shorter separation when compared to existing fixed-block signalling systems and ETCS Level 3 (which would at least require 405 m for the same braking rate of 0.6 m/s^2). After having unintentionally decoupled, the follower switches again to a coupling state driving at maximum power so to catch up and couple with the leader.

In the scenario of stopping trains (*Figure 4e*), the follower unintentionally decouples from the leader every time it leaves a stopping station, since when moving from a standstill over an uphill it does not have sufficient speed to keep up with the leader. However, the follower couples back to the leader anytime this latter slows down to approach a stop. Such alternating transition between coupling and unintentionally decoupling is also due to the assumption of our model which aims at reducing train separation without optimally controlling speeds taking into account motion resistances, so to keep a constant separation between the trains.

When running on the same route the two trains will couple back as soon as track conditions allow, running as a coupled convoy until Surbiton (*Figure 4e* and *g*). When the trains have different routes instead (*Figure 4f* and *h*) the follower will intentionally decouple from the leader before the diverging junction in Berryland switching back to an ETCS Level 3 supervision.

Dashed lines (letter *h*) represent separation and speed differential after the two trains have decoupled and run over different routes.

4.2 Comparative capacity analysis

Figure 5 reports the outcome of a capacity analysis where Virtual Coupling (in blue) is compared to TPWS (gold), ETCS Level 2 (grey) and ETCS Level 3 (orange) in terms of train separation (solid lines) and headway (histograms) at the main interlocking areas. Results are provided for the two scenarios of non-stopping (top) and stopping trains (bottom) for the cases of trains having the same (letters a and c) or a different route (letters b and d). For all scenarios and cases, Virtual Coupling massively reduces train separations and time headways, when compared to the other signalling systems. In the case of non-stopping trains having the same route (Figure 5 a) Virtual Coupling reduces critical headways by 67%, 61% and 53% when compared with TPWS, ETCS Level 2 and ETCS Level 3, respectively. This translates into a corresponding separation decrease by 50%, 44% and 25%.

For non-stopping trains having different routes (Figure 5 b) Virtual Coupling decreases the maximum time headway by 60%, 51%, and 32%, meaning a reduction in train separation by 62%, 42% and 24%.

Capacity benefits of Virtual Coupling are even more significant for the scenario of stopping trains where we observed a very similar performance of TPWS and ETCS Level 2, especially in terms of train separation, given that their diagrams are almost entirely overlapped. In such a scenario and for the case of train having the same route (Figure 5 c) Virtual Coupling decreases the critical line headway by 63%, 61% and 28% when referenced to TPWS, ETCS Level 2 and Level 3, respectively. This translates into a reduction of the maximum train separation by 85%, 84%, and 40%. For the case of trains with different routes (Figure 5 d) reductions of line headways reach up to 79%, 77% and 43% when compared with TPWS, ETCS Level 2 and Level 3, respectively. Such results correspond to a decrease in the max separation by 85%, 64% and 43%. This represents a very promising result since the biggest capacity improvement provided by Virtual Coupling is obtained for the operational scenario more frequently applied in practice with stopping trains running over different routes.

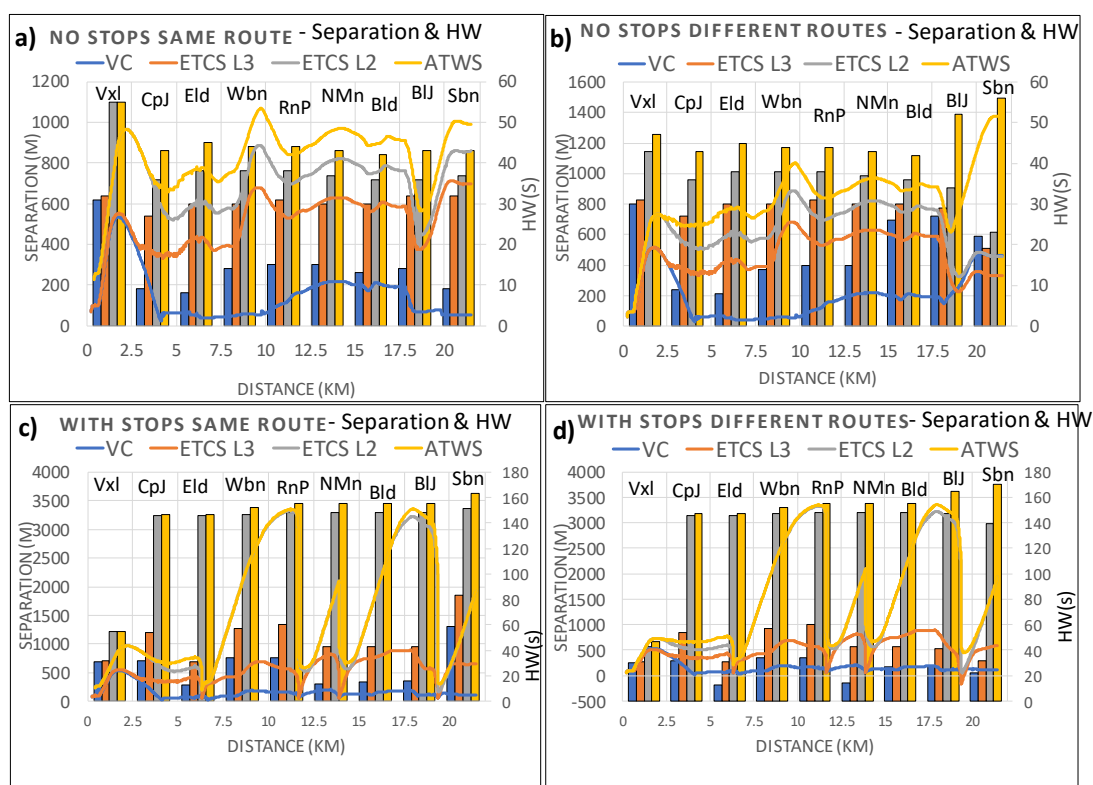


Figure 5. Train separation and time headway (HW) at main interlocking areas for non-stopping (top) and stopping trains (bottom) using the same (left) or a different route (right).

A further analysis has been carried out to identify advantages of Virtual Coupling over ETCS Level 3 moving-block under disturbances (e.g. a rolling stock malfunctioning) which limit the maximum speed of the leader in the area after Reynes Park. By simulating multiple disturbed scenarios imposing different speed limitations to the leader it is possible to grasp the operational speed below which absolute braking distances are comparable to relative braking distances, resulting in similar performances of Virtual Coupling and ETCS Level 3. Figure 6 illustrates such a comparison in terms of train separation over the entire line, for the case of stopping trains having the same route (so that the follower is forced to be behind the leader). Train separation under Virtual Coupling (blue line) and ETCS Level 3 (orange line) is reported for undisturbed operations (letter a) and for each disturbed scenario respectively limiting

leader's speed to 80 km/h (b), 60 km/h (c), 40 km/h (d) and 20 km/h (e). The disturbed area is represented in light yellow. Figure 6 f) provides instead the ratio η between the running time under Virtual Coupling and the running time under ETCS Level 3 of the follower for the undisturbed and the disturbed scenarios.

For Virtual Coupling the follower runs under ETCS Level 3 until Clapham Junction (km 6 on the route) where it finally catches the leader and couples to it. This explains why train separation diagrams of the two signalling systems are overlapped until Clapham. In the disturbed area, the difference in train separation between Virtual Coupling and ETCS Level 3 visibly decreases with the imposed speed limitation until it becomes marginal when the limit goes down to 20 km/h. When running at very low speeds the absolute and the relative braking distances become hence comparable, making advantages of Virtual Coupling negligible. Such a result is also observed in Figure 6 f) where the running time ratio η of the follower gradually increases when reducing the speed limitation until it reaches a value very close to 1 for a limit of 20 km/h. The performed analysis provides preliminary evidence that the concept of Virtual Coupling might be very beneficial over moving-block on high-speed, conventional and regional lines, while on suburban and rural networks with limited operational speeds, investments might not be worth it.

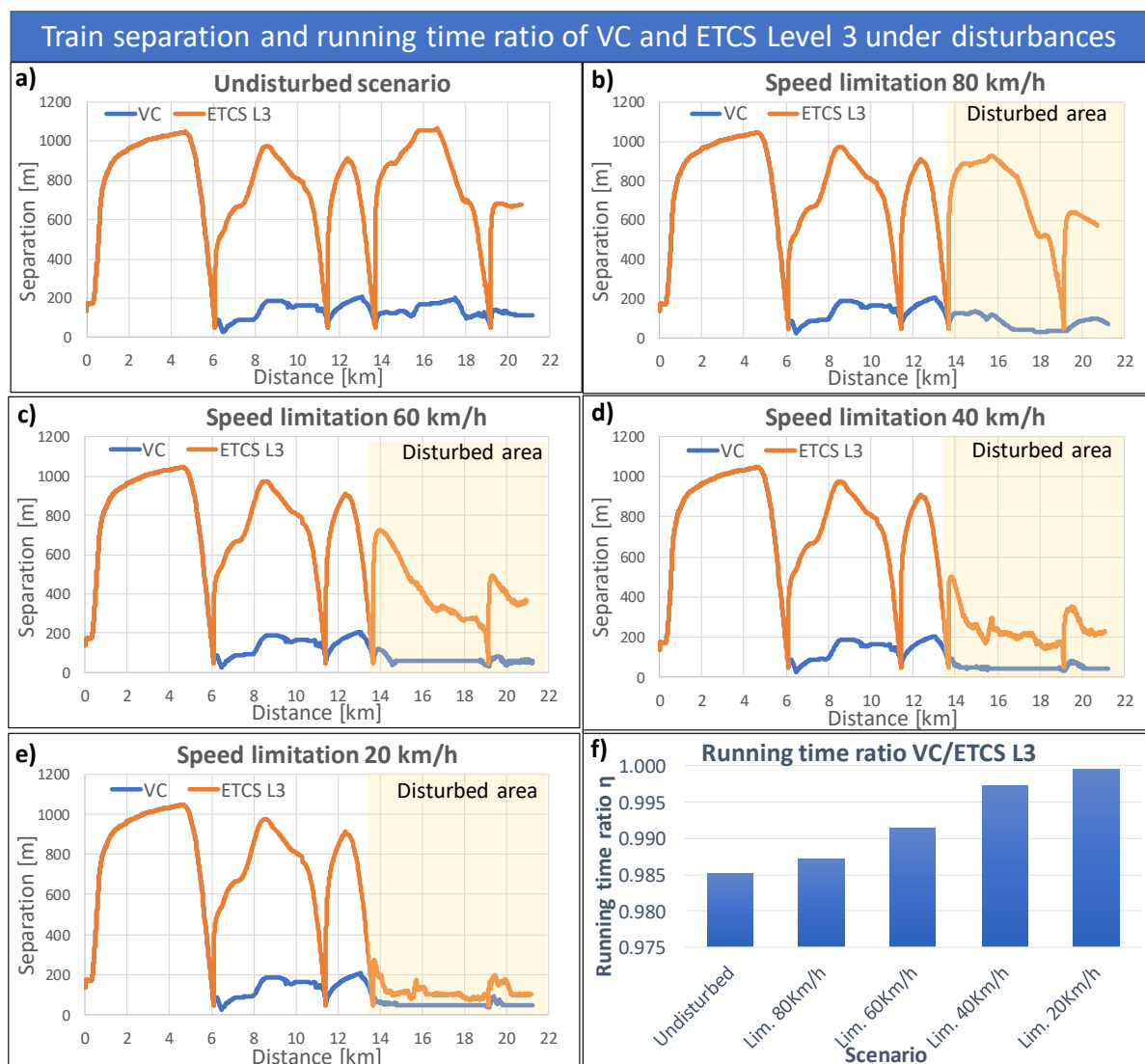


Figure 6. Comparison of train separation and running time ratio of the follower for Virtual Coupling and ETCS Level 3 under disturbances limiting the speed of the leader.

5 CONCLUSION

This paper performed a comparative analysis of the innovative concept of Virtual Coupling train operations to understand actual capacity benefits versus fixed-block and moving-block signalling systems. For the first time in the literature, safe operational scenarios and a novel multi-state train-following model were introduced to analyse train dynamics under different operational states and state transitions when running under Virtual Coupling. Several simulation experiments were performed on a stretch of the South West Main Line in the UK showing that Virtual Coupling outperforms fixed and moving-block signalling systems in terms of train separation and line headways for all the operational scenarios considered of stopping and non-stopping trains and for both cases of trains having the same or a different route. A very promising result is that the biggest capacity gains are observed for the operational scenario more frequently seen in practice of stopping trains having different routes, where Virtual Coupling reduces line headways by 43% over moving-block. An analysis of multiple disturbed scenarios limiting the maximum speed of the leader has then shown that absolute and relative braking distances become comparable at low running speeds below 40 km/h, resulting in very similar performances of moving-block and Virtual Coupling. Such a result suggests that Virtual Coupling investments might be worth on high-speed, conventional and regional lines and not on low-speed suburban and rural networks.

Future research will be devoted to analysing virtual coupling of multiple trains having different rolling stock characteristics and understanding how heterogeneity of braking performance can affect capacity gains. Also, propagation of train delays under virtual coupling will be investigated by considering stochastic distributions of dwell and running times. Another line of research will be looking instead at different operational procedures which for instance consider coupling/decoupling of trains only at stations. On some railway segments, like regional and urban lines, distances between stations might indeed be not sufficiently long to allow for coupling/decoupling on-the-run. In such cases is therefore necessary to study implications on capacity when virtual coupling can only be performed when trains are at a standstill at stations.

6 ACKNOWLEDGMENTS

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