Article:

Ketphat, N, Whiteing, A orcid.org/0000-0003-3480-1255 and Liu, R orcid.org/0000-0003-0627-3184 (2022) State movement for controlling trains operating under the virtual coupling system. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 236 (2). pp. 172-182. ISSN 0954-4097

https://doi.org/10.1177/09544097211043747

State Movement for Controlling Trains Operating under The Virtual Coupling System

Naphat Ketphat [a,1], Anthony Whiteing [a,2], Ronghui Liu [a,3]

[a] Institute of Transport Studies (ITS)
University of Leeds, Leeds, UK, LS2 9JT
[1] E-mail: tsnk@leeds.ac.uk, Phone: +44(0)752 179 5941
[2] E-mail: A.E.Whiteing@its.leeds.ac.uk, Phone: +44(0)113 343 5359
[3] E-mail: R.Liu@its.leeds.ac.uk, Phone: +44(0)113 343 5338

Abstract

Train Virtual Coupling System (VCS) has been proposed as a new signalling system for controlling trains by building a group of trains as convoys in order to increase line's capacity. This is achieved because the consecutive trains under the VCS is separated only by a relative braking distance; this is much shorter than the separation distance required in the Fixed Block Signaling (FBS) and Moving Block Signaling systems (MBS). In order to achieve the high capacity obtained from the VCS, the trains in a virtually coupled convoy should keep at a distance as close to the relative braking distance as possible and run at the same speed for maintaining the safe distance between them.

In this paper, we propose a distance and velocity difference approach and introduce the multiple state movements for stimulating train's movement under the VCS. The simulated results show that the capacity can be significantly increased and maximized in which the actual separation distance between trains when they are in convoy state is slightly longer than the minimum safe distance. It could be ensured that the train has proceeded safely in that the actual separation distance is surely longer than the minimum safe distance throughout the operation time period. In addition, we show that the trains can also proceed smoothly, in that a following train catches up with its leading train and joined in the convoy with a stable movement.

Keywords — virtual coupling, signalling system, separation distance, merging, convoy, capacity, stability, safety.

1 Introduction

The Virtual Coupling System (VCS) has been introduced as a new way for controlling trains by creating the multiple convoys and reducing the distance between successive trains (1). A train could follows each other and maintain safe distance from a train ahead. The safe distance between them must be not less than the relative braking distance which relies on the relative velocities of both trains and braking distance of the following train (Eq. (1)). The line capacity could be increased due to a short separation distance between trains which is normally shorter than the separation distance required for FBS and MBS. The basic concept to control a following train's movement under the VCS is to stimulate the train decelerates or accelerate depending on the distance separated from its front train. A following train is forced to decelerate if the distance separated from a leading train is shorter than the minimum safe distance. It will be forced to accelerate when the distance between them is longer than the minimum safe distance, and to operates by constant velocity if the actual gap is in the acceptable tolerance (2-3). The benefit of the VCS will be limited if the separation distance between trains is extremely longer than the minimum safe distance. The trains might not operate safely if the actual gap between them is shorter than the required braking distance. In that the train has tried to adjust the distance separated from a leading train equaling to the minimum safe distance, it could not obtain stable travelling causing higher energy consumption (4-5). To deal with these shortcomings, trains in a virtually coupled convoy should keep at a separation distance as close to the relative braking distance as possible and run at the same speed. In addition, it is important to ensured that a distance between them is not shorter than minimum safe distance that may cause an unsafe situation. Many approaches has been introduced for controlling trains under the VCS but these could be used to control trains only when they have operated along the plain line. In addition, in most previous approaches, the impact of junction is ignored.

2 Train's movement under the VCS

2.1 The concept of the VCS

The concept of train virtual coupling system is to group the trains as a convoy which can be merged or split trains during transit. Based on this system, a train can run closer following its leader running on the same track. Two successive trains must be separated by a sufficient separation distance in order to ensure that the following train has a sufficient braking distance and can stop before reaching the leading train in the case that the leading train applies brake (1). There are mainly two sub-controls included in the system (6). In the first control, non-convoy state, the trains has operated under the MBS where the distance between trains must be longer than the absolute braking distance. Real-time velocity and position of each train have continuously been sent to the control centre. Then, all trains data within control area will be used to calculate the Movement Authority (MA) sending back to each train. After that, the velocity profile is calculated by the on-board computer informing the driver about the allowable maximum velocity and the current position of the object in front.

The second control will be applied when a train start controlled by the VCS. A following train will merge itself to a group of trains or a train in front by sending the convoy proposal to its leader. A leading train can either accept or reject the convoy proposal. The first train in convoy is still controlled by MBS while the rest in convoy operate under the VCS. The safety of VCS relies on the safety integrity level of the communication between trains. In the case that communication between trains is lost, the train operation must be switched back to non-convoy state.

2.2 Controlling trains under the VCS

2.2.1 Minimum safe distance under the VCS

The minimum safe distance under the VCS ($\Delta x_k^{VCS}(t)$) relies on the relative velocities of the leading (v_k) and the following train (v_{k+1}), the braking capability of the following train (b_{k+1}^{max}), and safety margin (SM) provided for preventing any error due to system and communication delay. The SM is the distance compensated due to driver response time, system operation and system delay time such as data transmission, Euro-balise spacing, etc. (7). It can be calculated by using the equation below (8).

$$\Delta x_k^{VCS}(t) = \frac{v_{k+1}^2(t) - v_k^2(t)}{2b_{k+1}^{max}} + SM \quad (1)$$

2.2.2 Operating along the plain line

To control a train operating under VCS, many approaches have been introduced. Many theories have been applied as a base model for controlling the following train movement such as discrete event model (9), discrete-time model (10), cellular automation model (11), velocity difference model (12) and the theory of car following model (1, 4, 13-14). Especially, the car-following model can be considered as the famous model used as the based model improved for simulating a following train's movement under the VCS. This is because the movement of a following train when it has proceeded under the VCS is similar to the car proceeding on highway road. Due to a wider range of deceleration and acceleration of car movement in road traffic, the car-following model might not be well described train's movement. Li and Guan (4) introduced an additional term into the traditional optimal velocity car-following model for limiting the range of deceleration and acceleration. The simulated results shows that their proposed model is effective to simulate a following train's movement in that the rate of acceleration/deceleration are limited in realistic range. Similar to the study by Li, Gao (15) in which the rang of acceleration and deceleration can be limited by modifying the velocity function in the optimal velocity car-following model. According to their simulated results, the region of deceleration and acceleration is reduced improving smoothness of train's velocity profile. One obvious problem seen in the previous model based on the car following model is that the train could not obtain stable travelling due to the fluctuation of optimal velocity computed by these models. Ye, Li (5) proposed a new model to control train's movement in order to reduce the velocity fluctuation. Their proposed model could be effectively used for controlling a following by helping a train obtaining stable travelling. Moreover, these studies prove the benefit of the VCS compared to other signalling system. The line capacity is increased due to the decrease of separation distance between a couple of trains.

Another effective theory used as a base model for controlling train's movement is the distance difference control model. The condition is to adjust the actual distance between trains to be as close as possible to the minimum safe distance. For example, the study by Li, Gao (16) which proposed a new railway traffic model under the MBS. According to their proposed model, when a leading train accelerates increasing the distance separated from a following train, a following train will be forced to accelerate as well when the actual distance between them is longer than minimum safe distance. When a leading train decelerates shortening the distance from a train behind, a following train will decelerate to the same velocity when the separation distance between them is shorter than minimum safe distance. Cao, Xu (17) also use the distance control model to control a following train's movement. They obtained the same result as both models mentioned above in which a following train has operated according to the difference separated from its front train. Not only the distance difference but also the velocity difference between trains impacts the following train's movement (18). Pan and Zheng (19) introduced three control laws based on the velocity and distance difference concept to simulate train's operation under the MBS. Following their proposed model, the acceleration rate depends on both velocity and distance difference. But when the distance between trains is shorter than minimum safe distance, the following train will be forced to slow down by a deceleration rate that relies on its operating velocity only. Henke and Trachtler (12) proposed the distance and velocity difference control laws to simulate following train's movement under the VCS. The velocity difference between trains to be merged into the same convoys consists of two states including high and low velocity difference. Based on their proposed model, the train has operated safely in which the distance between successive trains is surely longer than the relative braking distance. Quaglietta and Goverde (20) proposed the control law to transfer trains into the convoy state. They recommend that a couple of trains will be transferred into the convoy state when the difference between the actual gap and minimum safe distance is smaller than distance tolerance and velocity difference between them must be not higher than velocity different limit. Ketphat, Whiteing (21) modified the equation to calculate the minimum safe distance as the range of safe distance and introduced the movement conditions to control trains under the VCS. Their simulated results showed that the route capacity is increased. However, It is restricted that, in the convoy state, following train is not simulated and not stimulated to accelerate or decelerate instantly limiting the benefit of the VCS. In addition, the movement of trains when passing a junction is ignored.

2.2.3 Passing a junction

There is no clear approach introduced to control a group of trains when passing a junction. In the case that the separation distance before passing a junction is shorter than the minimum safe distance required for passing a junction, a following train has to slow down and operate at a lower velocity than its leader for lengthening the gap separated from its front train (6). Similarly, the concept to control trains under the VCS to pass a junction reviewed by Rabouël, Robin (22) and Schumann (23) argued that the safe separation distance between trains must be extended before passing a junction in order to allow the junction's equipment switched back to the right position before allowing another train passing.

3 The proposed approach to control trains operating under the VCS

3.1 Modified minimum safe distance

There are 3 moving states under the VCS including merging, convoy, and splitting states. The minimum safe distance as shown in Equation (1) is considered as the reference line from which a following train must compute its optimal acceleration and velocity in order to adjust the gap separation from the front train. A following train is forced to decelerate to the same velocity as its front train when the distance between them ($\Delta x_k(t)$) becomes equal to the required minimum safe distance ($\Delta x_k^{min}(t)$). However, due to the time step (Δt) delaying the updated position and velocity of a train, a following train could not instantly decelerate although the distance separated from its leading train is shorter than the minimum safe distance. In addition, due to a higher velocity that a following train decelerate from, the travelling distance of a following train during the transferring state is longer than the distance covered by a leading train. To avoid this unsafe situation during the transferring state, additional term will be added into the traditional minimum safe distance's equation. To improve the equation used to calculate the minimum safe distance, we now consider the movement behaviour of a following train in 2 critical situations including when trains are transferred from merging to the convoy state and when the leading train decelerates while it is in the convoy state. For the first situation, the relative braking distance should be compensated by $1.5((v_{k+1}(t) - (v_k(t))\Delta t$ while in the second situation when a leading train decelerates when it is in the convoy state, $\left[\frac{1}{2}b_k^{max}(\Delta t)^2\right] + v_k(t)\Delta t$ should be added to the original equation (Equation

(1)) for preventing unsafe situation. Comparing between 2 critical situation, the compensated distance from the second situation is more critical that results a higher compensated distance. Thus, the modified safe distance between trains under the VCS can be calculated by

$$\Delta x_k^{smin}(t) = \left(\frac{(v_{k+1}(t))^2 - (v_k(t))^2}{2b_{k+1}^{max}} + SM\right) + \Delta x_k^{cps}(t) \tag{2}$$

Where $\Delta x_k^{cps}(t)$ is the compensated distance provided for ensuring safe distance between trains. It could be computed by

$$\Delta x_k^{cps}(t) = \left[\frac{1}{2} b_k^{max} (\Delta t)^2\right] + v_k(t)\Delta t \tag{3}$$

When a group of trains built into the same convoy is approaching a diverging junction, the trains might need to slow down for passing junction by the velocity not higher than velocity limited at the junction (v^{maxp}). A following train needs to decelerates for lengthening the separation distance away from its leading train. The minimum safe distance between trains required when passing a diverging junction is normally longer than the minimum safe distance required when proceeding along plain line due to the impact from the leading train's length (l_k) and junction operation time (T^{pnt}). A leading train must pass a junction by its whole length before allowing a junction equipment moved back to the required position. Thus, the minimum safe distance between trains when passing a diverging junction can be calculated by using the Equation (4).

$$\Delta x_k^{mdvr} = \left(\frac{(v^{maxp})^2}{2b_{k+1}^{max}} + SM\right) + \left(T^{pnt} v^{maxp}\right) + l_k \tag{4}$$

It is different when a group of trains is approaching a converging junction. The minimum safe distance when trains passing a converging junction is the same as the minimum safe distance for plain line shown in the Equation (1).

3.2 Optimal splitting point

Based on the assumption that a train should be able to stop before reaching a junction if the switch point cannot be completely locked at its required position, the safe zone in front of junction is created. The safe zone in front of the junction is equal to the absolute braking distance which is directly related to a permissible velocity that a train could pass a junction (v^{maxp}) and maximum braking rate (b^{max}). When a group of trains is approaching a junction which normally requires a longer safe distance, a following train will adjust its velocity in order to split out from convoy. It is noted that the splitting process has to be finished before reaching the safe zone. Thus, to split out and obtain enough distance away from a leading train for passing a junction, a following train should start splitting when it reaches the optimal splitting point.

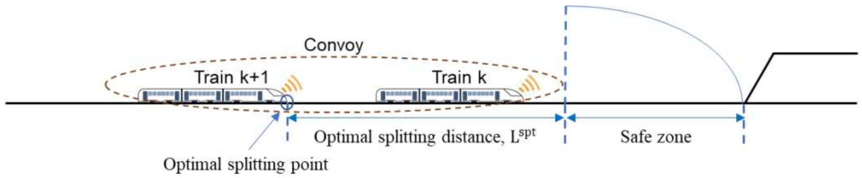


Figure 1: Safe zone and optimal splitting point

It is measured from the beginning of the safe zone (Figure 1). The distance for splitting or the splitting zone (L^{spt}) is expressed by using the Equation (5).

$$L^{spt} = v_k(t^{dec}_{k+1} + t^{cst}_{k+1}) \quad (5)$$

Where t^{dec}_{k+1} refers to the total time that a following train decelerate from its current velocity (v^{con}_{k+1}) to its splitting velocity (v^{spt}_{k+1}). It can be calculated by $t^{dec}_{k+1} = \frac{v^{con}_{k+1} - v^{spt}_{k+1}}{b^{max}_{k+1}}$. And t^{cst}_{k+1}refers to the total time for splitting out from the convoy which is related to the distance needed to be expanded, and the splitting velocity of the leading (v^{spt}_k) and the following train (v^{spt}_{k+1}). It can be calculated by $t^{cst}_{k+1} = \frac{\Delta x^{cst}_k}{(v^{spt}_k - v^{spt}_{k+1})}$.

For example, Assuming that a couple of trains under the VCS are approaching junction and then will continue on different routes. Both trains have operated by the same velocity at 60 m/s maintain 3 km separation distance between them. If the minimum safe distance for passing the junction is 3.8 km. So, the distance needed to be extended before entering the safe zone (Δx^{exd}_1) is 800 m. The following train 2 will start splitting by decelerating from 60 m/s to 50 m/s. The total time that the train 2 decelerates to its splitting velocity (v^{spt}_2) is $\Delta t^{dec}_2 = \frac{v^{spt}_2 - v^{spt}_2}{b^{max}_2} = \frac{60 - 50}{0.5} = 20$ sec. So, the travelling distance between trains in this state is $\Delta x^{dec}_1 = \frac{1}{2} b^{max}_2 (t^{dec}_2)^2 = 100$ m. The distance needed to be extended in the next step is $\Delta x^{cst}_1 = \Delta x^{exd}_1 - \Delta x^{dec}_1 = 800 - 700 = 100$ m. The total time that the distance between trains has be extended for 700 m. is $\Delta t^{cst}_2 = \frac{\Delta x^{cst}_1}{(v^{spt}_1 - v^{spt}_2)} = \frac{700}{(60 - 50)} = 70$ sec. Thus, the estimated splitting zone's length with 10 m/s. velocity gap is $\Delta x^{spt}_2 = 60(20 + 70) = 5400$ m. It means that the optimal point that the following train 2 should start splitting is approximately 5.4 km away from the safe zone.

3.3 State movement for controlling trains under the VCS

There are 3 states included when controlling trains operating under the VCS;

3.3.1 Merging state

Any couple of train has to adjust velocity ready to be built into the same convoy. The different merging velocities between two trains (Δv_k^{mer}) is set as target velocity in that the trains need to adjust to. A leading train's velocity might be decelerated, accelerated, or maintained while a following train's velocity will be adapted relaying on merging velocity of a leading train (v_k^{mer}) and the merging velocity difference (Δv_k^{mer}). Thus, the merging velocity of the following train is expressed by

$$v_{k+1}^{mer} = v_k^{mer} + \Delta v_k^{mer} \qquad (6)$$

It is suggested that a leading train should proceed by constant velocity through the merging state. It will be allowed to accelerate or decelerate after transferred into the convoy state. If a leading train's velocity is changed while it is in the merging state, a following train's merging velocity will be computed again using the Equation (6).

3.3.2 Convoy state

A couple of trains will be transferred to the convoy state when the separation distance between them is equal to or slightly shorter than the modified minimum separation distance stated in the Equation (2). A couple of trains will be transferred and convoyed based on the states shown in the Table 1. A following train will operate relying on the velocity and distance difference compared with its leading train.

Table 1: Optimal acceleration rate during the merging and convoy states

State		Distance difference		Vel. difference	Acceleration	Remark
1	Splitting state	$\Delta x_k(t) > \Delta x_k^{smin}(t)$	AND	$v_k(t) > v_{k+1}(t)$	a_{k+1}^{opt}	Eq. (7)
2	Convoy state	$\Delta x_k(t) > \Delta x_k^{smin}(t)$		$v_k(t) = v_{k+1}(t)$	0	-
3	Merging state	$\Delta x_k(t) > \Delta x_k^{smin}(t)$		$v_k(t) < v_{k+1}(t)$	0	-
4	Transition state	$\Delta x_k(t) \le \Delta x_k^{smin}(t)$		$v_k(t) > v_{k+1}(t)$	0	-
5	Merging state*	$\Delta x_k(t) \le \Delta x_k^{smin}(t)$		$v_k(t) = v_{k+1}(t)$	b_{k+1}^{max}	-
6	Transition state	$\Delta x_k(t) \le \Delta x_k^{smin}(t)$		$v_k(t) < v_{k+1}(t)$	b_{k+1}^{opt}	Eq. (8)

* The state provided in the case that the distance between successive trains is shorter than minimum safe distance after transferring to the convoy state.

Based on the movement state for building trains into the same convoy as shown in the Table 1, the state movement that a couple of trains transferred from the merging to the convoy state could be explained by the Figure 2. Starting with the State 3 in that two successive trains are in the merging state where the actual separation distance between trains is still longer than the minimum safe distance ($\Delta x_k(t) > \Delta x_k^{smin}(t)$

). The Δx_k^{smin} is the modified separation distance calculated by the Equation (2). In which a following train has operated by a higher velocity for catching up with a front train ($v_{k+1}(t) > v_k(t)$), the separation distance between them has been shortened then will be equal to or slightly shorter than the Δx_k^{smin} (State 6) stimulating a following train decelerates by b_{k+1}^{opt}. A following train is stimulated to decelerate until $v_{k+1}(t) = v_k(t)$ in order to be transferred to the convoy state (State 2) where the velocity of successive trains is equal to maintain the separation distance between them. Due to the deceleration of a following train, the minimum separation distance is re-calculated resulting the decrease in the required minimum safe distance. It can be confirmed that the actual separation distance when trains have operated through the convoy state is slightly longer than the current minimum safe distance. It is in the range between the current minimum safe distance and minimum safe distance required before transferred into the convoy state. When a couple of trains is in the convoy state, a leading train might accelerate lengthening the distance away from its following train. Suddenly after accelerating, current leading train's velocity is higher than a following velocity ($v_k(t) > v_{k+1}(t)$) and the required minimum separation distance is updated again and tend to be decreased due to a higher velocity of a leading train. The state movement of the trains is transferred from the State 2 to the State 1. As a result, a following train is stimulated to accelerate as well by a_{k+1}^{opt} until $v_k(t) = v_{k+1}(t)$ which merging a couple of trains into the State 2 again. If a leading train decelerates when it is in the convoy state, the distance separated from a following train is shortened but the minimum safe distance is increased due to a higher operating velocity of a following train. Thus, the actual separation distance after a leading train decelerates is definitely shorter than the required minimum safe distance leading both trains transferred into the State 6. Consequently, a following train is forced to decelerate by b_{k+1}^{opt} until $v_k(t) = v_{k+1}(t)$ that will transfer both trains moved back to the convoy state (State 2) again.

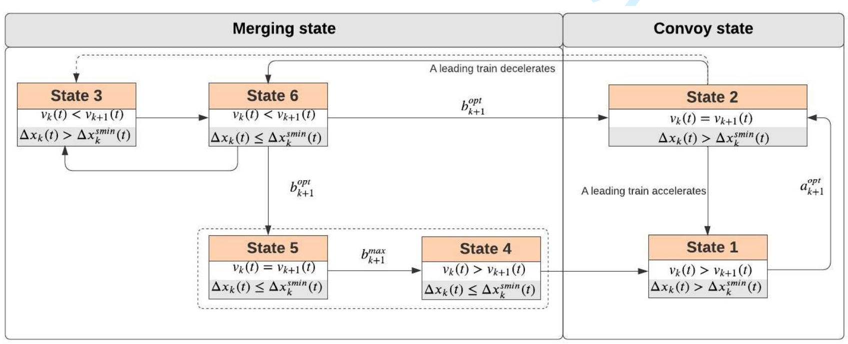


Figure 2: State movement of trains through the merging and convoy state

It is noted that the State 4 and State 5 is provided for avoiding unsafe movement during transferring state. In the case that a following train is forced to decelerate to be transferred into the convoy state, but after decelerating until $v_k(t) = v_{k+1}(t)$, the distance separated from a leading train is shorter than the minimum safe distance (State 5). In this case, a following train is stimulated to decelerate by b_{k+1}^{max}. Suddenly after decelerating, the trains are transferred from State 5 to State 4 in which a following train's velocity is lower than a leading train's velocity ($v_k(t) > v_{k+1}(t)$) and the distance between them is shorter than minimum safe distance ($\Delta x_k(t) \leq \Delta x_k^{smin}(t)$). A following train is not forced to decelerate for lengthening the distance from a leading train. It can proceed by constant velocity for lengthening the distance from a front train until the distance between them is longer than the minimum safe distance (State 1). After that, a following train is forced to accelerate by a_{k+1}^{opt} (m/s²) in order to be transferred to the convoy state (State 2). The acceleration and deceleration rates are limited and can be calculated by using the equations below. These could be ensured that the acceleration/deceleration rate not exceed the train capability.

$$a_{k+1}^{opt} = \min\left[a_{k+1}^{max}, \left(\frac{(v_k(t) - v_{k+1}(t))}{\Delta t}\right)\right] \quad (7)$$

and

$$b_{k+1}^{opt} = \min\left[b_{k+1}^{max}, \left(\frac{(v_{k+1}(t) - v_k(t))}{\Delta t}\right)\right] \quad (8)$$

A following trains might need more than one time step to adjust its velocity for transferring itself to the convoy state. For example, a following train with 0.5 m/s² maximum braking rate, has operated by 68 m/s for catching up with a train in front which has operated by constant velocity at 60 m/s. With 10 sec communication time step (Δt), the optimal braking rate of a following train is $b_{k+1}^{opt} = \min\left[0.5, \left(\frac{(68 - 60)}{10}\right)\right]$ = 0.5 m/s². A following train will firstly decelerate by 0.5 m/s² in which its velocity will be reduced from 68 m/s to 63 m/s. Due to the deceleration of the following train's velocity, the minimum separation distance between trains is also reduced forcing a following train moving by 63 m/s. until the actual distance separated from front train is lower than the current minimum safe distance. Then, a following train's velocity will be decelerated by $b_{k+1}^{opt} = \min\left[0.5, \left(\frac{(63 - 60)}{10}\right)\right]$ = 0.3 m/s² from 63 m/s. to 60 m/s to be transferred into the convoy state.

3.3.3 Splitting state

A following train split out from convoy by decelerating and has operated by a lower velocity than a front train until the actual distance separated from a front train is longer than the minimum safe distance required for MBS.

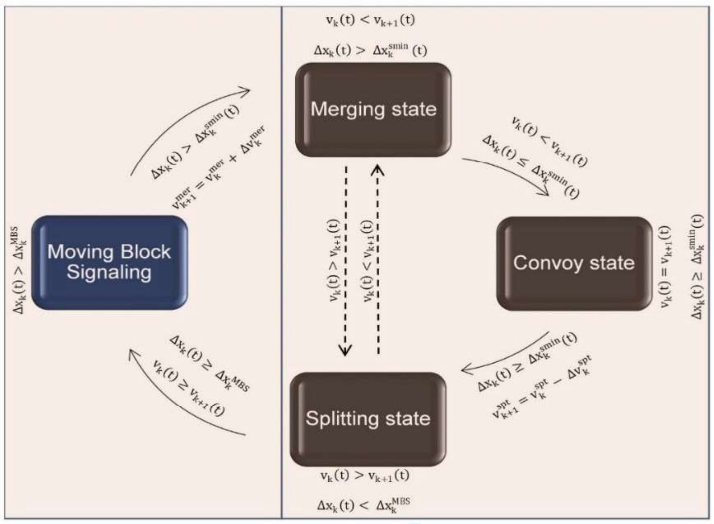


Figure 3: Transition between the MBS and the VCS

The Figure 3 shows the state movement of trains transited between the MBS and VCS. A following train can split out from convoy from every state by decelerating and has operated by a lower velocity for lengthening the gap separated from its front train. It is recommended that when a group of trains is approaching a junction and will continue on different lines, a following train should start splitting when it reaches the optimal splitting point (It is explained in the Section 3.2).

4 Test case and simulation results

The proposed approach introduced in the Section 3 is applied for controlling a following train in order to prove that whether the proposed approach is effective to control a following train's movement under the VCS.

Table 2: Operational parameters used in the simulation

Operational parameters			
1) Velocity limit along the line (v^{max})	70 m/s	7) Max. deceleration rate (b^{max})	0.5 m/s^2
2) Velocity limit at junction (v^{maxp})	30 m/s	8) Junction operation time (T^{pnt})	12 sec.

3) Time step (Δt)	10 sec.	9) Converging point (x^{cvr})	50 km.
4) Safety margin (SM)	2.4 km.	10) Diverging point (x^{dvr})	2 km.
5) Buffer at junction (SM^{pnt})	300 m.	11) Train length (l)	100 m.
6) Max. acceleration rate (a^{max})	0.5 m/s^2		

It is assumed that the trains have operated under normal conditions (i.e. no impact from weather and track elevation) and based on the operational parameters shown in the Table 2. Their movement have been simulated based on the proposed approaches using MATLAB (R2019a). Assuming that the trains depart from station A every 3 minutes and two successive trains will be merged into the same convoy proceeding by 60 m/s. when they are in the convoy state. The safety margin (SM) used in the VCS can be the same as used in the MBS (20).

According to the simulated distance and velocity profile of two successive trains shown in the Figure 4. Assuming that the successive trains have been merged as the same convoy by 5 m/s. merging velocity difference. The leading train 1 accelerates to 55 m/s. while the following train 2 accelerates to 60 m/s. after departing from station A. The separation distance between the leading train 1 and following train 2 has been decreased due to a higher velocity that the train 2 has operated for catching up with the leading train. The train 2 is stimulated to decelerates to 55 m/s. to be transferred into the convoy state when $\Delta x_k(t) \le \Delta x_1^{smin}(t)$ (Red dotted circle, at time 1570 sec.). Focusing on the operation through the convoy state, it is clearly seen that the following train has operated in relation to the leading train's movement. The following train 2 is forced to accelerate when the leading train 1 accelerate. It accelerates to the same velocity for maintaining the safe separation distance away from the train 1 (Time between 2840 - 2860 sec. and 3700 – 3730 sec.). When the train 1 decelerates (Time between 2350 – 2390 sec and 3150 – 3160 sec), the following train's velocity is not reduced instantly. It could operate by constant velocity then will be stimulated to slow down when the distance separated from the leading train is shorter than the minimum safe distance. If the leading train has moved by constant velocity, the following train has moved by the same velocity as well.

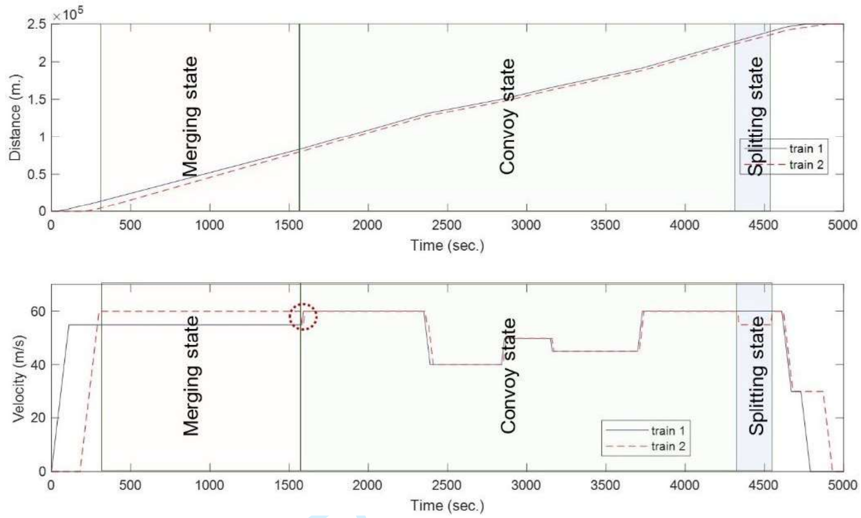


Figure 4:Distance and velocity profile of trains under the VCS

It could be concluded that the proposed approach can be applied for controlling a following train movement effectively in that a following train has proceeded according to the movement of its leading train.

5 An effectiveness of the proposed approach

Three aspects are determined to measure an effectiveness of the proposed state movement.

5.1 Capacity

It is assumed that the planning separation time between trains under the MBS (Δt^{MBS}) is 180 sec. Theoretical 20 trains could operate in an hour. The maximum number of trains operating under the VCS could be computed by using the Equation (9).

$$C^{max} = \frac{3600}{\Delta t^{avr}} \quad (9)$$

Where Δt^{avr} refers to the average separation time between trains within 1 hour time period. It is calculated by $\Delta t^{avr} = \left(\left(\sum_{k=1}^{N} \Delta t_k^{sht}\right) + \Delta t^{MBS}\right)/N$. where Δt^{MBS} is minimum permissible separation time under the MBS and N is the number of trains built in the same convoy. According to the simulated separation distance between two successive trains trough the convoy state shown in the Figure 5, it is seen that the separation distance between two trains is ranged between 3200 m. and 3550 m. resulting approximately 60 sec. separation time. Thus, the maximum theoretical number of trains under the VCS in case of 2 trains built as the same convoy is 30 trains/hour. 10 additional trains can be inserted into the line if compared with the MBS scenario.

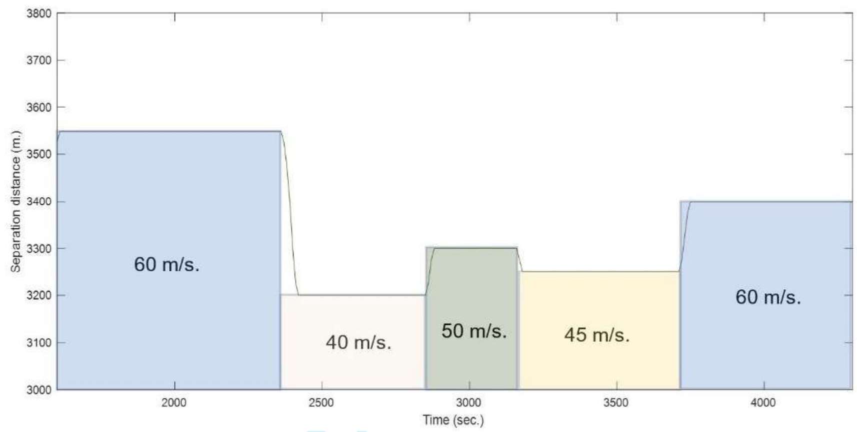


Figure 5: Actual separation distance during the convoy state

Based on the operational parameters in the Table 2, the minimum safe distance required for passing the diverging junction is about 3.8 km. (approximately 126 sec.). Referring to the simulated velocity profile when passing the junction shown in the Figure 6, the actual separation distance when passing junction is approximately 130 sec. headway time. Thus, the theoretical maximum capacity in terms of the number of trains passing the diverging junction is approximately 23 trains/hour (It is increased by 3 trains per hour comparing to the maximum number of trains under the MBS).

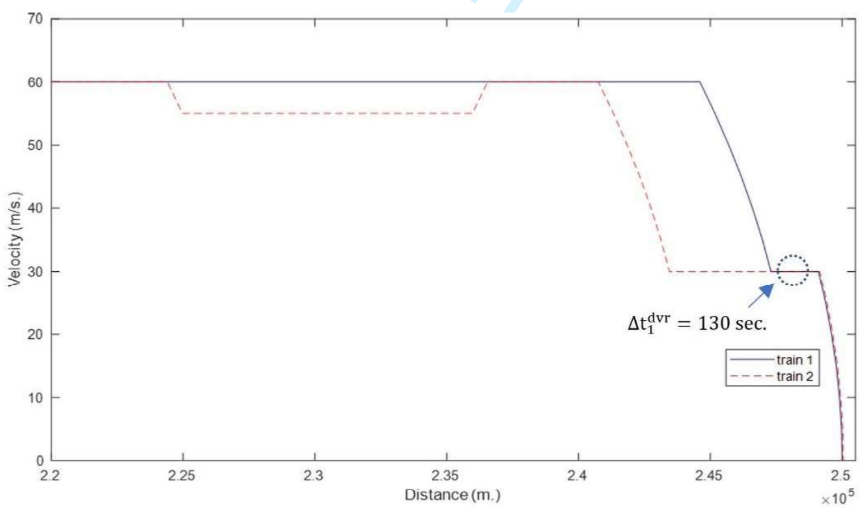


Figure 6: Velocity profile when passing a diverging junction

5.2 Safety

It can be decided that a following train has moved safely if the distance separated from its front train is longer than the minimum safe distance. The comparison between the actual and the minimum safe distance is shown in the Figure 7. It is obviously seen that the actual separation distance between trains is significantly longer than the minimum safe distance. Excepting the different distance in the red dotted circle, the actual distance between trains is shorter than the minimum safe distance due to the deceleration of a leading train while it is in the convoy state. It could be guaranteed that the trains still operate safely. This is because the minimum safe distance used in the proposed state movement (Equation (2)) is modified in that the additional term is added to prevent unsafe movement in the case that a leading train decelerate while proceeding during the convoy state. In the case that the separation distance between trains is shorter than minimum safe distance, the emergency brake is applied in which a train will be required to brake by the maximum braking rate. We provide state 5 in the proposed state movement (Figure 2) to adjust the distance between trains to make sure the distance between them is long enough.

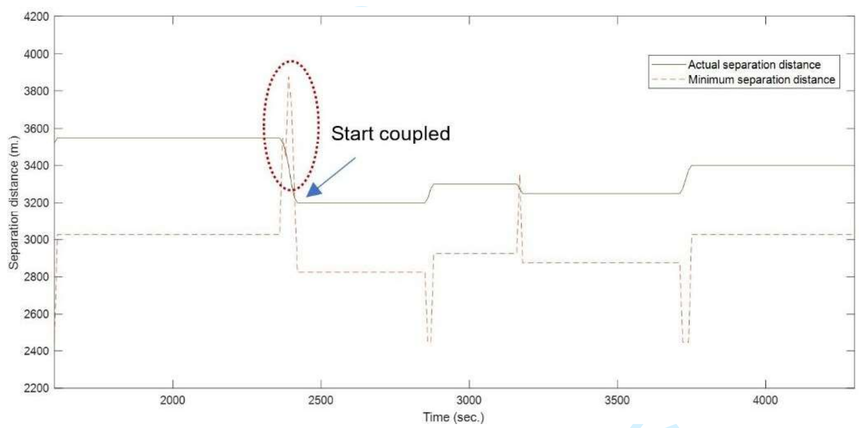
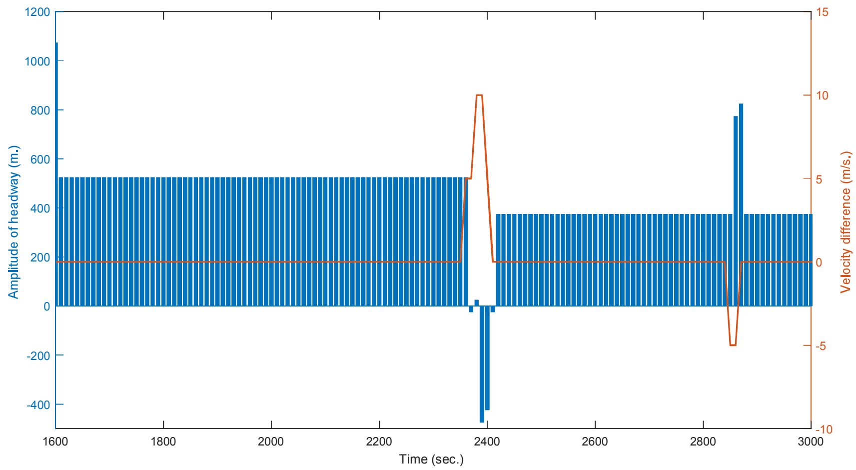


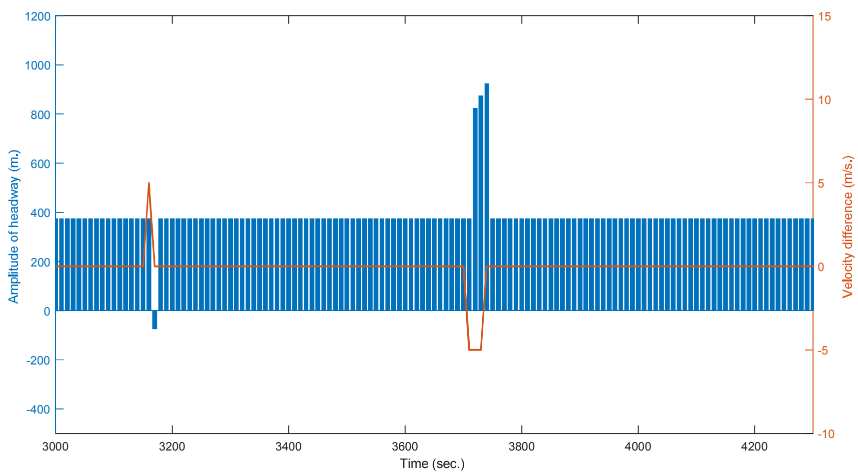
Figure 7: Actual and minimum separation distance between trains during convoy state

5.3 Stability

The variation of amplitude of headway distance (the distance from head to head of successive trains built into the same convoy) during the convoy state has been simulated as shown in the Figure 8. After transferred to the convoy state (Time: 1580 – 4300 sec.), the amplitude of headway between trains has been stable at 525 m. before reducing to 375 m. when the convoying velocity is decreased from 60 m/s. to 40 m/s. It is seen that the headway is mostly higher than 0 except in the case that the leading train decelerates causing a shorter gap than the minimum safe distance for a short time period. Interestingly, it is obviously seen that the amplitude of headway has been stable whenever the train accelerates or decelerates. Thus, it can be concluded that the trains under the proposed approach obtain a stable travelling headway through the time of operation.



(a) Convoy state: between 1600 – 3000 sec



(b) Convoy state: between 3000 – 4300 sec

Figure 8: Amplitude of headway distance

6 Conclusion

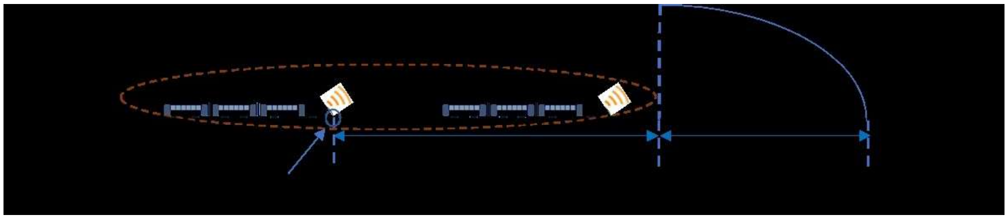
According to the simulation results shown above, it can be concluded that the proposed state movement could be applied for controlling a following train's movement under the VCS effectively. It can be used effectively achieving 3 objectives including an increasing in capacity, improving safety, and improving stable travelling. The capacity is maximized as the actual separation distance when trains has operated during the convoy state is slightly longer than the minimum safe distance and is increased comparing to the capacity under MBS. Approximately 50% capacity is increased compared to the capacity under the MBS.

It could be confirmed that the trains have proceeded safely preventing the collision between them in that the actual separation distance between successive trains is longer than the minimum safe distance. The following train has driven smoothly and obtain stable travelling in every state. It is merged, convoyed, and split by using constant velocity. It only moves in an unstable manner for a short period during the transferred state.

7 Reference

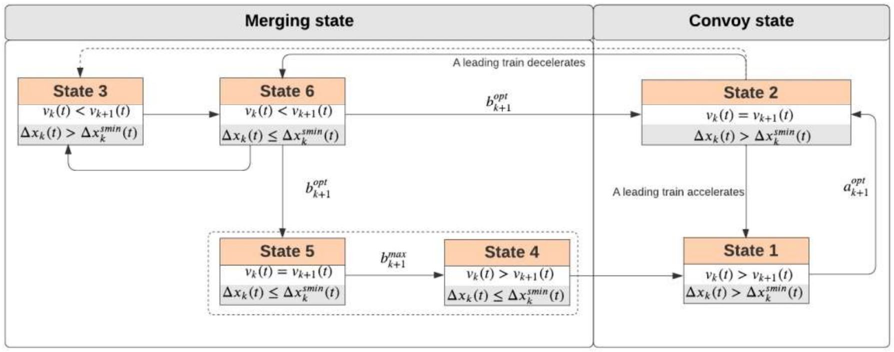
1. Flammini F, Marrone S, Nardone R, Petrillo A, Santini S, Vittorini V. Towards railway virtual coupling. ResearchGate. 2018.
2. Duan H, Yang Y, Duan Y, Zhang J. Research on Virtual Coupling Train Operations Based on Moving-Block and Vehicle-to-Vehicle Communication. Journal of Physics: Conference Series. 2020.
3. Quaglietta E, Wang M, Goverde RMP. A multi-state train-following model for the analysis of virtual coupling railway operations Journal of Rail Transport Planning & Management. 2020;15.
4. Li K, Guan L. Simulating train movement in railway traffic using a car-following model. Chinese Physics B. 2009;18.
5. Ye J, Li K, Jiang X. Stability analysis of train movement with uncertain factors. Mathematical Problems in Engineering. 2015;2015.
6. Mitchell L. ERTMS Level 4, Train Convoys or Virtual Coupling. International Technical Committee; Report on topic 39. 2016.
7. McNaughton A. Signalling Headways and Maximum Operational Capacity on High Speed Two London to West Midlands Route High Speed Two Ltd. 2011.
8. Zhao Y, Orlik VP, Kalmar-Nagy T. Improvement of train transportation performance by convoy signaling. 2015.
9. Xu X-M, Li K-P, Yang L-X. Discrete event model-based simulation for train movement on a single-line railway. Chin Phys B 2014;23.
10. Yang L, Li F, Gao Z, Li K. Discrete-time movement model of a group of trains on a rail line with stochastic disturbance. Chin Phys B. 2010;19.
11. Li K-P, Fan H-Q. The relationship between energy consumption and train delay in railway traffic. Chinese Physics B. 2010;19.
12. Henke C, Trachtler A. Autonomously Driven Railway Cabin Convoys – Communication, Control Design and Experimentation. 2013;International Conference on Connected Vehicles and Expo (ICCVE).
13. Li K, Gao Z. An improved equation model for the train movement. Simulation modeling practice and theory. 2007;15:1156-62.
14. Ye J, Li K, Jin X. Simulating train movement in an urban railway based on animproved car-following model. Chin Phys B. 2013;22.
15. Li K-P, Gao Z-Y, Tang T. Modelling and Simulation for Train Movement Control Using Car-Following Strategy. Communications in Theoretical Physics. 2011;55.
16. Li K, Gao Z, Ning B. Cellular automaton model for railway traffic. Journal of Computational Physics. 2005;209:179-92.
17. Cao C-X, Xu Y, Li K-P. Modeling and simulation of high-speed passenger train movements in the rail line. Chin Phys B. 2013;22.
18. Henke C, Vocking H, Bocker J, Frohleke N, Trachtler A. Convoy operation of linear motor driven railway vehicles. LDIA 2005; Kobe-Awaji, Japan2005.
19. Pan D, Zheng Y. Dynamic control of high-speed train following operation. Traffic&Transportation. 2014;26.

20. Quaglietta E, Goverde RMP. Exploring Virtual Coupling: Operational Principles and Analysis. ASPECT 2019. 2019.
21. Ketphat N, Whiteing A, Liu R, editors. Train Movement Under the Virtual Coupling System. The 6th Thailand Rail Academic Symposium; 2019; Thailand: Springer.
22. Rabouël J, Robin P, Boagey A. Operational concept study technical note: HS2 Capacity and Reliability. Systra: Systra; 2011. Contract No.: B120A001,B120/SC/EUR/635-11.
23. Schumann T. Increase of capacity on the Shinkansen high-speed line using virtual coupling. Int J Transp Dev Integr. 2017;1:666-76.



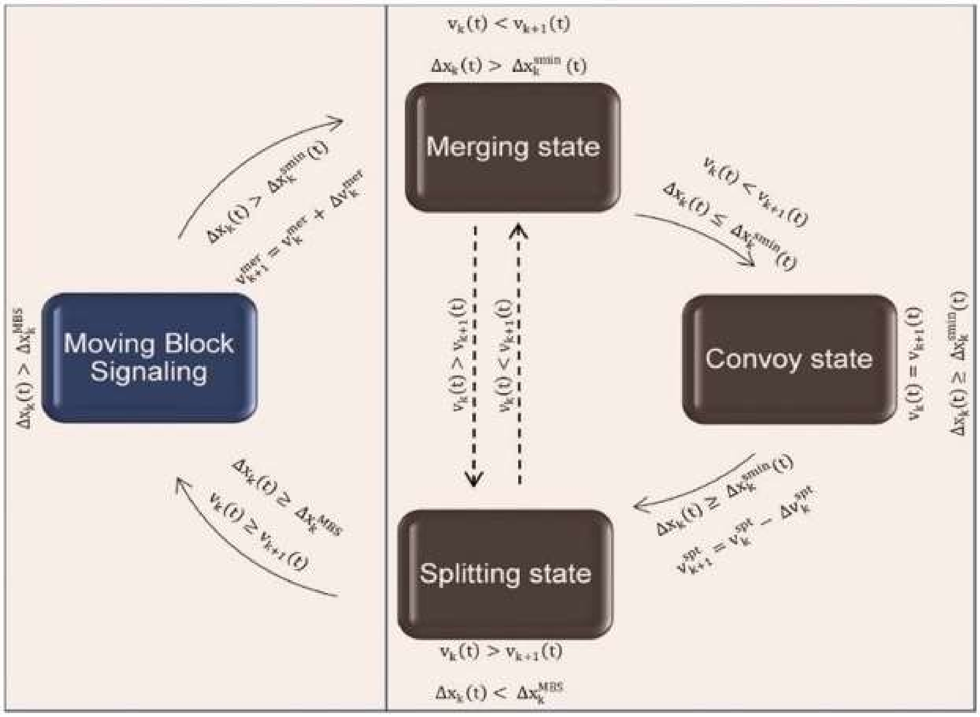
Safe zone and optimal splitting point

200x42mm (150 x 150 DPI)



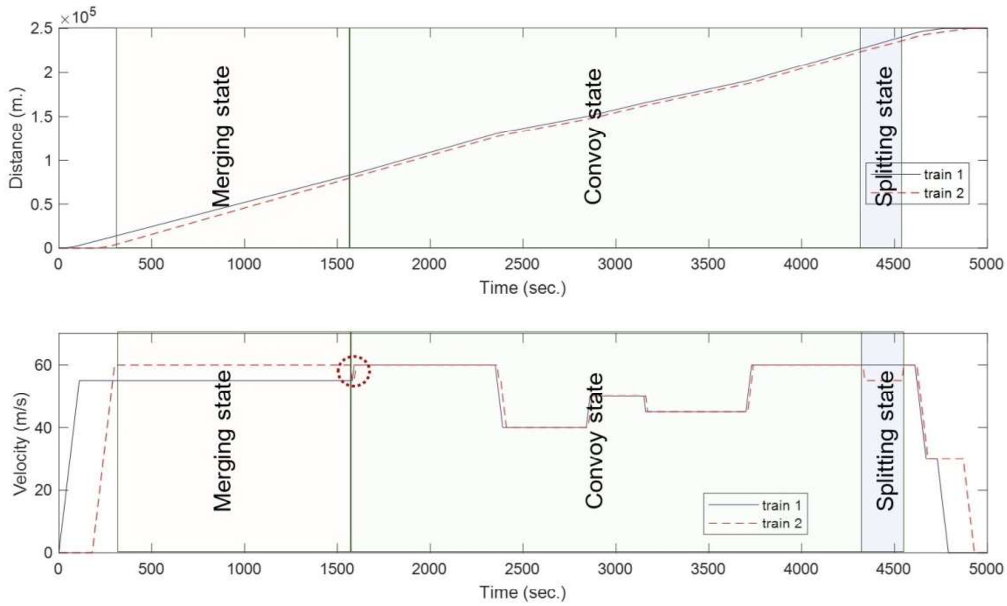
State movement of trains under the VCS

253x102mm (160 x 160 DPI)



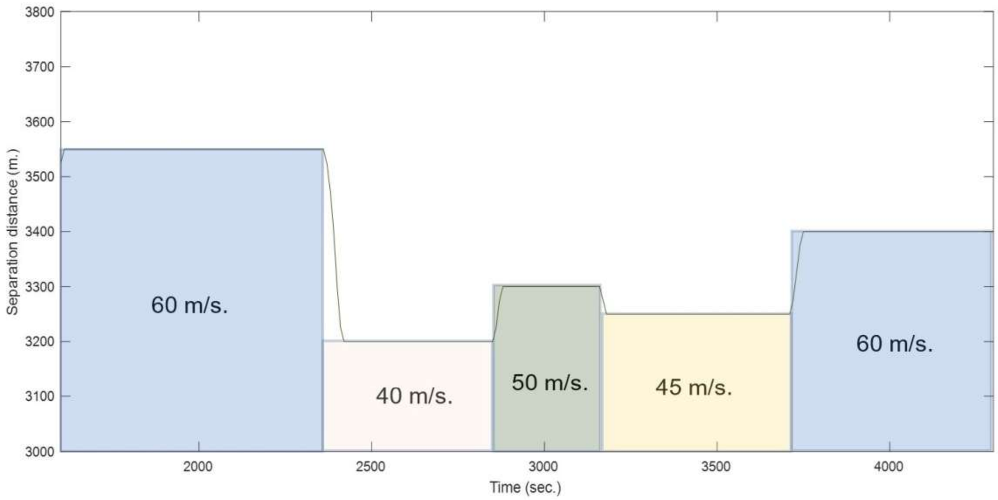
Transition between MBS and VCS

112x82mm (144 x 144 DPI)



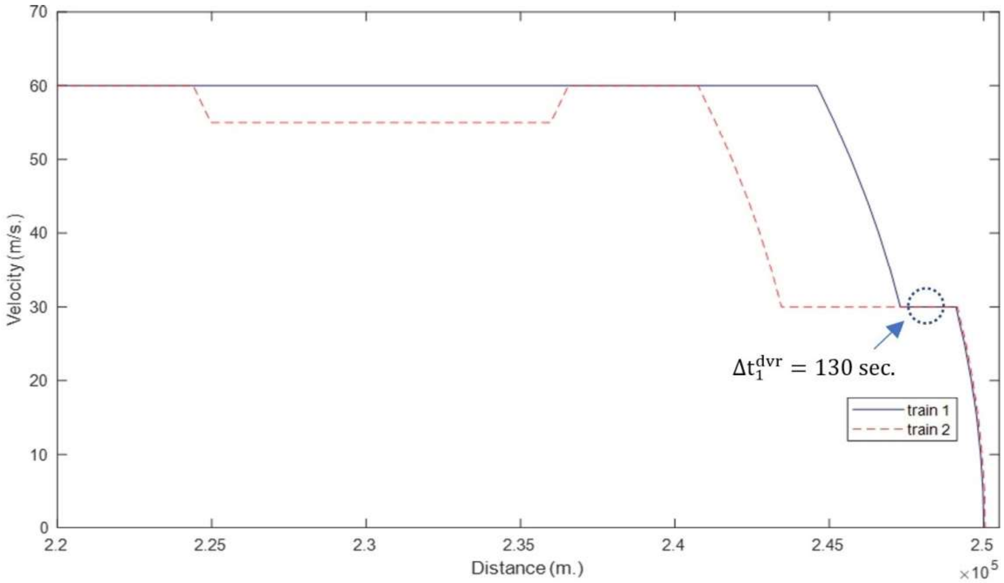
Distance and velocity profile of trains proceeding under the proposed state movement

263x158mm (144 x 144 DPI)



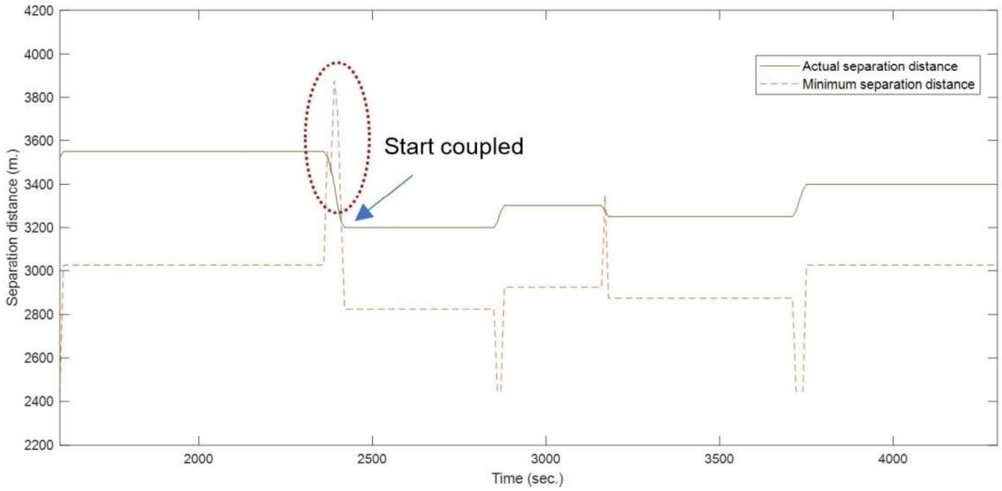
Actual separation distance during the convoy state

264x133mm (144 x 144 DPI)



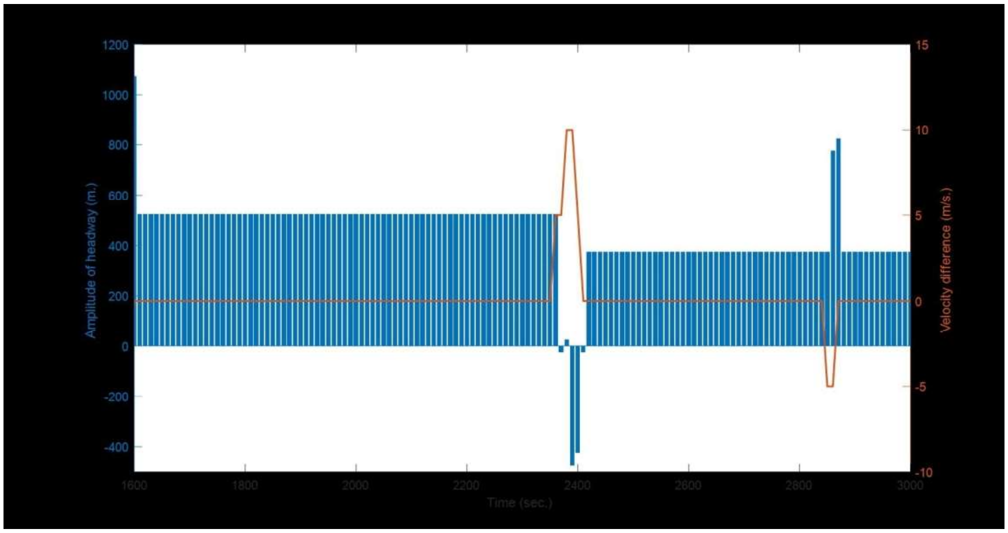
Velociy profile of trains when passing a diverging junction

264x152mm (144 x 144 DPI)



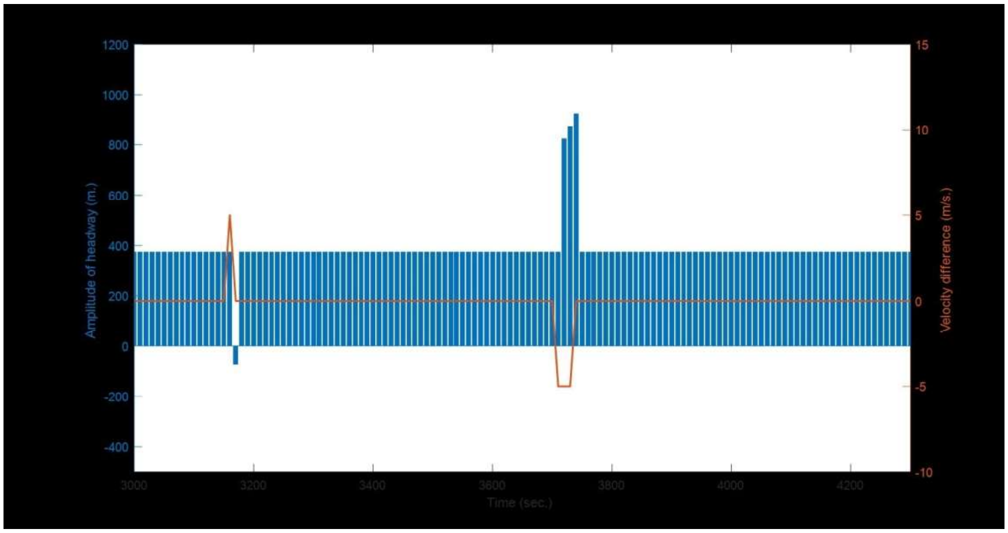
Comparision between actual and minimum safe distance

263x128mm (144 x 144 DPI)



Amplitude of headway distance (a)

291x153mm (144 x 144 DPI)



Amplitude of headway distance (b)

291x153mm (144 x 144 DPI)